Mori: A Modular Origami Robot

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***Abstract*—This paper proposes a new robotic platform based on origami robots and reconfigurable modular robots. The concept combines the advantages of both robot types into a mobile, quasi-two-dimensional, lattice-type reconfigurable modular origami robot, Mori. A detailed description and analysis of the concept is validated by the presentation of a first prototype that incorporates the key functionalities of the proposed system. The modular robot prototype is mobile, can be connected to other modules of its kind, and fold up to create task-specific three-dimensional reconfigurable structures. Three implementations using the prototype in different configurations are presented in the form of individual modules, modular reconfigurable surfaces, and is applied to closed-loop object manipulation. The experiments highlight the capabilities and advantages of the system with respect to modularity, origami-folding, mobility, and versatility.**

***Index Terms*—Modular robotics, origami robotics, reconfigurable robotics.**

I. INTRODUCTION

RECONFIGURABLE modular robots are self-contained robotic units that, in combination, form robotic systems with the ability to change shape, configuration, and function. Reconfigurability in robotics allows systems to be more versatile in terms of the approach to, as well as the type of, the task at hand. Modularity, on the other hand, promotes the collaboration of multiple robotic units to perform tasks, which can encapsulate distributed computing, actuation, and sensing. Reconfigurable modular robots are a promising solution to multifunctional systems that can augment human–robot interaction. As there is no theoretical limit to the number of units comprising a modular robotic system, recent research efforts are focusing on extending their potential. This has been facilitated by advancements in the building blocks of reconfigurable modular robots, including actuator and sensor development, computing capacities, materials, and fabrication methods.

Similarly, the development of robotic origami, taking inspiration from the Japanese art of paper folding, has also been permitted by these advancements. It utilizes the transformation of light-weight two-dimensional (2-D) structures into three-dimensional (3-D) shapes to change morphologies and to address diverse tasks. The folding pattern can be used to achieve specific behaviors of the structure, while embedded actuators and sensors can provide the tools for versatile robots that can perform in all sorts of environments. The low thickness and weight of origami robots make them easy to store, transport, and expand into functional robots when needed. The flexibility arising from a large number of degrees-of-freedom (DoF) allows robotic origami to easily mold to and interact with an object's surface such as the human body. Robotic origami is inherently reconfigurable; however, it is not modular. It is constrained to the dimensions of the folding structure, as is a sheet of paper. Once the overall dimensions of an origami sheet are defined, it cannot be separated and rejoined elsewhere to allow for different morphologies without damaging the structure.

This work presents a new reconfigurable robotic system that takes inspiration from the concepts behind both modular and origami robots: Mori, a modular origami robot. A modular origami robot merges the features inherent to origami robots, namely low thickness, simplicity, and reconfigurability through folding, with the versatility achieved by modularity. The proposed concept consists of quasi-2-D robotic modules that, when combined with one another, can fold up on each other to create versatile 3-D configurations and fulfill tasks accordingly. We further present a first prototype, which has been implemented in multiple configurations, where each module is an equilateral triangle of thickness 6 mm, side length 80 mm, and a weight of 26 g. The work yields a new type of robot that overcomes some of the limitations of existing origami robots and introduces an innovative concept for a new type of reconfigurable modular robot that, to our best knowledge, has not been analyzed or implemented before.

This paper is organized as follows. Section II reviews existing work on reconfigurable modular robots and origami robots as well as their capabilities and applications. Section III presents the proposed concept of a modular origami robot, discussing key features, scalability, and potential. Section IV outlines our current design and prototype. Section V explores three functional implementations and experiments of the developed concept and prototype. The last section summarizes the paper and discusses the proposed system, prototype, and future work.

The main contributions of the work presented herein are as follows.

1) Introduction and analysis of a new robotic concept, a modular origami robot, taking inspiration from origami robots and reconfigurable modular robots.

Manuscript received October 23, 2016; revised January 19, 2017 and April 2, 2017; accepted April 11, 2017. Date of publication April 23, 2017; date of current version October 13, 2017. Recommended by Technical Editor Z. Xiong. This work was supported in part by the Swiss National Science Foundation START project and in part by the Swiss National Centre of Competence in Research (NCCR) in Robotics. *(Correponding author: Jamie Paik.)*

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Digital Object Identifier 10.1109/TMECH.2017.2697310

2) A functional prototype of the proposed concept, Mori, embodying the key attributes of a modular origami robot.
3) Experimental validation of Mori with three application-oriented implementations that highlight the key characteristics of the robot in terms of modularity, origami-like folding, mobility, and functional versatility.

II. Related Work

The robotic concept introduced in this paper relates to origami robots as well as reconfigurable modular robots. Previous work in both fields is outlined below.

A. Reconfigurable Modular Robots

Reconfigurable modular robots are classified by how modules are connected to one another, as well as by the type of modules within the system. Individual modules can be considered mobile-type, chain-type, or lattice-type [1], and systems can be homogeneous or heterogeneous [2]. These classifications are by no means exclusive [3] and many robots show overlapping features. Mobile-type reconfigurable robots, being the first such type presented in the literature [4], are characterized by individual modules being highly mobile [5]. They are often closely related to the study of self-assembly and swarm robotics, where a large number of independent mobile robots can fulfil tasks independently or work together through simple attachments such as grippers [6].

Chain-type reconfigurable robots have a characteristic serial architecture amongst modules with a common possibility of tree-type configurations [7], [8]. Being the first to practically show the potential of reconfigurability, these robots are very versatile in terms of locomotion gait patterns but computationally more demanding [1]. They typically have one or two degrees of internal actuation including bending and twisting. Various resulting possibilities in gait patterns have been highlighted and include side-winding, rolling, transforming, and walking amongst others [9]–[13]. Lattice-type reconfigurable robots, on the other hand, can be connected in a regular pattern either in 2-D such as hexagons [14] or in 3-D such as cubes [15]. This allows for a higher degree of reconfigurability and simpler alignment but complicates locomotion. More recent reconfigurable robots tend to combine these classifications into hybrid-type systems [16], [17].

Modules in reconfigurable robotic systems can be homogeneous [18], with all units being the same, or heterogeneous, with differing modules that can embody different functions [19]. Homogeneous systems are simpler overall and allow for modules to be replaced easily, while heterogeneous systems can have specialized modules with allocated functionalities, making individual modules simpler. Furthermore, systems can make use of passive modules to, for example, provide structurally supporting elements [20]. Another addition to the capabilities of reconfigurable modular robots that has been studied since their inception is the ability to self-reconfigure. Rather than manually attaching and detaching individual modules, systems can achieve various morphologies autonomously. This requires an automated attachment mechanism, of which various types have been demonstrated including hook systems [21], magnets [22], self-soldering [23], and hot melt adhesives [24]. The versatility of reconfigurable modular robots is yet to find its limits as researchers are producing various applications including furniture [25], space exploration [26], education [27], adaptive tools [24], and search and rescue [28].

Previous work on reconfigurable modular robots has produced a number of interesting concepts and prototypes that highlight the promising potential, as well as the drawbacks, of modularity in robotics. While multiple concepts have been studied, there are ample types and features that remain unobserved, including quasi-2-D lattice-type systems with 3-D reconfigurability.

B. Origami Robots

From appearances in nature [29], computational geometry [30], [31], to potential applications in engineering [32]–[34], origami provides insight and inspiration in various fields. More recently, it has proven a useful tool in the field of robotics and has been implemented in several ways. Self-actuating robotic sheets with a predefined crease pattern and embedded actuators can fold into a number of morphologies [35], closely embodying a true robotic conception of origami. Other approaches have focused on utilizing origami characteristics in the form of passive parts to guide actuation [36], vary actuation [37], and to provide the means for external actuation [38]. Origami has been realized structurally to create complete robots from precut foldable sheets [39], as well as in combining structure with actuation to create novel robotic concepts [40]–[42].

Smart materials have played a significant role in the development of self-folding robots [43]–[46] by reducing complexity of the mechanical assembly. Aside from traditional actuators in preassembled origami robots, fully integrated self-folding origami robots have been predominantly created using heat-activated shape memory materials [47]–[50]. These allow for a much lower thickness of the overall system compared to traditional actuators. Furthermore, 2-D layer fabrication techniques can provide origami robots with distributed actuation and sensing in combination to accommodate feedback and control systems [51], [52].

Previous work on origami robots has primarily focused on the novel fabrication of precut 2-D structures or full rectangular sheets with predefined foldable lines, resulting in a limited number of possible morphologies. However, a modular robotic origami system and its advantages have not been presented or discussed.

III. Concept Definition

A modular origami robot, Mori, can fold like origami but is also entirely modular and reconfigurable. The proposed system consists of self-contained robotic modules that, when connected, can fold up on one another. When multiple modules are connected, the resulting system behaves like origami, transforming from 2-D patterns into various 3-D configurations. While “modular origami” has been explored as a way of achieving more complex paper-structures by joining smaller, prefolded el-

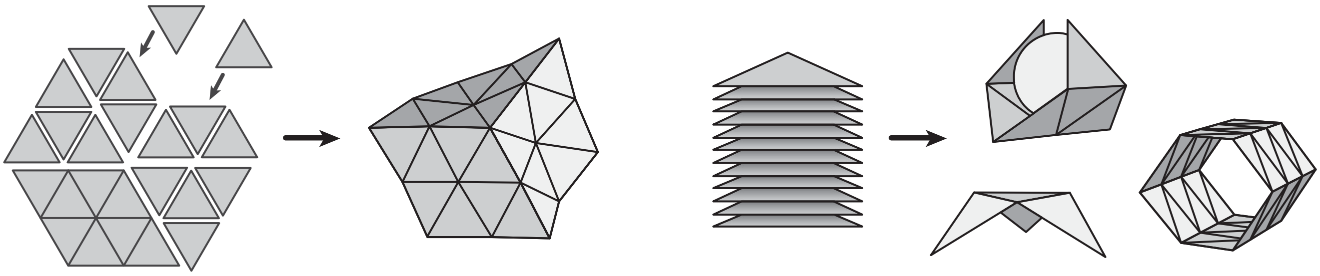


Fig. 1. Conceptual illustration of a modular origami robot. Left: single entities in the shape of equilateral triangles come together to form a modular reconfigurable surface. Such a surface can take the shape of an underlying object or serve as a stand-alone surface that can change its shape. Right: a stack of individual modules can be turned into any desirable, task-specific shape such as a gripper, a platform, or a tube. The geometric concept illustrated in this figure is used in the development of the robot presented herein.

ements [53], our robot does not rely on this principle as individual modules are quasi-2-D rather than prefolded 3-D elements. Mori is an origami robot that is modular, a modular origami robot.

For a modular system to be fully reconfigurable, all modules need to be of an identical form that allows for a repeatable pattern, a lattice. While there are several 2-D shapes that allow for this, including equilateral triangles, squares, and hexagons, we propose the use of equilateral triangles. This reduces the complexity of individual modules and results in a high degree of reconfigurability, as highlighted in Fig. 1.

A. Scalable Modular System

Lattice-type modular robots inherently do not have a theoretical limit to the size and number of modules within a robotic assembly. In practice, however, the scalability of such systems is of major concern. The larger the assembly of modular robots, the higher the likelihood of exceeding physical limits of individual modules such as torque of actuation or physical strength of the structure.

Complex assemblies and structures cannot be generalized in terms of physical requirements as these greatly depend on a variety of case-specific factors such as geometry, assembly sequence, and other reconfiguration strategies; therefore, they are often subject to optimization. It is, however, possible to generalize the scalability of modular robotic systems on the basis of simple scenarios that are likely to pertain in a variety of cases. Fig. 2 highlights three such scalable structures of a modular origami robot. Considering the geometries of these structures, we can formulate the scaling of torque requirements, i.e., given the torque requirements of the smallest structure, we can determine the torque requirements for any scaling factor. Considering the proposed geometry of our modular robotic origami concept, for a scaling factor n the maximum torque per joint $\tau^{\max}$ for the three example structures in Fig. 2 is given by

$$\tau^{\max}_{n=i} = \tau^{\max}_{n=1} * n^2, \quad i \in \mathbb{Z}^+. \tag{1}$$

The maximum torque requirements of scaled elements can be reduced dramatically by optimizing folding sequence and actuation pattern. Folding of elements in Fig. 2(a) and (b) for $n > 1$ can be optimized by folding external vertices first, while folds along larger sheets such as in Fig. 2(c) can be further optimized by actuating multiple vertices at once.

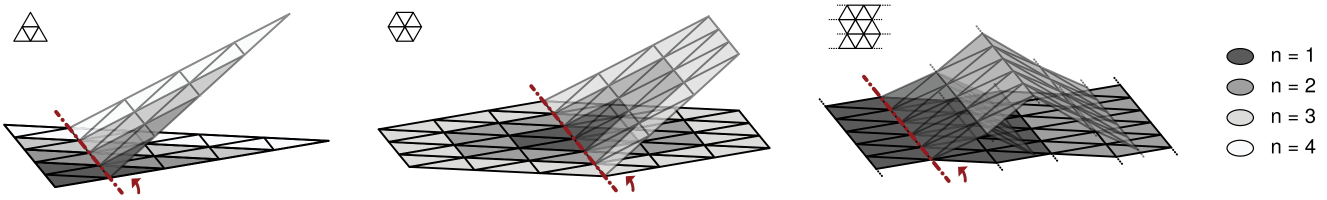
B. Key Features

Origami robots, on the one hand, need to be lightweight, reconfigurable, and low-profile to allow for the transformation between quasi-2-D to 3-D configurations. Fully modular robots, on the other hand, inherently call for an attachment mechanism that allows any edge of one module to be connected to any edge of another, i.e., it must be genderless. Furthermore, while modular robotic systems tend to rely on the combination and interaction of modules to fulfil tasks, a system is more versatile if each module retains as much independence as possible. This may entail attributes such as single module mobility, on-board sensing, and on-board control. Consequently, the overall features of a modular origami robot can be summarized as follows.

1) It has to be reconfigurable at each interface with genderless mechanisms for both attachment and actuation in place.
2) It has to have an actuation system at each interface which allows folding over the engagement axis to incorporate origami-like reconfigurability.
3) Each module has to be an equilateral triangle with a quasi-2-D structure for maximum folding possibilities and range.
4) It has to be mobile and largely independent.

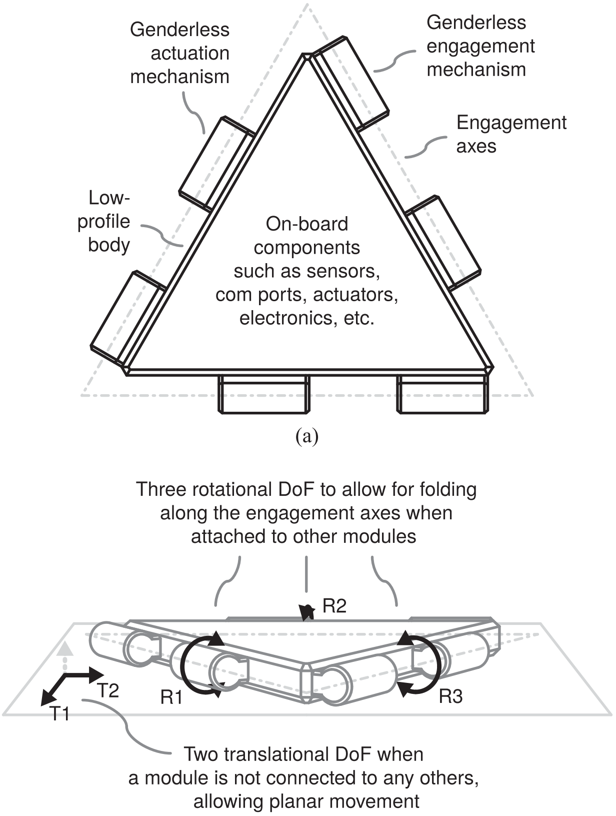
These key features are illustrated in Fig. 3(a) by a modular origami robot in the shape of an equilateral triangle with a slenderness ratio of over 10:1. Identical, genderless engagement and actuation mechanisms protrude at each edge, allowing any side of one module to be connected to another, as implemented in Section IV. The engagement mechanism serves as a hinge, restricting connected modules radially and axially but not in rotation. The actuation mechanism can fold and unfold connected modules and is also used for a single module to move independently when disconnected. The triangular body of the proposed modular origami robot houses all other necessary components including electronics, sensors, control components, and actuators.

Given that the design includes a genderless and standardized engagement mechanism, additional components, attachments, and mounts can easily be used in tandem. This may be in the



(a) (b) (c)

Fig. 2. Structural elements for analyzing scalability with respect to torque requirements using the proposed geometry of modular origami robots (the active folding axis is indicated by a red line): (a) an equilateral triangle actuated at the longest internal axis where $n = 1$ contains four modules; (b) a hexagon actuated at the central axis where $n = 1$ contains six modules; and (c) a sheet of undefined size made up of modular robotic elements, where the fold is actuated by a single axis and $n = 1$ lifts a single adjacent axis.



(a)

(b)

Fig. 3. Schematic design highlighting the key features of a modular origami robot: (a) a robotic module in the shape of an equilateral triangle with genderless mechanisms at each engagement axis and various on-board components; (b) each module has three rotational DoF, R, when connected to other modules and two translational DoF, T, when not connected to other modules, allowing for planar motion.

form of task-specific tools, modules with varying geometry, or external support structures. The use of passive modules, simple connections between active modules where no actuation is needed, is also possible as demonstrated in Section V-A. These passive modules can then be used to carry additional components, such as power supplies, or serve as structural support. Furthermore, the top and bottom faces of a module can be used to mount extra components, tools, or additional modules directly to a module without affecting the geometric structure of a reconfigurable surface, as shown in Section V-C. This greatly extends the potential of the modular origami concept as multiple structures, which may not be possible to combine into a single surface, can easily be joined together.

As highlighted in Fig. 3(b), the proposed concept has three rotational DoF as well as two translational DoF stemming from a single actuation system. When two modules are connected, the actuators provide rotation about the engagement axis in order to fold the two modules. However, when a module is not connected, the same actuators can drive across flat surfaces and make the robot mobile, as demonstrated in Section V-B. These two modes of actuation from a single system greatly extend the robot's capabilities while maintaining mechanical simplicity.

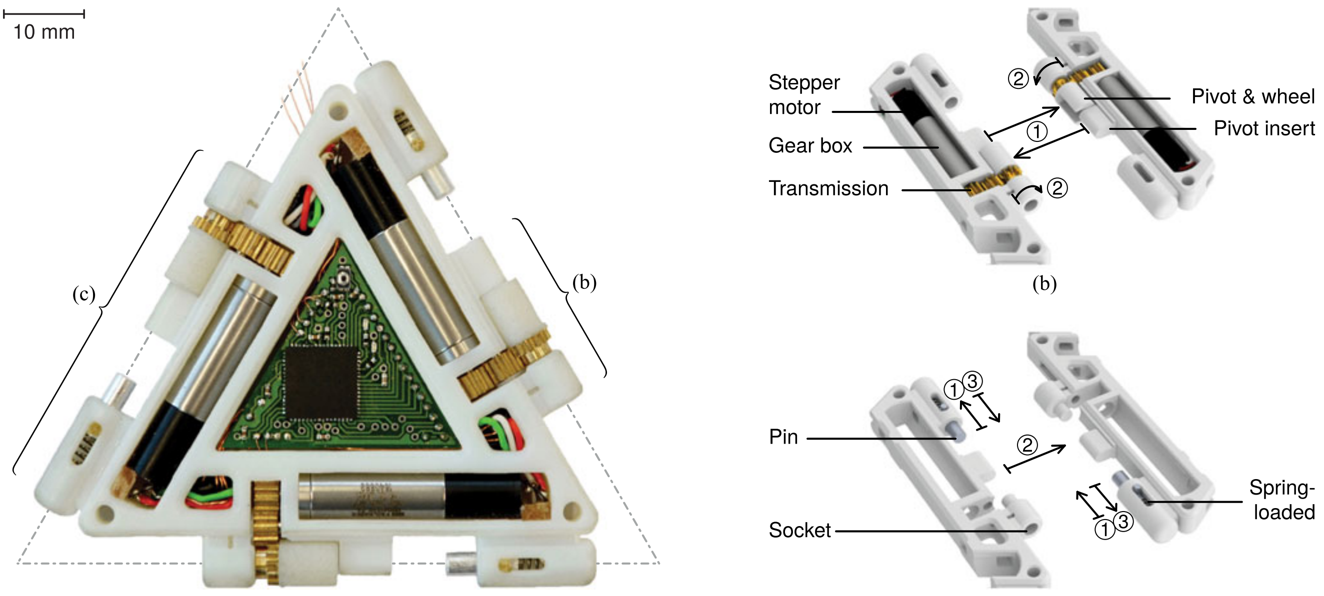
IV. MORI: A SYSTEM OVERVIEW

Following the conceptual description of a modular origami robot, this section describes our functional prototype, Mori, shown in Fig. 4(a). Its design parameters were carefully selected toward low thickness, simplicity, functionality, and actuation at each interface of an equilateral triangle for origami-like reconfigurability, modularity, as well as mobility.

A. Design and Mechanisms

The first prototype of Mori is a flat robot of triangular shape. It is mobile on flat ground, can be attached to other modules of its kind, and turn from quasi-2-D shapes into 3-D structures. Furthermore, the prototype is self-contained with on-board control, actuation, and sensor integration, with the exception of power supply. The robotic origami system achieves modularity through the engagement and actuation mechanisms, which in their combination account for the key characteristics of the robot, namely, modularity and origami folding. Each side of a module contains both protruding and receiving elements of both mechanisms, allowing any side of one module to be connected to any side of another. The two genderless mechanisms are illustrated in Fig. 4(b) and (c).

As a low profile is desirable in origami robots to allow for a maximum folding angle, component selection focuses on minimizing the overall thickness of the robot. The remaining dimensions are primarily defined by a minimal design that houses all necessary mechanisms and components at a minimum weight. Mori's main body has a thickness of 6 mm and the side-length of the equilateral triangle formed by the engagement axes is 80 mm. It is fabricated using a multijet 3-D printer (Objet Con-



(a) (b) (c)

Fig. 4. The first functional prototype. (a) Mori, a modular origami robot (dotted lines indicate the engagement axes for attachment and folding). Two genderless mechanisms allow any side of one module to be connected to another (their sequences are shown in arrows and are numbered). (b) The actuation mechanism serves both translational motion of an individual module as well as folding of two attached modules. (c) The engagement mechanisms is used to attach two modules to each other.

nex 500). The total weight of Mori's prototype is 26 g, of which over two thirds are consumed by the actuation mechanisms in Fig. 4(b).

Actuation is provided by a stepper motor fixed in parallel to the engagement axis (Faulhaber FDM0620, 6 mm diameter, 0.25 mN·m holding torque, 18° step angle). A stepper motor was chosen as it has a fixed step size, permitting open-loop position control, provides a holding torque, and can be free to rotate if necessary. A planetary gearhead with a ratio of 256:1 is attached to increase the effective torque and reduce the step size. A secondary gear system consisting of three spur gears with ratios 1:1:1.2 is installed to translate the actuation from the motor to the engagement axis. A slotted pivot is attached to the final gear in the transmission system, forming the active part of the actuation mechanism. This u-shaped pivot forms the counterpart for an insert, which is integrated into the housing. The actuation mechanisms of two modules are brought together, as indicated by ① in Fig. 4(b). The passive part of one module is inserted into the pivot of another such that when a torque is applied to the pivot it causes the two modules to fold up on one another, denoted by ② in the same figure.

The engagement mechanism, which is operated manually, consists of a spring-loaded pin that enters the socket of another module. The pin is first retracted, denoted by ① in Fig. 4(c), and the two engaging modules are brought together by aligning their engagement axes, denoted by ②. The pin is then released so that the spring-loaded mechanism locks the two engagement axes to one another, denoted by ③ in the same figure. A hinge is thereby formed, restricting motion radially and axially so that only folding about the engagement axis is possible when two modules are connected.

B. Electronics and Control

The unique concept behind Mori requires a special electronics design to account for the specific components and computational needs of the robot. In order to have full control over the behavior of the three stepper motors, each motor requires four pulse-width modulation (PWM) channels that are transformed into the necessary signals for the motor windings through H-bridges. Furthermore, the on-board controller must be powerful enough to compute live kinematics and apply closed-loop control.

We use a 16-bit microcontroller, PIC24EP512GP806 from Microchip, with 64 leads and dimensions of $9 \times 9 \times 0.9$ [mm] running at 3.3 V. It is configured to provide 12 PWM outputs (4/motor), two reconfigurable communication ports (UART, I2C, etc.), three digital input and three digital output pins, three analogue input pins, and two status LEDs. The PWM channels are connected to three motor driver chips, Texas Instruments DRV8835. All electronic components are mounted on two triangular printed circuit boards (PCBs), placed on top of each other in the center of Mori's body. The current prototype consumes around 600 mA when all three motors are active and requires four external connections to operate; two for power and two for serial communication. Current draw from the motors can be reduced by adjusting and optimizing their on-time, which is necessary when incorporating internal power supply. Currently available batteries with a high current drain that would fit the current housing (with modifications to the PCB) can provide 50 mAh for a motor-runtime of 5 min with the current firmware at a weight of 1.2 g.

Application specific components, such as accelerometers and proximity sensors in Section V-C, can easily be connected to the existing communication ports. The six digital pins are accessible but unconnected in the current version to allow for synchronization and communication amongst neighboring modules in the future. For this purpose a communication protocol needs to be established which synchronizes actuation and provides information about neighbouring modules. Similarly, the three analogue input pins are left unconnected and are intended for additional sensors in future versions of Mori.

Mori's electronics allow for various forms of closed-loop control to be implemented depending on the task and configuration at hand. Angular position sensors can be added to provide position feedback of the motors or the folding pivots, other on-board sensors can provide position feedback based on the device's kinematics, or external sensory systems can be implemented to provide the relevant control signals. The latter two methods are demonstrated in Section V-C in the form of an on-board accelerometer and a proximity sensor, as well as an external camera tracking system.

C. Performance

Each module is self-contained and has three separate actuation systems. The motor signals for each actuation system are updated at a frequency of 800 Hz resulting in a maximum motor speed of 200 steps/s (one step is 0.06°) or 2 rpm. The effective driving torque at the engagement axis of a module is around 30 mN·m, accounting for gear ratios and transmission efficiencies. Therefore, when two modules are connected and their actuation is synchronized, the effective torque at the hinge is 60 mN·m. Considering a weight of 26 g and a moment arm of 23 mm, the required torque to lift one module from a horizontal position is 5.9 mN·m. Connecting two further modules to the remaining edges of the module being lifted, the torque required to lift them from a horizontal position will increase to 30 mN·m. Lifting a total of six modules connected in a hexagon from one of its external edges would require a total torque of 106 mN·m per hinge, which exceeds the capabilities of the current system.

However, reconfiguration strategies can be adjusted to minimize the maximum torque experienced by each joint at any given time, increasing the likelihood of a target shape being achievable. For example, connecting three modules to a central one yields an equilateral triangle of double the side length, which is used in Sections V-B and V-C. If all four modules are fully assembled, the total weight of the configuration is 104 g. The corresponding torque required to lift the central module from a horizontal position using only one of its neighboring modules is 70 mN·m, exceeding the capacity of the current system. However, this can be overcome by initially using multiple neighbouring modules to lift the center and subsequently lowering the remaining joints until the target position is achieved. Thus, the possibility of transforming from a 2-D or 3-D configuration into another 3-D shape is subject to optimization.

V. IMPLEMENTATIONS & EXPERIMENTS

The principal objective behind reconfigurable modular robots is to create systems that can adapt their shape and functionality depending on a desired task [2]. Thus, a specific modular robot does not have a unique task it is designed for and it is difficult to evaluate the performance of such a system by means of a single function. This would diminish the significance of other potential tasks and thereby unjustly bias the robot's evaluation. By contrast, a single modular robotic system can be evaluated by means of a number of different scenarios that demonstrate a multitude of functionalities, with specific attention to the set of key attributes of the robot. The following three application-oriented implementations of our prototype were selected to demonstrate the versatility of the system and highlight the features that define it.

An initial implementation displays the robot's origami-inspired reconfigurability and modularity in form of a reconfigurable modular surface, followed by a demonstration of its mobility on flat surfaces and maneuverability in small spaces. Finally, the prototype of our modular origami robot is integrated within a closed-loop manipulation experiment where a ball is balanced on a floating three DoF platform assembled from the robot's modules.

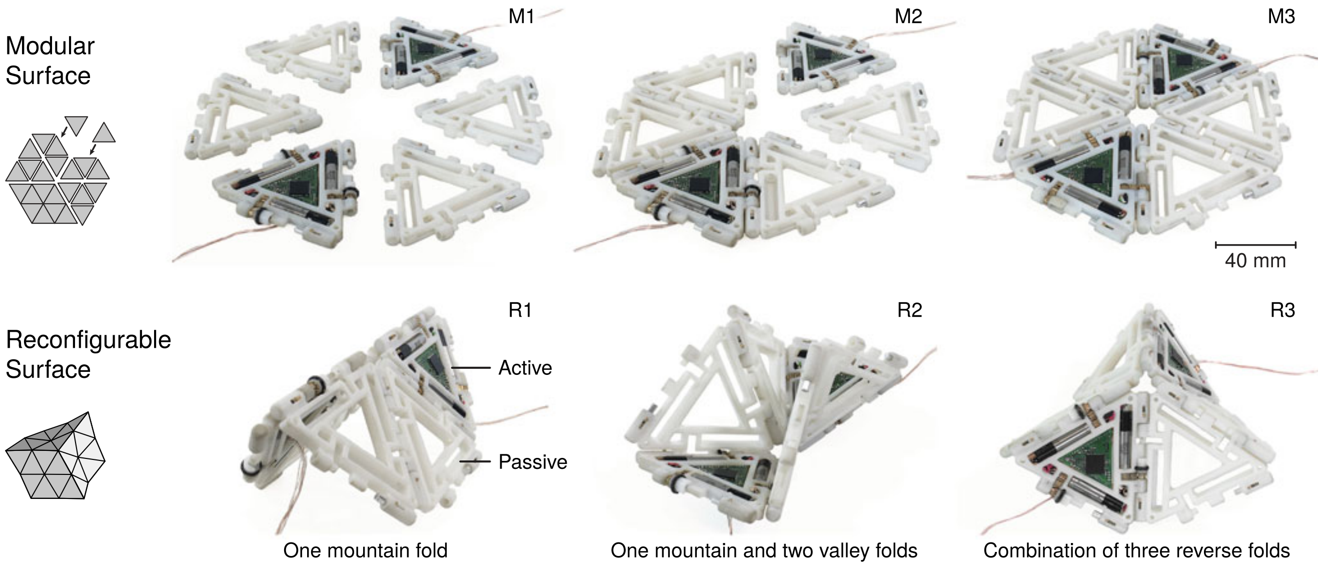
A. Modularity and Origami

The concept of a modular origami robot, as proposed in Section III, combines two types of robotic systems in order to gain a unique set of functionalities. In the following demonstration, the two defining aspects of Mori, namely modularity and origami, are highlighted. Six modules are connected in a closed chain, forming a modular reconfigurable surface in the shape of a hexagon, which then folds up on itself to create multiple structures.

In this experiment two fully functional Mori prototypes are used along with four passive modules. The passive elements consist of Mori's frame and only have the components for the engagement mechanism embedded. This allows for testing of the modularity and reconfigurability of the system without the need to produce a large number of robots with embedded actuators and electronics. The two active modules within the closed chain are connected opposite to one another in order to separate the two uncontrolled rotational joints, which become constrained through symmetric actuation of the active modules.

The connection sequence of the modular hexagon is shown in subset M1–M3 of Fig. 5. This six-piece element forms the only possible configuration of modules around a single vertex that is entirely flat (valency equal to six) and can be extended indefinitely by adding further modules. It is thus the base element for reconfigurable surfaces made up of modular origami robots. Once connected, the surface is controlled manually to recreate three combinations of origami folds, as shown in subset R1-R3 of Fig. 5. R1 represents a simple mountain fold, R2 combines one mountain fold with two valley folds, and R3 shows a combination of three reverse folds. These configurations are examples of a large number of possible shapes that a reconfigurable surface of modular origami robots can assume.

We have hereby developed a modular robotic system that is capable of reproducing surfaces in 3-D. While most physical displays capable of recreating surfaces do so in 2.5-D with protruding linear actuators, our robot is capable of producing surfaces in full 3-D with a relatively low surface thickness. This can be used to interactively visualize computer-generated



One mountain fold

One mountain and two valley folds

Combination of three reverse folds

Fig. 5. Modularity and origami demonstration using two active modules along with four passive ones. The top row shows how the six pieces come together to form a modular reconfigurable surface in form of a hexagon. The bottom row shows three surface configurations that are achieved by the modular robotic system using the origami principle of folding surfaces to create 3-D structures.

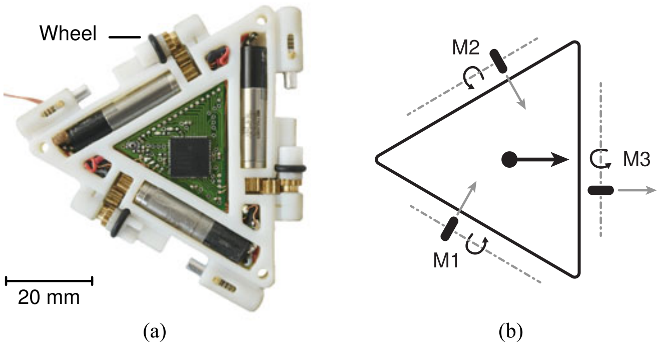
surfaces and structures. Increasing the number of modules in the system improves the approximation of surfaces whereas altering the number of modules around a single vertex enables the recreation of more complex and non-developable surfaces and structures.

This demonstration emphasizes the advantages gained by bringing together modularity and origami folding in our modular origami robot. Modularity allows the system to be assembled into any formation desirable while origami-inspired folding permits the system to reconfigure from 2-D modules into various 3-D structures.

B. Mobility

Reconfigurable modular robots typically operate and fulfil tasks in collaboration with one another. However, it is also desirable for a single entity to be mobile, as discussed in Section III-B. The current prototype is turned into a mobile-type reconfigurable modular robot by incorporating rubber o-rings into each rotating pivot, turning them into wheels that slightly protrude the device's thickness. This allows a single module to drive in different directions on flat surfaces by using combinations of rotational speeds and directions of the three wheels, M1–M3, as illustrated in Fig. 6. Initial tests of the robot's driving performance on a relatively smooth medium density fiber surface showed a speed of around 3.5 mm/s.

Being mobile not only allows a module to travel between locations, where it is coupled and used as part of a larger structure, but also to access small spaces and perform maneuvers within. As a result of its low thickness and quasi-2-D profile, the robot is able to drive through gaps as small as 7 × 70 [mm]. We have prepared the following demonstration to highlight our prototype's mobility and maneuverability: A module enters a room through the gap underneath a door and is thereafter used to pick up an object, connect to three other modules, and reconfigure into a container.



(a) (b)

Fig. 6. Mori turns mobile: even a single module with three motors can travel across flat surfaces. (a) A rubber o-ring is attached to each rotating pivot and serves as a wheel. (b) A module can then travel between tasks or configurations by combining different rotational speeds and directions of the three wheels.

The module is controlled with a joystick by a user who first steers the robot from one room into the other. The user subsequently drives the robot toward an object, in this case a Lego figure, which is considered to be located out of the user's reach, such as underneath a bed. The object is then moved onto the robot's surface using environmental constraints and driven toward three other, passive modules, which are attached by the user. The configuration of four modules is then folded up to form a modular container in form of a three-sided pyramid, a regular tetrahedron. Fig. 7 shows a sequence of frames taken during the demonstration.

This implementation of our robot illustrates the importance of mobility in modular robotic systems and highlights the advantages of a modular origami robot in comparison with other types of robots. Due to its small size and low profile, the prototype is able to pass through unknown and small openings whereas its modularity enables large volumetric expansions and dimensional reconfigurations.

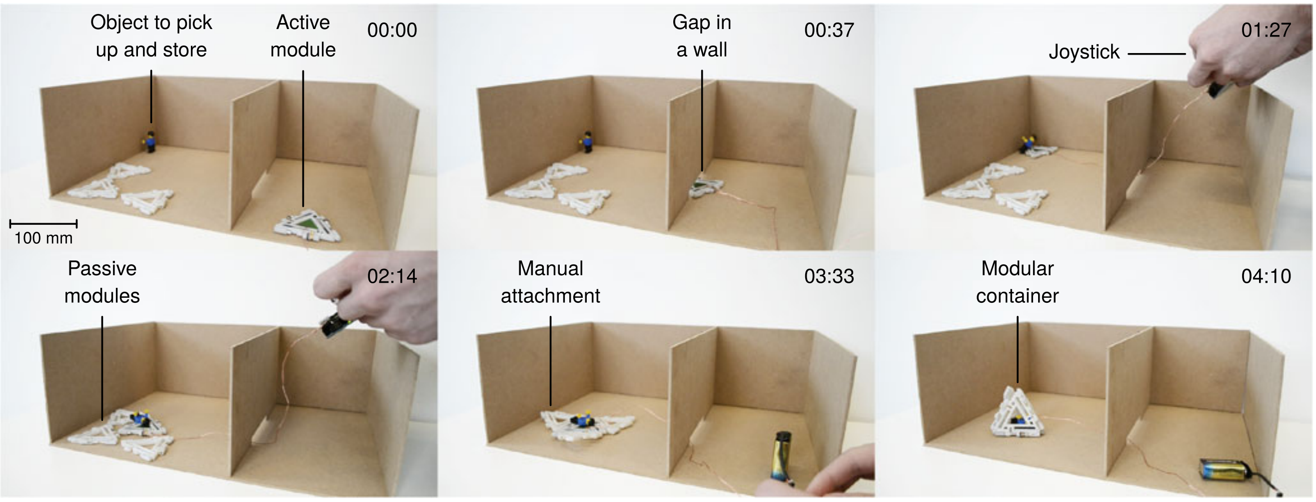


Fig. 7. Demonstration of Mori's mobility and manoeuvrability. A module is steered through a gap in a wall from one room into another and used to pick up an object from outside of the user's reach. The robot is subsequently driven toward three other modules, which are attached by the user. The four modules are then folded into a container in form of a regular tetrahedron. As seen in the images, the prototype is connected to an external joystick and a battery.

C. Closed-Loop Object Manipulation

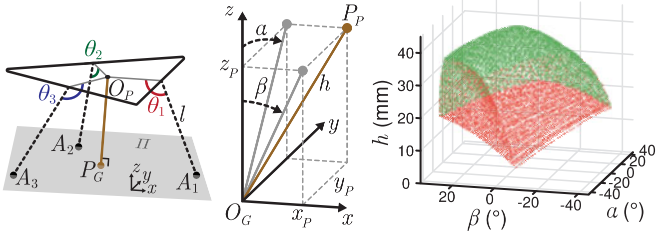
In the final implementation using our prototype, Mori is coupled with an external camera system to manipulate an object. This scenario provides an example of our modular origami robot being applied to a real-life situation, where it is automatically controlled and interacts with its environment and objects within. For this purpose three passive modules are attached to a central active one and folded downward such that the central module is lifted. A floating platform with three DoF is thereby formed, which is then used to balance a ball on its surface. A kinematic analysis of the system is followed by a ball-balancing experiment using our current prototype.

Although conceptually similar to a simplified Stewart platform [54], its kinematics are distinctive due to the lack of a fixed frame of reference for the base. Therefore, the center of the platform is taken to be the origin O_P for developing the forward kinematics, as shown in Fig. 8(a). The ground plane, Π, is formed by the endpoints of the legs, $[A_1, A_2, A_3]$, whose coordinates are given by (2) in terms of the length of each leg l and the angles between the legs and the platform $\theta_{i=1,2,3}$, where $90^\circ \leq \theta_i \leq 180^\circ$.

$$A_1 = \begin{bmatrix} l(1/3 - \cos(\theta_1)) \\ 0 \\ -l\sin(\theta_1) \end{bmatrix}$$

$$A_2 = \begin{bmatrix} (l/2)(-1/3 + \cos(\theta_2)) \\ (l\sqrt{3}/2)(1/3 - \cos(\theta_2)) \\ -l\sin(\theta_2) \end{bmatrix}$$

$$A_3 = \begin{bmatrix} (l/2)(-1/3 + \cos(\theta_3)) \\ (l\sqrt{3}/2)(-1/3 + \cos(\theta_3)) \\ -l\sin(\theta_3) \end{bmatrix} \qquad (2)$$



(a) (b) (c)

Fig. 8. Illustrations and notations used in the kinematic analysis of the floating three DoF platform. Due to the platform floating on a low-friction surface, forward and inverse kinematics use two different notations that are directly relatable. (a) In the forward kinematics the center of the platform is the origin O_P and the three leg endpoints $[A_1, A_2, A_3]$ form the plane Π, which represents the floor but has no fixed frame of reference. (b) The inverse kinematics denote point P_P as the center of the platform, which is defined by the three control parameters α, β, and h, and the origin O_G is the point where the normal to the platform connects point P_P to the ground. (c) The workspace of the platform shows the possible combinations of the three control parameters. Green points denote maxima and red points minima of the enclosed envelope. Note that the figures in (a) and (b) are not to scale, nor do the two depictions represent the same set of variables.

The three parameters of interest for the kinematic analysis are α and β, the angles about the x- and y-axis respectively, as well as the height of the platform h, which is the shortest distance between the origin and the plane Π. A plane equation for the plane Π can be found by determining the normal vector $\vec{n} = [a, b, c]$ through the cross product of two lines between coordinates A_1, A_2, and A_3, yielding $ax + by + cz = d$, where $d = ax_i + by_i + cz_i$ and $i = 1, 2, 3$. The coordinates of the intersection point P_G of the line orthogonal to plane Π passing through the origin is then given by

$$P_G = \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} + \vec{n}s = \begin{bmatrix} as \\ bs \\ cs \end{bmatrix} \qquad (3)$$

where s can be found by substitution into the plane equation such that $s = d/(a^2 + b^2 + c^2)$. The three relevant kinematic parameters are then given by

$$\alpha = \arctan(b/c)$$

$$\beta = \arctan(a/c)$$

$$h = \sqrt{(as)^2 + (bs)^2 + (cs)^2}. \tag{4}$$

In order to implement closed-loop control based on the position of the platform, the three kinematic parameters need to be inversely related to the three control output angles θ_1, θ_2, and θ_3. An arbitrary point on the ground plane is taken as the origin O_G to establish a fixed frame of reference for the ground. Given parameters α, β, and h, the coordinates of point P_P, illustrated in Fig. 8(b), can be found by substituting x_p, y_p, and z_p for as, bs, and cs, respectively, in (4). Finding x_p, y_p, and z_p yields the plane equation for the platform, $x_p x + y_p y + z_p z = h^2$. Substituting the expressions for the coordinates of points A_i from (2) into this plane equation yields three equations for the three output angles θ_1, θ_2, and θ_3, as shown in

$$\begin{aligned}
&x_p l(1/3 - \cos(\theta_1)) - z_p l \sin(\theta_1) = h^2\\
&(x_p l/2)(-1/3 + \cos(\theta_2)) + (y_p l\sqrt{3}/2)(1/3 - \cos(\theta_2))\\
&\quad - z_p l \sin(\theta_2) = h^2\\
&(x_p l/2)(-1/3 + \cos(\theta_3)) + (y_p l\sqrt{3}/2)(-1/3 + \cos(\theta_3))\\
&\quad - z_p l \sin(\theta_3) = h^2.
\end{aligned} \tag{5}$$

Given a set of desired variables α, β, and h, the bisection method can then be used to solve the expressions in (5) above to yield the three desired angles θ_1, θ_2, and θ_3 for closed-loop control, since the interval for its value is known. A workspace analysis has been performed, depicted in Fig. 8(c), showing the possible range of motion in terms of α, β, and h.

The practical implementation of this three DoF platform using our modular origami robot is shown in Fig. 9. The control loop is closed by attaching an accelerometer to the top of the central module (ST LSM303D), returning angles α and β, and a proximity sensor to the bottom of the central module (ST VL6180X), returning height h. The platform is then coupled with a Simulink model and a camera to balance a ball on its surface. A 100 × 100 [mm] wooden plate is placed on the central module to provide an even surface and slightly enlarge the balancing area.

The Simulink model determines the location of the central module by tracking three coloured markers (one green and two red) as well as the location of a blue ball, depicted in Fig. 9. The markers are identified by extracting a binary version of the input image with separate color outputs of red, green, and blue, with auto-threshold and blob analysis in place. The model continues to calculate the distance of the ball to the center of the module in terms of x and y, e_x and e_y. The two resulting values are sent to the module via serial communication at a frequency of roughly 15 Hz.

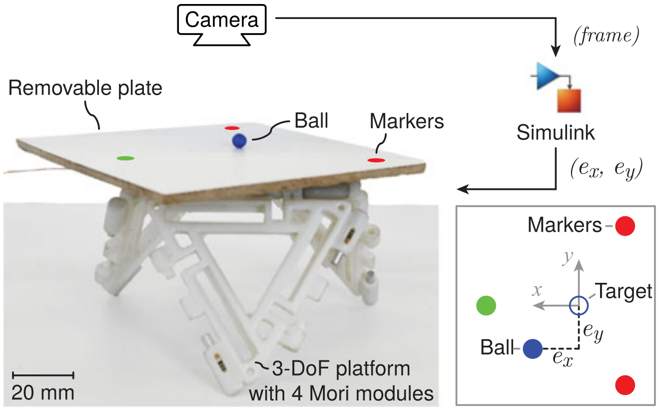
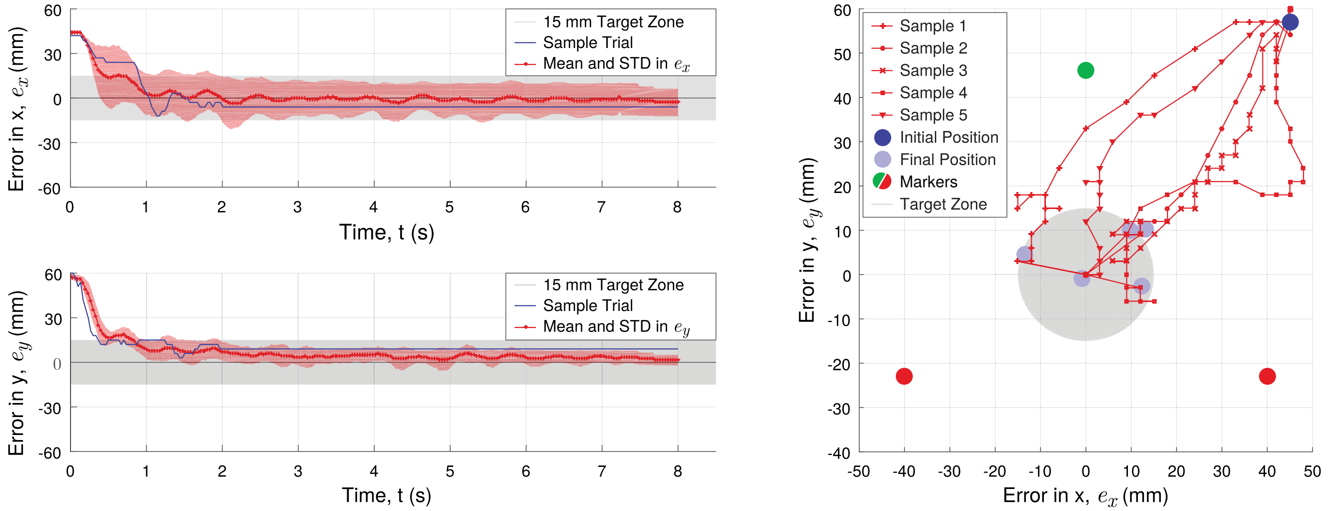


Fig. 9. Testing setup to evaluate the floating three DoF platform. One central module is connected to three passive ones and a flat plate is mounted with colored markers; a camera feeds image frames into Simulink, which analyses the errors in x and x of the distance between the ball and the center of the module. The errors are passed to the central module, which performs closedloop control of the tilt angles to ensure the ball is balanced on the surface.

The ball coordinates e_x and e_y are used by the module as the error signal for proportional-derivative (PD) control, controlling the angle of the platform, in order to balance the ball on its surface. The height of the platform h is kept at a constant 25 mm and the angles of the platform are changed according to the position of the ball. The module calculates the change in angle of each leg based on a change in the angles of the platform by using the inverse kinematics described previously. Since the range of motion during balancing is within $\pm 5°$ for both α and β, the change in leg angle relative to the platform angles is taken to be linear (real errors of a linear fit are less than 5%).

The following test validates the capabilities of the balancing platform: a ball is placed in one of the corners of the platform while it is even. The center of the triangle, indicated by the three markers, serves as the target position and the platform moves the ball to the center. Fig. 10(a) shows the mean error and standard deviation of all ten repetitions while Fig. 10(b) shows the recorded trajectory from five selected samples. An accepted error band of 15 mm was introduced, both in the control and in the figures, to account for a slight roughness of the surface and unevenness of the ball. The ball was successfully balanced on the surface in all ten repetitions of the test and reached the accepted error band in less than 7 s.

This ball-balancing experiment effectively demonstrates how our prototype of a modular origami robot can be configured to manipulate objects, further manifesting its ability to change shape and function depending on the task at hand. The incorporation of external sensing systems and additional on-board sensors into a closed-loop application highlights the versatility of the system toward a viable modular robotic framework that can tackle even more complex engineering problems. While its performance with respect to the balancing task cannot be compared with dedicated, single-purpose systems, it does show that our robot is highly reconfigurable toward a multitude of functions.



(a) (b)

Fig. 10. Testing results of the floating three DoF platform constructed from our prototype balancing a ball: (a) error in x and y of one sample trial, corresponding mean, and standard deviation, STD, of all repetitions and the 15 mm target zone; (b) the trajectory of five selected samples from starting point to final position in terms of errors e_x and e_y.

VI. DISCUSSION

In this paper, we propose a new robotic concept taking inspiration from both origami robots and reconfigurable modular robots. It combines the advantages of the two types of robots into a versatile system that has the potential to overcome their individual limitations. A modular origami robot is quasi-2-D, light weight, and at the same time fully reconfigurable, modular, and mobile, greatly extending its potential use in various fields such as human–robot interaction.

Along with the conceptual introduction and analysis, we present Mori, a prototype of a modular origami robot. Mori has a low-profile triangular structure with a manual engagement mechanism and a folding actuation mechanism at each edge. It is mobile on flat surfaces, can be attached to other modules of its kind and fold into any 3-D configuration desirable.

Three functional implementations using the current prototype are presented in order to demonstrate, analyze, and evaluate its key characteristics. The first demonstration highlights the modularity and origami-inspired reconfigurability of the system by implementing it in form of a modular reconfigurable surface. Similarly, the demonstration of mobility highlights the advantages of modular systems being mobile and effectively uses modularity to achieve large volumetric expansions.

The final experiment consolidates the versatility of the modular robot by configuring into a floating three DoF platform for object manipulation. Integrating on-board sensors and an external camera allows the robot to balance a ball on its surface and shows how this system consisting of relatively simple entities can realize more complex engineering solutions.

While the individual implementations of our robot may not match the performance of dedicated single-purpose systems, the true potential of reconfigurable modular robots lies in the ability to change shape and function depending on the task at hand. Such systems are therefore best evaluated by considering how well they can adapt their functionality for different purposes and successfully accomplish a variety of tasks. The collection of experiments carried out by our robot furthermore highlights its advantages over other types of robots in terms of modularity, origami-folding, and mobility.

This promising outlook on modular origami robots calls for further work on the system, including control strategies, analysis of the structural possibilities of the platform, as well as hardware extensions such as automated engagement and power autonomy. We hope that the work presented in this paper, bringing together origami and modular robots, will encourage more work on reconfigurability and modularity in robotic systems, ultimately bringing such robots one step closer to our day to day lives.

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