A Literature Review on the Utilization of Origami in the Design of an Active Surface for 3-DOF In-plane Manipulation

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Abstract

Due to its many advantages, origami is increasingly used in the design process of engineers in the last decades. While static origami is extensively used in a range of industries, kinematic origami remains less explored. One application where kinematic origami is a promising solution is in the design an active surface that manipulates an object in the three in-plane degrees of freedom. In order to explore how origami can be utilized in the locomotion of such an active surface, this review categorizes locomotion principles found in mobile robots, presents a solution map of origami-based devices that use these principles, and examines how they can be integrated into the design of these surfaces.

Origami-based locomotion has been found in eight out of eleven locomotion categories, giving rise to multiple new feasible locomotion strategies where origami can be utilized. Conversion of these locomotion concepts has resulted in five feasible families of active surface concepts based on vibration, stretching, peristaltic motion, walking, and undulant rolling; these concepts can serve as a starting point for engineers in the design process of an active surface.

Keywords: Origami, Manipulation, Locomotion, Active Surface

1 Introduction

The traditional Japanese paper art of origami has been practiced for centuries to create intricate three-dimensional structures out of two-dimensional sheets of paper. While originally used for aesthetic and traditional reasons, in the recent decades it has increasingly sparked the interest of engineers to be utilized in more practical applications. Advances in the mathematical understanding of origami, combined with advances in computer science, have resulted in new design techniques that enable engineers to utilize origami efficiently. Due to its broad range of advantages it has been applied in leading industries with complex design problems such as the biomedical, space, and high-tech industry.

In engineering, origami is generally utilized in two different ways: it can be used as *static origami*, or as *kinematic origami* [1]. In static origami applications, the origami is merely used to transform a 2D sheet into a desired 3D shape. Often it used for compact storage and deployment, e.g., in minimally invasive biomedical applications [2,3], compact transportation in space [4–9], and portable defense structures, [10–12]. Furthermore, static origami is used to create objects that can transform their shape in order to change properties, such as antennas with variable frequency [13], shape morphing building envelopes for climate control [14] or wheels with a variable diameter for different terrain types [15, 16]. It can also be used to create material structures that have enhanced load bearing [17, 18] or energy absorption [19–21] capabilities. Finally, it can simply be used as a method for cheap and general 2D manufacturing.

Contrary to its static counterpart, in kinematic origami, the crease lines are exploited to function as joints in a mechanism when the system is in folded state. This effectively results in an origami-based mechanism that consists of revolute joints (the creases) and spherical joints (the vertices). Kinematic origami is more challenging to model, and therefore less explored than its static counterpart, but it is very versatile and could be used in a range of applications. Currently, it is used in compliant grippers for soft gripping of fragile objects [22–26], meta materials [27, 28], and locomotive robots.

The use of kinematic origami has several advantages over the use of conventional mechanisms. Conventional systems often require highly specialized and expensive fabrication and assembly processes, which lack customizability. Origami-based mechanisms have the potential to be made monolithically from a sheet, allowing for general, high-precision, 2-D fabrication techniques such as laser cutting, electrical discharge machining (EDM), and photolithography [29–33]. These 2-D techniques, combined with the possibility of integrated printed circuitry [34, 35], printed smart actuation [36], and self-

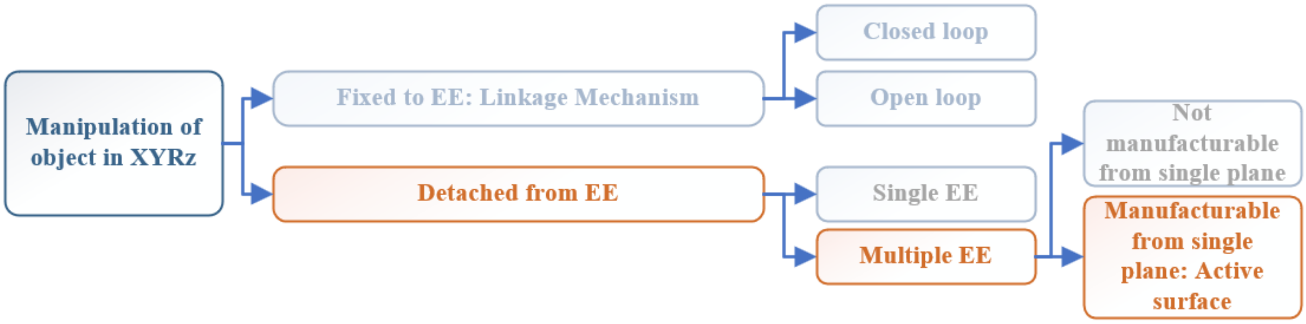

Figure 1: Classification of manipulators for X, Y and R_z. A full description is provided in Appendix A.

folding assembly [37, 38], enable a fully automated fabrication process.

These monolithic mechanisms have similar advantages to compliant mechanisms, such as the elimination of hysteresis in joints, getting rid of extra inaccuracies. Another advantage of the possibility of using compliant joints, is that no friction takes place, which increases their lifetime, and decreases particle generation, which is essential in clean room environments. Furthermore, no lubrication is needed in such joints, which makes them suitable for use in vacuum and cryogenic environments.

Due to its possibility to be manufactured monolithically, and due to the wide range of production techniques possible to create patterns, origami mechanisms are also easily scalable. They can be used from microscale, in Microelectromechanical Systems (MEMS) [30–33], to mesoscale and macroscale [14, 39]. Due to this scalability, tessellated origami has great potential to be used in metamaterials and metasurfaces.

Furthermore, origami can be utilized to introduce special properties to a mechanism or material. Metamaterials can be created with self-locking capabilities, and/or tunable (negative) Poisson's ratio [40, 41]. Due to its thin-walled structure, multi-stability can be achieved [40–42]. Moreover, origami mechanisms with adjustable stiffness can be created [43].

One application where kinematic origami is a promising solution is in the design of devices that manipulate an object in the three in-plane degrees of freedom: X, Y, and R_z. In order to make such a device, one could simply replace the joints in a traditional linkage-based manipulator with an origami equivalent. However, utilizing origami in the design of an *active surface*, is a much more promising approach, in which all advantageous properties of origami can be exploited. An active surface is a surface, which can be created by a single planar sheet of material, that can manipulate an object that is positioned on top of it. Figure 1 describes a definition of what we define as an active surface. A full description, together with a comprehensive categorization on 3-DOF in-plane manipulators can be found in Appendix A.

This paper will focus on these active surfaces over other manipulation techniques, because they are an excellent platform to utilize the advantageous properties of kinematic origami. When trying to scale down these surfaces, challenges arise that can easily be solved by utilizing origami, such as assembly and actuation problems. Furthermore, since origami can be created from a single sheet, it offers a perfect manufacturing method for these active surfaces. Moreover, a large advantage of active surfaces in general, compared to linkage systems, is that there are no large moving masses except for the object being manipulated. This could increase dynamic performance. Another reason to focus on active surfaces is for purely scientific reasons: these surfaces are more novel, which gives more opportunity for innovation, and studying these can contribute more to science than simply converting an already existing linkage mechanism. One of the difficulties, why this technology does not exist yet, is that a proper locomotion system has to be used. When one wants to manipulate an object on an active surface, different locomotion principles offer different properties, and not all locomotion principles are useful. Therefore, a literature study is needed in order to study these principles, and examine their feasibility to be integrated into an active surface.

The purpose of this paper is to create a solution map of locomotion principles that can be utilized in an origami-based active surface for 3-DOF in-plane manipulation. Since, at the moment of writing, no origami-based active surfaces exist yet, this paper chooses an approach where we study locomotion principles used to propel terrestrial mobile robots. These locomotion principles are categorized and analyzed, and an overview of origami-based robots that use these principles is presented. Subsequently, we examine whether new origami-based locomotion mechanisms can be created based on knowledge gaps, and their feasibility is studied. Finally, it is examined in what ways the origami-based locomotion principles found can be inverted and utilized into the design of an active surface.

2 Locomotion

In order to properly analyze the different origami-based locomotion concepts, classification is necessary (Fig-

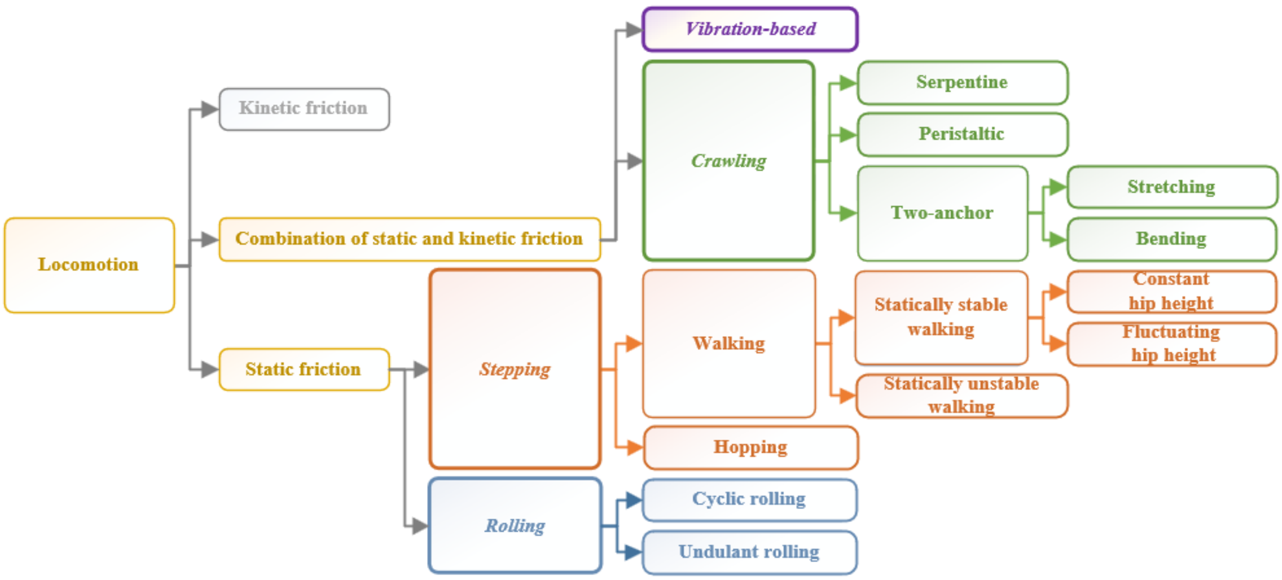

Figure 2: Classification of locomotion principles

ure 2). The structure of this section is based on this classification.

Firstly, the types of locomotion are classified on the type of friction that occurs when they are in operation. This can be either pure static friction, or a combination of both static and kinetic friction. With two types of locomotion, both types of friction are necessary to perform the motion. For *crawling*, this happens in a statically stable way. During the motion one or several components are anchored to the surface, while other components slide over the surface at the same time. With *vibration-based locomotion* both friction types occur in a statically unstable manner. When vibrating, the normal forces that the components of the robot exert on the surface constantly change, which causes an alternating sequency of static and kinetic friction. Note that with crawling, the two types of friction happen simultaneously in different components, while with vibration, the two types happen alternately, in the same component.

Robots using *stepping* and *rolling* both use only static friction to propel themselves; all segments of the robot that touch the ground have zero velocity. A system that can theoretically operate by pure static friction, but in practice skids, is also considered under this class. Rolling is defined as a motion with an infinite number of contact points; the point of contact with the ground changes continuously. On the other hand, stepping motion has a discrete amount of contact points where the points of contact change discretely with each step.

The type of division entails that a third class exists where only kinetic friction occurs. The lack of static friction implies that in this kind of motion, the friction coefficient between the robot and the surface is very low. In all known cases, this type of locomotion is a non-idealized, less energy efficient equivalent of locomotion of another class (e.g. rolling or two-anchor inching with constant slipping). Therefore these cases will be considered in the appropriate section of their idealized class.

Some mobile robots contain origami-based elements that do not directly incite the movement but serve other purposes. For example, in the Salamanderbot [44], an origami structure is used to deform its body, in order to adapt to different environments. In the PUFFER [8], created by NASA, origami is used in order to compactly store the robot before deploying it at its destination, and in the self-folding origami robot by Miyashita [45], origami is merely used for self-assembly. Since in these robots the origami does not directly contribute to the locomotion, their principles are not relevant to active surface design, and therefore they will not be included.

Crawling

In crawling locomotion, certain segments of a robot are anchored into the ground, exerting a forward force on the robot, while other segments move over the ground in a sliding fashion, causing kinetic friction. A pattern can be seen that the relative motion between these anchoring and sliding segments is usually caused by a deformation of the entire body of the robot. This makes crawling a popular method of locomotion in soft robotics. Chen et al. [60] have collected a large amount of crawling soft robots, categorized by their method of actuation. Calisti [61] presents, among other forms of locomotion, a description of crawling mechanisms and some of their applications in soft robotics. This paper uses the three distinct types of crawling motion Calisti presents: *two-anchor crawling*, *peristaltic crawling*, and *serpentine crawling*.

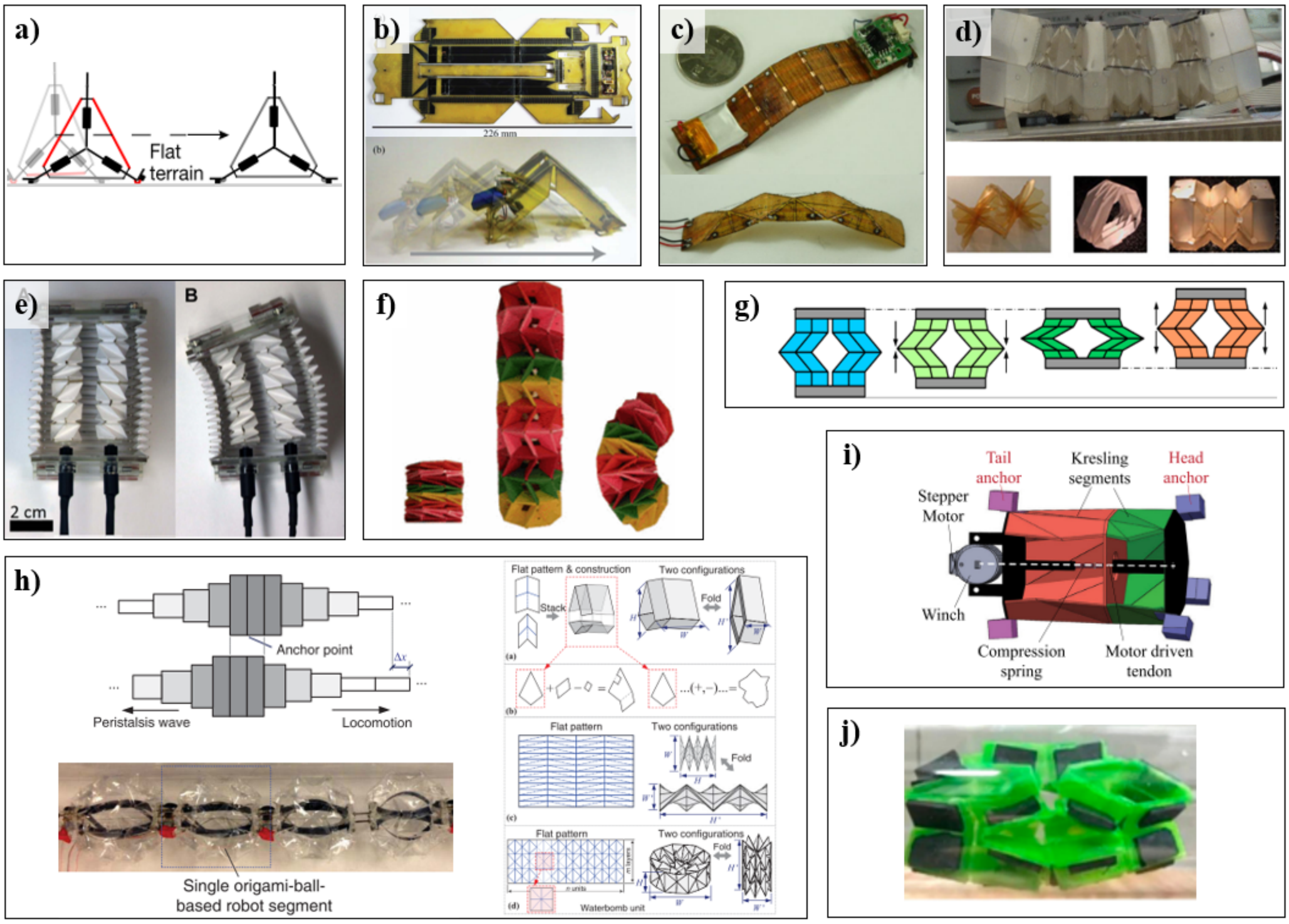

Figure 3: Origami robots that perform a crawling motion. a) Inching gait by Tribot. From [46]. b) Self-folding inching robot. From [47]. c) The inching Omegabot: using parallel creases (top), and a waterbomb pattern (bottom). From [48]. d) Inching robot based on expanding tubular origami structures (top), and proposed structures to be used in inching robots (bottom). From [49]. e) Steerable inching robot with two Kresling tubes. From [42]. f) Steerable inching robot with single twisting tower tube. From [50]. g) Flat steerable inching robot. From [51]. h) Peristaltic wave for crawling locomotion (top left). Suitable origami patterns for segments of peristaltic crawlers (right). Peristaltic crawling robot using origami ball structure (bottom left). From [52]. i) Peristaltic robot using Kresling pattern. From [53]. j) Prototype of origami Flexiball. From [54].

Two-anchor crawling

Two-anchor crawling is also commonly referred to as *inching*. An inching robot consists of two anchors on either side of the robot, connected through a middle segment. In an ideal case, one of the anchors stays stationary, while the second anchor moves relative to the first one by sliding it over the ground. When the sliding anchor has reached its desired position, the two anchors switch roles. This motion can only exist if the friction of the stationary anchor is higher than the friction of the sliding anchor. This can be achieved with anisotropic friction, or by switching the friction of the segments during motion. In reality, if the friction difference is not sufficient, the intended stationary anchor can often slide along the surface as well. While this is less energy efficient, it still generates an inching motion as long as the friction of the intended stationary anchor is higher than that of the sliding anchor. Two-anchor crawling can be further divided by the way the relative motion between the anchors is realized: through bending and extending, or through shortening-elongation of the body.

The *Tribot* [46] uses bending to achieve a very simple inching motion using only one revolute joint (Fig. 3a). Next to inching, which is used for flat terrain, this robot has multiple other gaits suitable for other terrain types, such as flic-flac walking. These will be discussed in their appropriate subsection.

Another folding robot that exerts an inching motion using only a single revolute joint is the self-assembling robot designed by Felton et al. [47] (Fig. 3b). This robot self-assembles into a more intricate structure, which increases the load bearing stiffness by loading the facets in-plane. For the thin-walled facets, this in-plane compressive stiffness is significantly higher than the out-of-plane bending stiffness in which the Tribot is loaded. In

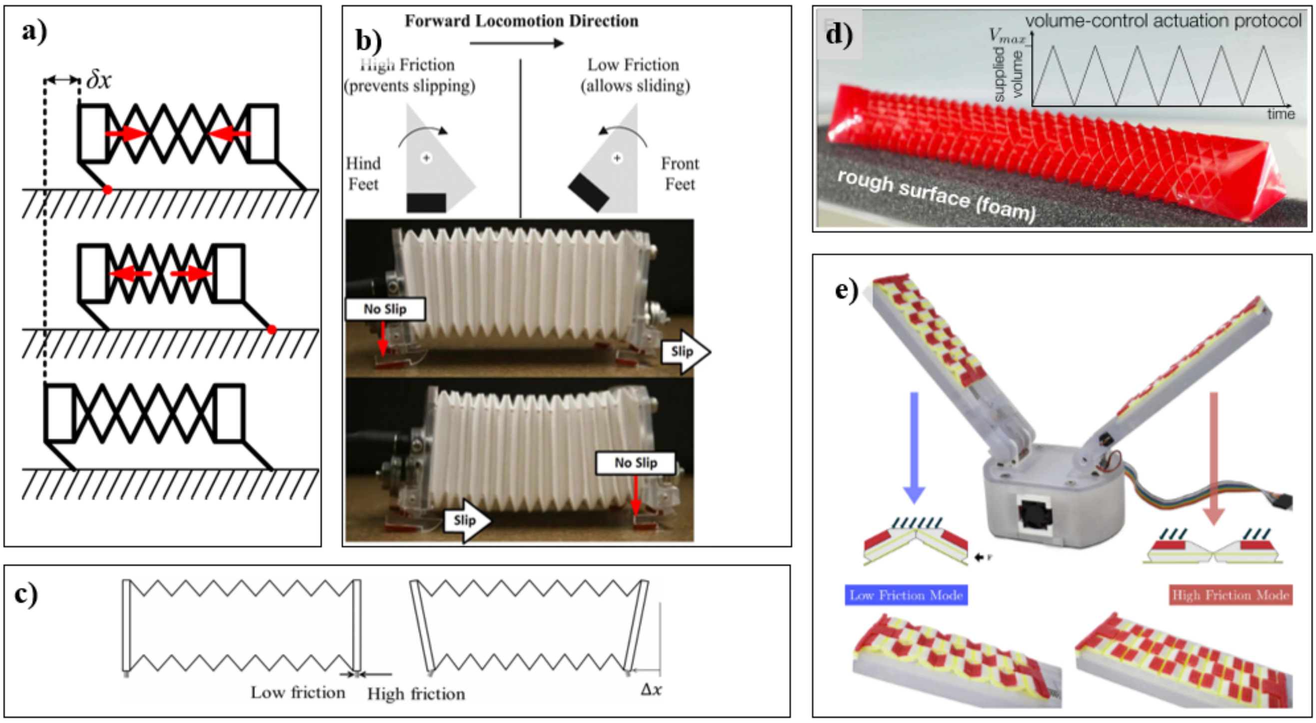

Figure 4: Methods to create adjustable friction. a) Anisotropic friction through angled pins. From [49]. b) Friction shift due to rocking feet (top), applied to inching robot (bottom). From [55] (top) and [42] (bottom). c) Flexible flap with different friction coefficients. From [50]. d) Bio-inspired kirigami snake skin. From [56]. e) Origami-inspired variable friction surface that can be manually triggered. From [57].

order to create the desired anisotropic friction, the legs of the robot are folded such that their contact points are angles backwards relative to the ground.

Furthermore, Koh et al. have introduced an origami-inspired robot called *Omegabot* [48](Fig. 3c). The simplest version consists of a strip with a set of parallel single creases to create a inching motion that can travel in a straight line. Further versions make use of a waterbomb pattern. With this pattern, when the robot is bent, an extra degree of freedom is introduced in the joints, which makes the robot able to change direction.

Often, in order to create achieve stretching two-anchor crawling with origami, tessellated crease pattern with many folds is needed to make the entire body of the robot extend and contract.

Onal et al. [49] present a method to create an inching motion based on stretching (Fig. 3d). This concept connects two anchoring segments with a tubular origami structure that can contract and expand. Both anchors are attached at an angle to create anisotropic friction. Three origami patterns are examined to build the tubular structure (Fig. 3d (bottom)): a waterbomb-based pattern, a modified Yoshimura pattern, and a modified diagonal pattern called "spring-into-action", designed by Jeff Beynon.

Pagano et al. present a similar concept [42] using the multi-stable Kresling pattern (Fig. 3e). This time, two tubes are used, with opposite chirality, such that the robot can carry out a turning motion.

OrigamiBot-I [50] can perform a similar motion using an origami tubular structure called *twisted tower* (Fig. 3f), first designed by Mihoko Tachibana. In this design, the robot is actuated with four tendons, which enables it to make a turning motion with a single tube.

Inspired by Pagano, Yu et al. [51] present a concept based on a Miura-Ori pattern (Fig. 3g). With this pattern, the tubes only expand sideways when contracting, making the robot especially suitable for a height-limited space. Several other tubular origami structures could be used to create a similar concept, such as the structures with high flat-foldability like the ones presented by Liu [62].

Peristaltic crawling

Robots using peristaltic motion exists of multiple segments, which can each perform a radial contraction simultaneous to an axial elongation. During motion, a wave of contraction travels through the robot in backward direction, making the robot move forward (Fig. 3h). This type of robots does not necessarily require anisotropic friction, because they can control friction by the amount of segments contracting at the same time. They can however benefit from it. It is often used in soft robotics, and different forms of actuation can be used, such as voice coils [63], pneumatic actuation [64], or SMAs [65].

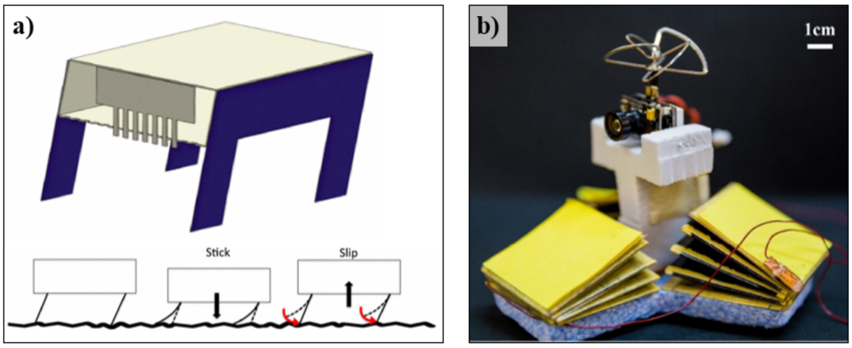

Figure 5: Vibration-based origami robots a) Self-foldable stick-slip robot (top), and its stick-slip locomotion principle (bottom). From [58]. b) Accordion-driven soft robot. From [59].

In order to create an origami-based peristaltic crawler, tessellated origami patterns with a positive Poisson ratio should be used. Fang et al. [52] examine of a several of those patterns (Fig. 3h): the stacked Miura-Ori structure, the spring-into-action, and an origami ball design. Eventually, the origami ball design is selected to be incorporated into the design of a peristaltic crawler. Banerjee et al. [66] have created a similar concept, using a Yoshimura pattern.

The control of peristaltic crawlers can be simplified significantly by using the bistable Kresling pattern [53] (Fig. 3i). In this design, anchors are attached to the edges of the pattern to provide for the necessary radial expansion during axial contraction. The Flexiball [54], shown in Fig. 3j is a similar concept with a slightly different pattern that enables easy magnetic actuation.

Serpentine crawling

Serpentine crawling (also known as lateral undulation) is inspired by the locomotion of snakes. During motion, a lateral wave propagates backwards through the body of the robot. When, during this wave, an element of the snake moves in inward direction, a friction force in the opposite direction is generated. When the component of this friction force along the body is higher then the tangential friction component, the body will move in forward direction. Therefore the key to serpentine locomotion is a difference in friction coefficient in the snakes body [67]. Hirose and Morishima have been the first to study this, and based on their findings, created multiple snake-like robots that utilize serpentine locomotion [68]. These robots consist of rigid discrete links performing the necessary lateral wave. The difference in friction is established by installing passive wheels. Similar robots have been designed by Saito et al. [67] and Klaassen et al. [69]. More recently, Onal and Rus have created a soft robot that utilizes the same concept to create a soft snake-like robot. This robot uses pressure to deform its body, similar to actual snakes [70]. Even though Onal's robot is soft, it still uses discrete segments. A soft robot that has the potential to move near-continuously is the graphene based soft robot by Yang et al. [71]. Next to serpentine locomotion, this robot can also perform concertina locomotion, which is similar to two-anchor crawling. To the author's knowledge, no origami-based robots currently exist that utilize serpentine crawling.

Friction

As stated, the friction of the segments of the robot that are in contact with the ground needs to be either anisotropic or variable in order to facilitate two-anchor crawling. Furthermore, variable or anisotropic friction can assist in peristaltic crawling.

Anisotropic friction can be achieved by adding an asymmetric structure to the contacting segments. This can be done on macro scale, adding angled pins or ratchets, such as is done with the robots by Felton [47] and Fang [49] (Fig. 4a). There are also similar solutions on micro scale to create anisotropic friction, such as building arrays of angled micro-fiber arrays [72]. These methods of anisotropic friction enable the robot to walk only in a single direction.

Variable friction can be designed to naturally change with the motion, or can be triggered manually by a controller. It can be achieved by variation in the friction coefficient of the material touching the surface, or by change in geometry. The inching-by-stretching robot by Pagano et al. [42] (Fig. 3f) uses rocking feet in order to change the friction coefficient of the feet automatically during motion. When the robot stretches, the feet turn into position such that the hind feet touch the surface with a high-friction material, while the front feet touch the surface with a low-friction material (Fig. 4b). The same method can be used in inching-by-bending, e.g. in the soft robot by Umedachi et al. [73]. Origamibot-I [50] uses a similar approach by attaching a flexible flap, with low-friction material on one side and high-friction material on the other side (Fig. 4c).

In the gripper created by Lu et al. [57], an origami-inspired pattern is used to manually trigger the friction coefficient of the surface of a gripper (Fig. 4e). In the prototype, this is done on macro scale, but the technique can be scaled down in order to create a micro scale variable surface.

In a design inspired by snake skin [56], Rafsanjani et al. utilize a kirigami pattern in order to automatically switch the amount friction in a soft crawling robot (Fig. 4d). When the diameter of a segment of the robot increases during crawling, buckling causes the skin texture to pop up, greatly increasing the friction. When the diameter decreases, the friction decreases again.

Vibration-based locomotion

The self-deploying robot by Weston-Dawkes et al. [58] performs vibration-based stick-slip locomotion. An eccentric rotating mass (ERM) motor causes the robot to vibrate, compressing and relaxing its compliant legs. These angled legs stick to the surface and flex when they are compressed, and slip when relaxed (Fig. 5a), which causes a linear motion.

The soft active origami robot by Li et al. [59] utilizes a different concept for vibration-based locomotion. An origami accordion with one constrained edge is made to expand and contract due to electromagnetic forces when subjected to AC voltage. Because one edge is constrained, the robot vibrates asymmetrically, which leads to a translation in the direction of the constrained edge. By attaching three origami accordion actuators to a soft platform, a multi-directional robot is created that can traverse a 2D plane (Fig. 5b). By aligning the axes of the actuators off-center, one could incorporate a rotating motion about the Z-axis.

Rolling

Cyclic rolling requires an unlimited rotational motion around an axis. It is the most common locomotion strategy used in mobile robots. It is simple to actuate with a continuous rotary motor, to fabricate, and to control. Most available rolling robots however, do not have three holonomic DOFs. Usually they can reach three non-holonomic DOFs through steering and forward or backward motion.

To the authors knowledge, no current mobile robots use an origami mechanism for rolling locomotion. Multiple robots have been developed that use origami-based wheels to change diameter [15, 16, 74]. However, in these wheels, the origami mechanism does not incite the motion; it is merely used to change the properties of the wheel itself, and will therefore not be included in this study.

In addition to cyclic rolling, where a continuous motion is required, Schonebaum et al. propose an extra subclass of rolling named undulant rolling [75]. This type of rolling does not require a rotational motion around an axis, but instead uses an undulant motion. However, it exhibits the required properties to be classified under rolling: it uses only static friction, and there exists a continuous point of contact. A mobile locomotive device that uses this type of rolling is the Animaris Mulus Strandbeest [76], created by Theo Jansen. No origami-based equivalents of this locomotion type currently exist.

Stepping

Stepping is defined as locomotion that depends only on static friction, and where the contact points with the ground are discrete. Due to its nature, in almost all cases stepping is performed by limbs, while the body of the robot does not change shape (unlike many crawling robots). Stepping can be further categorized into *walking*, where at least one leg makes contact with the surface at all times, and *hopping*, where at certain points in time all legs leave contact with the surface simultaneously. Walking can be either *statically stable* or *statically unstable*. For statically stable walking, the movement can be stopped in any position without reaching an unstable state: it can be performed arbitrarily slow without the object falling over or changing position. Statically unstable walking, on the other hand, this is not the case. This type of locomotion is dependent on dynamic movement, and thus requires a minimum velocity. Within statically stable walking, we make a distinction between walking mechanisms where the leg's attachment point (i.e. the hip) maintains a constant vertical position, and mechanisms where the height of this attachment point fluctuates depending on the position of the leg. We will refer to the former as *Constant-Height Statically Stable walking* (CHSS), and to the latter as *Fluctuating-Height Statically Stable walking* (FHSS).

Elaboration on CHSS walking

The coupler curve of a mechanism of a leg that performs CHSS walking needs to have several special properties. To create a continuous walking motion, the mechanism needs to generate a cyclical closed path for the feet. Because the attachment point to the robot stays in the same vertical position, a reciprocating motion would cause the feet to touch the ground when returning to the starting position. Furthermore, in order to keep this attachment point at a constant vertical position, the bottom section of the generated path needs to be a horizontal (approximate) straight line.

One way to generate this desired flat-sided coupler curve is through proper control of either planar or spatial linkage mechanisms with multiple actuated degrees of freedom. Walking mechanisms found in nature use this concept, and thus it is often utilized in bio-inspired robots [82]. Depending on the way they are controlled, these robots can often perform multiple stepping gaits next to walking, such as running or jumping. Furthermore, if a spatial mechanism is used, they can often actuate all three planar degrees of freedom with the same set of legs.

On the contrary, a stable constant-height walking mechanism can also be achieved by synthesising a 1-DOF mechanism that has the required path as an output. There exist several walkers consisting of planar mechanisms that have optimized their dimensions in order to create such a straight-line cycle while having only one degree of freedom. Strandbeest [83], designed by Dutch

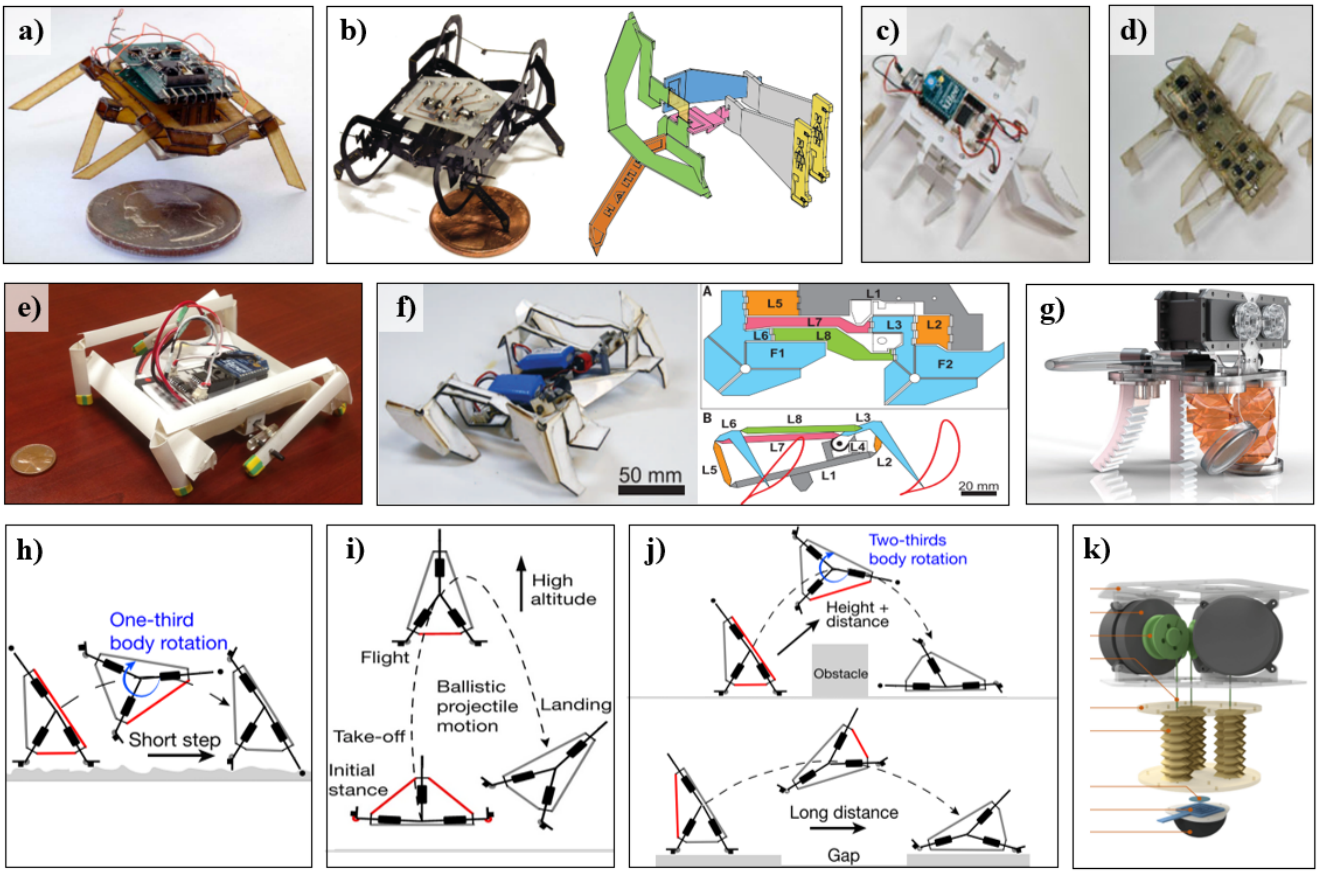

Figure 6: Stepping locomotion methods used by origami robots. a) RoACH. From [77]. b) Harvard Ambulatory MicroRobot (left) and its leg mechanism (right). From [78] c) Printed ant-inspired robot. From [35]. d) Hexapedal robot with rock-and-swing gait. From [35]. e) 2-DOF hexapedal locomotion platform by Faal et al. From [79]. f) Self-folding robot by Felton et al. (left), its crease pattern (top right) and the resulting leg mechanism (bottom right). From [34]. g) OPARO, bellow-based walking robot. From [80]. h) Flic-flac walking by Tribot. From [46]. i) Height jump by Tribot. From [46]. j) Distance jump (top), and somersault jump (bottom) by Tribot. From [46]. k) REBO hopper. From [81].

artist Theo Janssen, uses two connected four-bar mechanisms, driven by a crank. Using an evolutionary algorithm, he has optimized the system to create an efficient mechanism with a very long straight section. Similar systems are the Klann mechanism [84], the Plantigrade machine by Chebyshev [85], the Ghassaei leg mechanism [86], and the Strider [87] and Trotbot [88] mechanisms.

For very small angles ($\theta \ll 1$) a circular path can be approximated as a straight-line path ($\sin\theta \approx \theta$). Therefore, for a small range of motion, a system with just one continuously rotating leg, such as is used in the Zebro [89] and RHEx [90], can also be used for a constant-height walking system. Designing the feet, such that the contact points roll over the ground can greatly increase the range of motion. This kind of system can be considered a hybrid between stepping and rolling.

Statically stable walking

Statically stable walking usually requires four legs or more, since a minimum of three contact points with the ground is needed in order to stay in a stable position while other legs move.

Most of the currently existing origami-based robots use statically stable walking. In the walking mechanism of the hexapedal *RoACH* [77] (Fig. 6b), every leg has two degrees of freedom in order to create a closed-loop coupler curve. The pitch of the legs in the walking plane is controlled by a 4-bar mechanism. This generates a circular path of the feet, which causes the height of the legs fluctuate during motion. The roll of the legs, orthogonal to the walking plane, is used to lift the feet while the legs swing back to the start position, such that they do not touch the surface. These kinematics are designed such that the legs are coupled, and the full gait of the robot can be actuated with only two linear SMA actuators.

The *Harvard Ambulatory MicroRobot* (HAMR) [78] (Fig. 6c) has four legs, where every leg is based on a spherical five-bar mechanism. Like the RoACH, every leg has two degrees of freedom, one for the motion parallel to the walking direction, and one for lifting the leg orthogonally to the walking motion. These two DOFs are decoupled, and can be individually actuated per leg through piezoelectric actuation. Just like its hexapedal predecessors [91,92], the HAMR can perform both statically stable and dynamic walking depending on how it is controlled. The coupler curve of the leg mechanism can theoretically follow a rectangular shape, which is both cyclical and has a straight-line path at the bottom [93]. As a consequence, the body of the robot stays at a constant vertical position during motion, making it a CHSS walking mechanism. The design of the HAMR is not strictly origami-based, as it is made of multiple laminates and cannot be created from one plane. However, the concept can certainly be used for inspiration in the design of an active surface and is therefore included.

The printed ant-inspired robot by Onal et al. [35] (Fig. 6e) creates a statically stable walking gait through the utilization of static legs. While the four outer legs remain motionless, the two pairs of inner legs move in a circular motion. Therefore this mechanism can be classified as FHSS walking. During the bottom section of the circle, the static legs are lifted off the ground while the robot is propelled forward by the propelling legs. When the propelling legs are in the upper section of the circle, the robot rests on its static legs while the propelling legs move back in position. In order to turn, the two sets of propelling legs can be actuated independently. The circular motion is actuated with a DC motor, and there is no possibility for integrated actuation.

In the same paper, a hexapedal robot is introduced that performs a *rock-and-swing* gait (Fig. 6d). The two supporting middle legs move up and down, making the robot rock around its longitudinal axis. This rocking motion enables the two pairs of outer propelling legs to touch the ground alternately. This way, these outer legs need only one single degree of freedom; they move only forwards and backwards. Furthermore, it enables the legs to perform a turning motion by moving forward and backward alternately.

The design of a origami-based robot by Faal et al. [79] (Fig. 6f) has two sets of three legs. Each set has a single degree of freedom and is connected through a six bar linkage, of which the dimensions are optimized for step size. All six legs generate a non-flat coupler curve, which makes this robot perform FHSS walking. Similar to the ant-inspired robot by Onal et al., this robot is actuated by a continuously rotating DC motor, and thus integrated actuation cannot be used.

Both robots by Onal et al. (Fig. 6d,e), and the robot by Faal et al. (Fig. 6f) consist of linkage systems driven by a crank attached to a DC motor. In order to improve the stiffness of the linkages, the flat paper is folded into triangular beams. Felton et al. have also created a linkage-based foldable robot, driven by a continuously rotating crank [34] (Fig. 6g). However, instead of folding triangular beams, which have to be cut and require assembly, this robot uses a more sophisticated origami pattern. It uses single-vertex folds, which require no further attachment, and enable the robot to self-assemble. On each side of the robot, an eight-bar linkage drives two legs, creating a pointed closed coupler curve. An extra static leg (L1) supports the robot when the propelling legs are raised, enabling statically stable walking. In contrary to previous robots, this leg is not raised during motion, but instead slides over the surface, creating kinetic friction. However, since the forces this leg creates do not propel the robot, we classify this locomotion concept as walking.

In a completely different concept, the *OPARO* (Origami Pump Actuator Based Pneumatic Quadruped Robot) [80], shown in Figure 6h, uses two bellow-based front legs that are created with a Kresling pattern. These bellow legs are actuated by tendons in order to generate a walking motion. During motion, the bellows simultaneously work as a pump actuator for the hind legs, pumping air into them when contracted. With this pneumatic coupling the gait can be controlled using only two tendon-based actuators.

Statically unstable walking

During statically unstable walking, periods exist where the robot is in an unstable position. This is usually when two or fewer contact points with the ground remain when the legs are raised. In order to be able to perform this type of locomotion successfully, a dynamic movement is needed, or else the robot will fall over during motion.

A locomotion gait by an origami-based robot that can only be performed as unstable walking is the "flic-flac" gait by Tribot [46] (Fig. 6h). When taking a step, the SMA spring causes the robot to quickly shift its upper leg to the far right, causing it to tip over the right leg, and perform a one-third body rotation.

Hopping

Aside from inching and walking, the Tribot [46] can perform two types of hopping locomotion. In the "height jump", the two bottom legs "snap" together forcefully, propelling the robot upwards by pushing into the ground (Fig. 6i). Additionally, the Tribot can perform a "distance jump" or a "somersault jump" (Fig. 6j). These jumps are performed by snapping the upper leg and the right leg together with use of the SMA spring. Inertial forces then cause the robot to jump diagonally.

The *REBO Hopper* robot (Fig. 6k) [81] uses a tendon-driven bellow, in order to create a hopping motion.

3 Discussion

In this section, an overview is made for which locomotion principles an existing origami-based mechanism exist that performs this locomotion. Based on this overview, knowledge gaps are identified, and the feasibility of these knowledge gaps is studied. Secondly, we examine which of these locomotion principles are suitable to integrate into an origami-based active surface design.

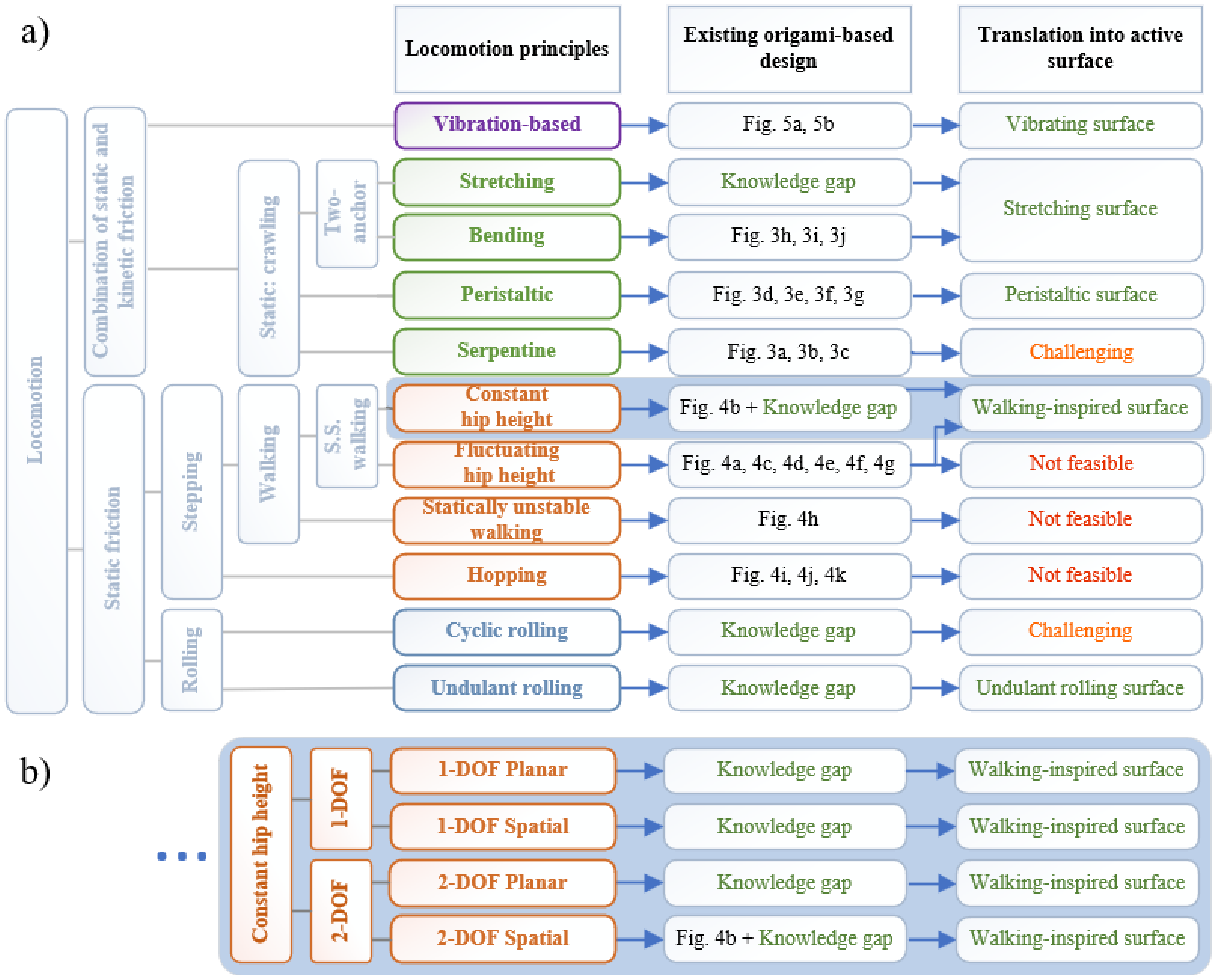

Figure 7: Overview of locomotion principles in terrestrial robots, their origami-based applications, and opportunities for translation into an active surface. a) For all locomotion principles discussed. b) For multiple methods to create CHSS walking.

In order to enable the opportunity to present more knowledge gaps, extra attention is payed towards the promising principle of CHSS walking. This type of walking is further subdivided according to the elaboration in the previous section; a distinction is made between 1-DOF systems and systems that use multiple degrees of freedom to achieve the required coupler curve. Moreover, planar and spatial mechanisms are separated.

Overview of locomotion principles

Figure 7 shows an overview of all subclasses of the locomotion principles, together with their existing origami-based applications. As can be seen, eight out of eleven locomotion principles are currently utilized, and knowledge gaps arise in four categories. This subsection studies the feasibility of these knowledge gaps.

As is shown, all crawling locomotion principles are currently utilized in origami-based robots, except for serpentine crawling. This type of crawling robot could be feasible. However, since this locomotion principle is complicated, and not a lot of conventional and soft robots have been developed that use it, designing the concept will be challenging. One challenge would be to create the required difference in friction coefficient without any wheels, while keeping the robot actuated locally. If one develops a large tessellated crease pattern that can perform transverse waves, inspiration for actuation and the control sequence could be found in the recently developed soft robots by Onal [70] and Yang et al. [71]. Undulant rolling is another concept that could be utilized in an origami-based terrestrial robot, but has similar challenges.

Cyclic rolling requires a continuous motion around a fixed axis. This is difficult to realize with origami because of its property that facets cannot intersect themselves, and thus the fold angle of a crease has a limited range of motion, depending on the facet thickness, with a maximum of $[-180°, 180°]$. The kaleidocycle [94] is an origami structure that can perform unlimited rotation. However, this motion cannot be performed when the kaleidocycle is attached to a base, since it will eventually collide with its attachment point. Only a single origami-based mechanism is known that does perform an unlimited rotation while fixed to a base. The origami rotor by Moses et al. [95] is a long kinematic chain of alternating tetrahedra that can perform this motion while the individual joints perform a limited rotation only. In their paper, Moses et al. propose a concept for a robot that performs a walking motion based on this rotor. This concept could be transformed to create a robot performing rolling, and therefore cyclic rolling is a feasible concept for new origami-based robots.

As can be seen in Figure 7b, only a single form of CHSS walking is currently utilized in origami-based mobile robots: the HAMR (Fig. 6b). This robot, however, is not strictly derived from origami, as multiple laminae are used in its construction. Therefore knowledge gaps exist in all four subcategories of CHSS walking.

One way to create an origami-based 1-DOF planar CHSS walking mechanism is to study and convert one of the mechanisms in FHSS walking robots (Fig. 6). It could be studied if these mechanisms are suitable to translate into an kirigami-based ortho-planar mechanism as described by Parise et al. [96]. One could also convert a straight-line system such as the Roberts, Watts, Grasshopper, or Peaucellier-Lipkin linkages, and extend them to become closed-loop. Lastly, one could design a completely new system with a novel topology that satisfies the requirements of ortho-planar mechanisms, and optimize this in order to approximate a straight line. Another option is to study an existing planar topology, such as the leg system in Figure 6e, and examine if the dimensions could be optimized to approximate the required coupled curve. Designing a true origami-based design without a continuously rotating crank input, is difficult. A major challenge with creating such a system is that one needs to create a closed-loop coupler curve with continuous motion without continuously rotating joints and with an open-loop reciprocating input. While the previously mentioned origami rotor [95] has proven it is mathematically possible to create such a system, it will be challenging to design. Moreover, because the input is reciprocating, one has to take into account singularities, further complicating the design. A similar problem arises when designing a 1-DOF spatial mechanism. This is however even more difficult. Next to the already existing challenges, no clear, structured design method exist to create such origami-based mechanisms.

Further knowledge gaps exist in the origami-based 2-DOF planar and spatial CHSS walking mechanisms. Similarly to a 1-DOF system, 2-DOF planar mechanisms could be converted to origami by creating an ortho-planar mechanism. Furthermore, the approach to modify the dimensions of an existing robot with (such as the self-folding robot by Felton et al. in Fig. 6f for planar mechanisms, or the RoACH in Fig. 6a for spatial mechanisms) could be optimized to fit the purpose. Moreover, a similar approach can be followed by analyzing the topology of the multilaminate HAMR, and examining if this topology can be converted to fit on a single lamina. Lastly, one could synthesise an entirely novel topology. Like the 1-DOF mechanisms, this will remain a challenge, as no structured design method exists for origami-based mechanisms with multiple degrees of freedom currently exist.

Origami locomotion principles in an active surface

Next to appointing knowledge gaps in origami-based locomotion, Figure 7 gives an overview of the feasibility of using these types of locomotion in an origami-based active surface. A total of five families of feasible active surfaces emerge, based on vibration, stretching, peristaltic waves, walking, and rolling. Two more families are deemed theoretically feasible, but have many challenges in its development.

Since the purpose of the active surface is to only move an object in-plane, without any vertical displacement, FHSS walking and hopping are not considered feasible solutions. Furthermore, due to its nature, statically unstable walking is not possible to be converted from mobile robots to active surfaces.

Vibrating surface

Vibration-based locomotion is an promising principle to be converted into an active surface.

Bristle-based stick-slip vibration, as used in Weston-Dawkes's robot (Fig. 5a) could be implemented one-on-one by turning the system around. Local or global actuation can be performed very simple by respectively attaching a single vibrating actuator [58], or an external magnetic field [97]. This makes an easily scalable, simple to manufacture active surface with a simple crease pattern. The direction, as well as the speed could be adjusted by changing the bristle angle with integrated distributed actuation. Another method of achieving multiple degrees of freedom is by equipping the surface with a range bristle angles that can be individually actuated (e.g., two for both directions along the X-axis, and two for the Y-axis). By actuating a combination of these sets, a rotational motion around the Z-axis could be achieved.

Stretching surface

Inspired by two-anchor crawling, one could create a surface folded into a tessellation that in its entirety can elongate and contract. This tessellation could be actuated with distributed actuation along the crease lines, or, when designed properly, can be locally actuated with a single actuator for each intended degree of freedom placed on the sides of the surface. When using local actuation, the tessellation should be designed to have exactly three decoupled degrees of freedom in the appropriate directions.

Incorporating a rotational aspect would be more challenging in this type of active surface. Several options exist. Firstly, one could get inspiration from the turning mechanisms used in the robots by Pagano (Fig. 3e), Yu (Fig. 3g), or the OrigamiBot-I (Fig. 3f). By contracting a certain section of the surface while extending a section parallel to it, a rotating motion can be generated. Moreover, the X- and Y-translation can be actuated simultaneously, which would also cause the object to rotate about the Z-axis. Lastly, one could incorporate a twisting property into the crease pattern of the tessellation. Many twists exist, ranging from simple regular triangle, square or hexagonal twists to irregular polygonal twists. Robert J. Lang describes multiple systematic approaches on how to synthesise twisting tessellations in his book *Twists, Tilings, and Tessellations* [98].

Peristaltic & Serpentine-based surface

Peristaltic motion is currently often used in tubular robots that inspect (sewer) pipes, or have to crawl through narrow spaces. However, the wave-like motion can also be used in the design of an active surface similar to the stretching surface. An undulating motion traveling through the tessellated surface could be used to manipulate the object on top of it. Two separate waves can be used in order to create a rotation around the Z-axis. The wave could be created using proper control of distributed actuation. However, in a more elegant solution, one could take advantage of the multi-stable properties of certain origami patterns in order to let the wave naturally propagate through the plane after an initial stimulation to the side, similar to the peristaltic robot by Bhovad et al. in Fig. 3i.

In a similar way, serpentine crawling can be an inspiration to create a surface that undulates in-plane instead of vertically. However, designing this is challenging due to the fact that there are no existing origami-based robots with this type of locomotion. Furthermore, a tessellation that only deforms in-plane, and satisfies the friction requirements for serpentine crawling, is difficult to design. Extending this to facilitate rotational motion around the Z-axis is deemed even more challenging.

Walking-inspired surface

A promising, and versatile approach to design an active surface is to implement locomotion inspired by CHSS walking. This surface can consist of a grid of unit cells, which each have the appropriate straight-line coupler curve. Creating the mechanism of such a unit cell can be done with a similar process as creating a novel origami-based CHSS walking system. All four subclasses that are distinguished in Figure 7b can be used. In the design of the unit cell, several extra concerns need to be addressed, such as the attachment point of the mechanism, and the way the mechanism is tessellated (tile size and shape). When using local or global actuation, a transmission between these unit cells is required.

In order to enable manipulation in both X- and Y-directions, one could implement two sets of unit cells that are orientated orthogonally. However, independent actuation of these two sets can be challenging when transmission is used. Rotation around the Z-axis can be achieved by operating the X- and Y-units simultaneously. Another option is to implement separate units. This could be a twisting unit similar to the one proposed for the stretching surface, or a unit with a curved coupler curve.

Rolling surface

One way to implement cyclic rolling into an origami based active surface is to modify the aforementioned origami rotor [95]. If this modified rotor is taken as a unit cell, and tessellated, a large surface can be created. By orienting the rotors in different directions, different degrees of freedom can be addressed. This design would however result in a very complicated crease pattern. Furthermore, actuation will be challenging due to singularity points, and local or global actuation will be impossible. This means every unit cell has to be actuated individually, which decreases the ability to scale down.

An undulant rolling surface is more feasible. Similar to the peristaltic surface, a wave can travel through the plane, causing undulant rolling of the object on top. The actuation can be achieved similarly, with either distributed actuation, or by using a multi-stable crease pattern. Analogous to the peristaltic surface, rotational motion can be achieved by two separate waves traveling in opposite directions.

Out of the five feasible families, the vibrating, stretching, and peristaltic surface experience friction between the object and the surface while the object is in motion. When designed properly, the walking-inspired and undulant rolling surface do not. The absence of friction is a major advantage, as it increases accuracy and decreases wear, which leads to less particle generation and a higher durability of the system.

4 Conclusion

The goal of this paper was to create a solution space for the design of a novel origami-based active surface.

To achieve this, existing mobile robots have been categorized based on their walking principles. Under the four main categories (vibration, crawling, stepping, and rolling), eleven subcategories have emerged. In eight of these subcategories, mobile robots with origami-based locomotion were found. Knowledge gaps were identified in four out of these eleven subcategories. By conversing the found locomotion principles has resulted in five feasible families of active surface concepts. These concepts are based on vibration, stretching, peristaltic waves, walking, and undulant rolling. Two families have emerged that could be feasible, but are deemed to have many complications. Three families have been considered infeasible due to displacement in Z-direction.

To the author's knowledge, no origami-based active surfaces have been developed yet. This paper studies this topic for the first time, and therefore, it can be used as a starting point for further research. The various opportunities presented in this paper can be used as a foundation for other engineers in the process of designing such an active surface. Future work can focus on finding specific topologies accompanying crease patterns to design these surfaces, as well as on their actuation and fabrication.

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A Classification of Manipulators

Many devices exist that manipulate and position an object in the three in-plane degrees of freedom. In order to examine how origami can be utilized in the design of these surfaces, different methods of manipulation are categorized. Because the main purpose is to utilize kinematic origami, only fixed-base manipulators based on solid mechanics are considered. Therefore other systems, such as those based on fluid mechanics [99] or electromagnetic forces [100] are not considered.

Within these fixed-base mechanisms, two main types of systems can be distinguished based on the attachment of their end effectors (EE), as seen in Figure 1. In the first type of manipulators, the object is attached to the end effector of the manipulator throughout the entire movement. Subsequently there will only be a single end effector, which will have the exact same degrees of freedom as the object. These linkage-based mechanisms consist of an open-loop or closed-loop kinematic chain of links, which are connected to each other through either rotational (R) joints, or prismatic (P) joints. The topology of these systems can vary based on its requirements, as well as the geometry of the links between them. A second type of manipulators consists of mechanisms where the object is detached from the end effector at certain points in the motion. This type can be further subdivided into multiple categories. There can be a single end effector, with either the same or more degrees of freedom as intended for the object, pushing the object around. These systems are comparable to attached-EE manipulators, thus origami applications will be similar. Furthermore, detached-EE manipulators can consist of multiple mechanisms, each with its own end effector, working in parallel to manipulate the different intended freedoms of the object. If the latter type can be manufactured from a single plane, we will refer to them as an *active surface*.