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Morphological flexibility in robotic systems through physical polygon meshing

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Robot design

The ability of the robotic platform to realise and articulate physical polygon meshes relies on the ability of each module to change its own polygonal shape as shown in Video S1 and Fig. S1. Individual modules have a triangular base shape with each edge able to independently increase in length. The three extending edges, Edges 1-3 in Fig. S2a, and the three hinges perpendicular to the edges, R1-R3, form a kinematic chain with three degrees of freedom (DoFs). Changing the length of any edge results in a change of the three angles between the edges, α, β, and γ, without affecting the length of the other edges. Simultaneously increasing all three edge lengths at the same rate leaves the angles unchanged but increases the area of the triangle.

Once two modules, A and B, are coupled to each other, one edge of module A shares an axis with an edge of module B, EdgeA2 and EdgeB1 (Fig. S2b). The resulting rotational link between the modules is the reference for their relative position, controlled using the angle between any two hinge axes, e.g. RA2 and RB2, denoted as δ. The dihedral angle between the two polygons is then $\pi - \delta$. When a module is not connected to another, it can drive on flat surfaces using the same actuation that controls δ in a coupled state. As the lines from the contact points of the three wheels, Wheels 1-3, perpendicular to the edges, do not cross the centre of the polygon, a module has three translational DoFs, x, y, and θ (Fig. S2c).

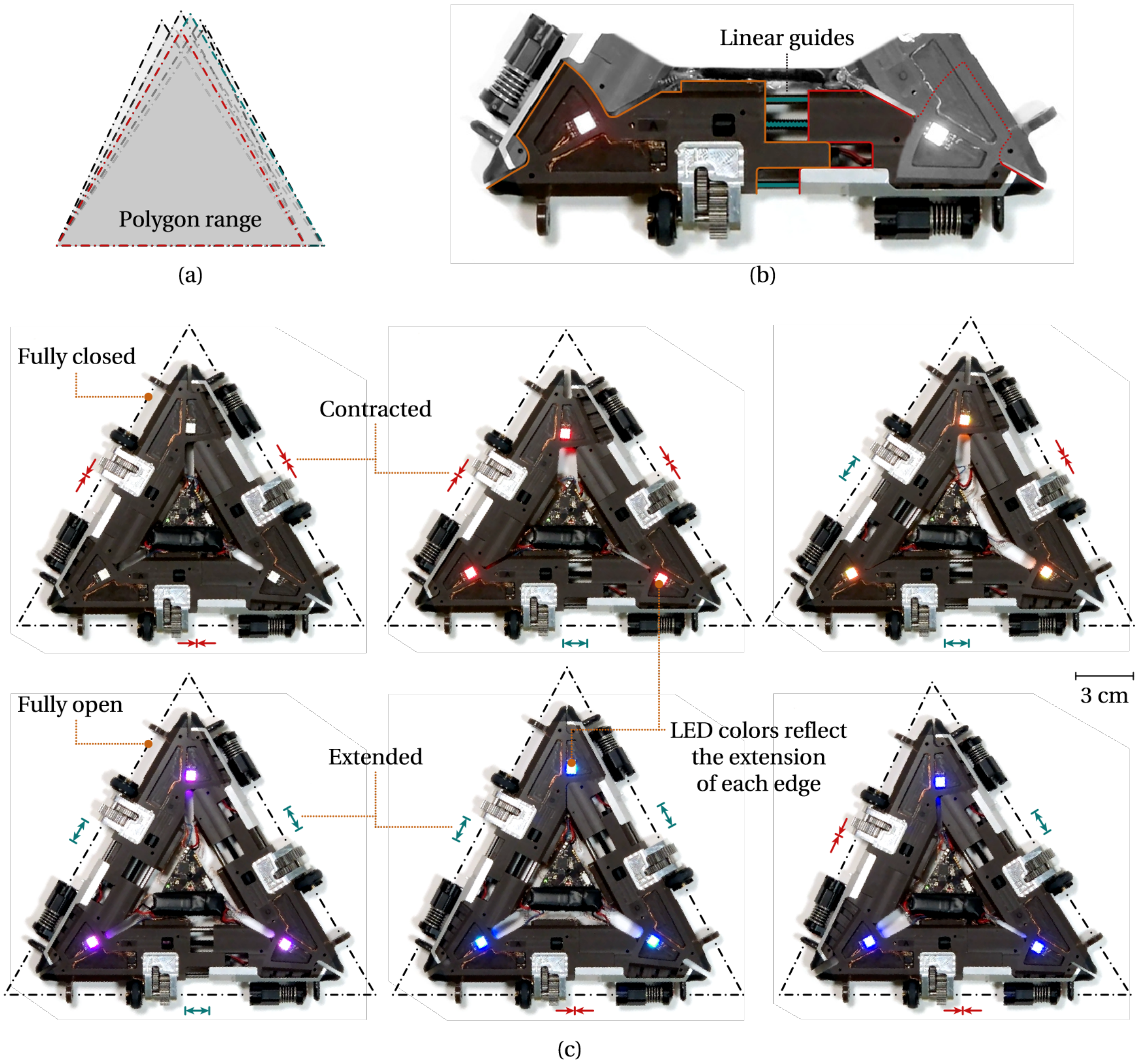

Fig. S1. Shape-change of the polygon-based modular robot. (a) A selection of possible shapes indicating the range of the polygon. (b) Mechanical components of each edge involved in edge extension are highlighted. (c) Different combinations of maximum and minimum extensions of the three edges.

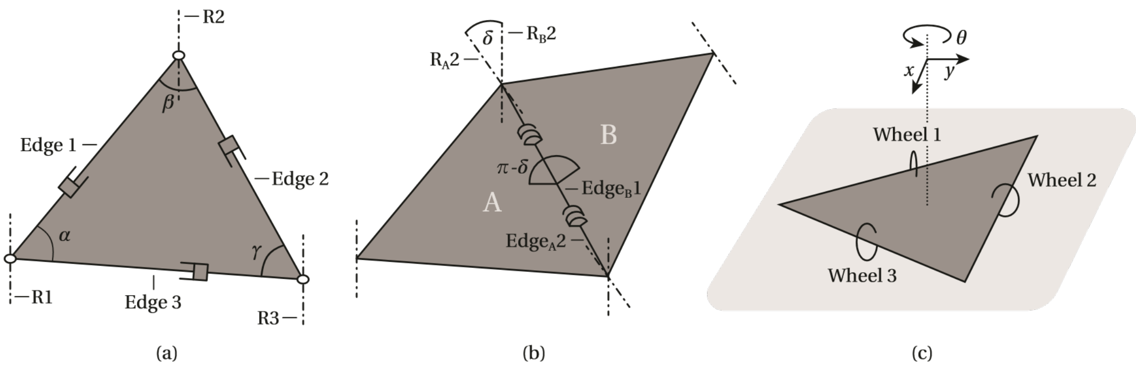

Fig. S2. Degrees of freedom and notations in different operational states of a module. (a) The kinematic chain of a single module formed by the three polygon edges. (b) Two coupled modules, the shared edge, and the resulting rotational joint. (c) The translational degrees of freedom of a single module driving on flat surfaces resulting from the three wheels.

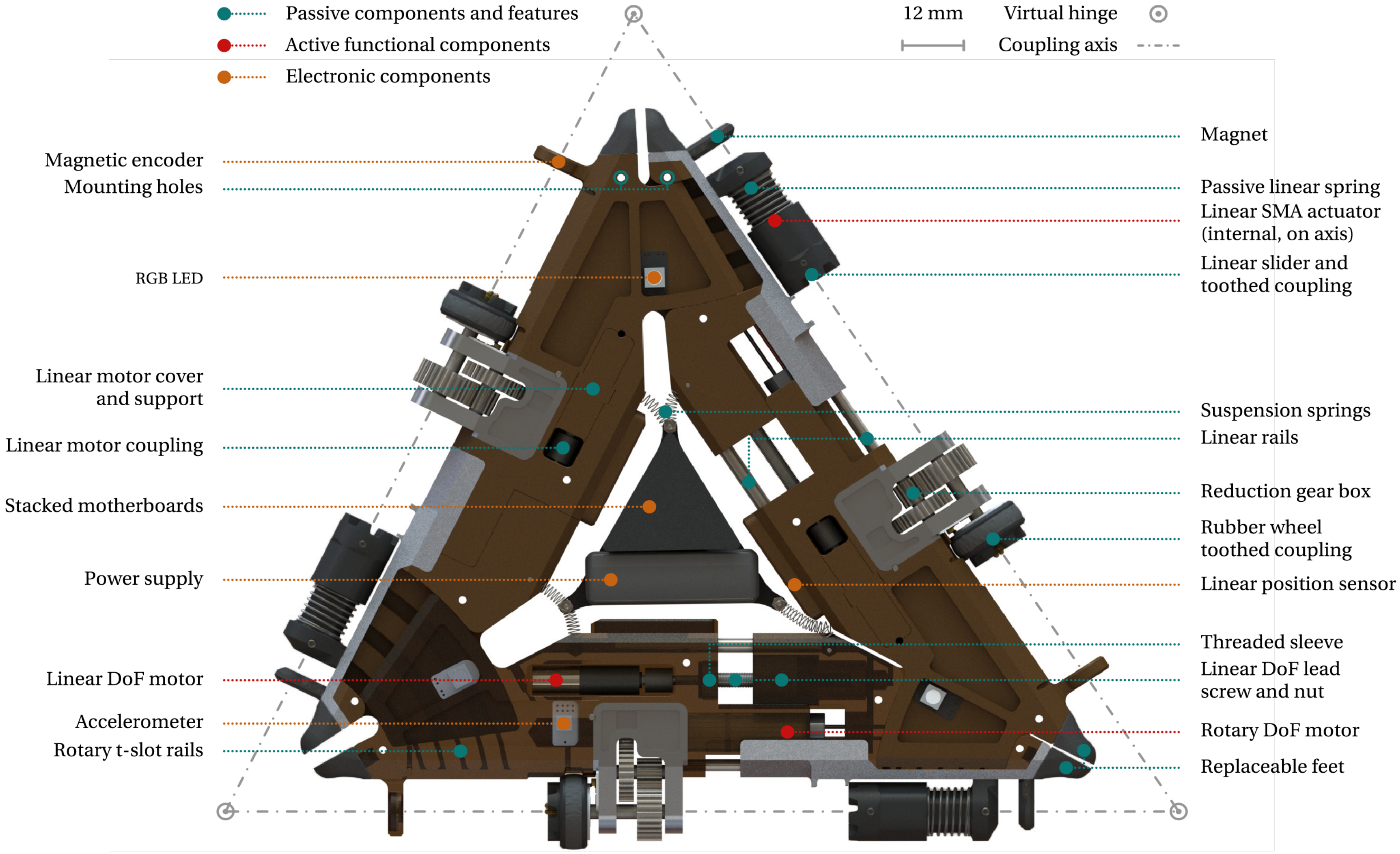

Fig. S3. Mechanical design render showing a full Mori3 module. The main functional components and features, active and passive, as well as electronic components are highlighted. Each edge in the design is identical and all components appear three times, except for the central electronics and the accelerometer.

The integrity of a polygon mesh relies on the vertices of connected modules to coincide in 3D space. For a physical implementation of a polygon mesh, these vertices are also hinge-points that allow the angle between edges to change when the length of an edge changes. The hinge mechanisms must therefore be off-set from the actual vertex to avoid collisions of neighbouring polygon modules. We have developed a unique implementation of this concept consisting of arced, interconnecting t-slots embedded in the two main pieces making up each edge. They provide a smooth hinge for the kinematic chain and rigidly couple the edges to each other. The two main pieces of a module are machined out of POM containing 13% PTFE to improve sliding properties for both the offset hinge and the linear rail. A render highlighting the overall module design and the main functional features and components is shown in Fig. S3.

The extension of each edge is guided by two linear steel shafts and additional features incorporated into the main pieces (Fig. S1). It is driven by an anti-backlash leadscrew assembly, Haydon Kerk NTG, coupled to a 6 mm diameter DC motor with a reduction of 699.5:1, Precision Microdrives 206-108. A round, smooth disk mounted to the leadscrew sits in a cut-out on the main piece containing the motor and is held in place by a threaded POM sleeve, axially supporting the assembly. The motor itself is glued into a slot and supported by a cover that diagonally slides into place. The base length of each edge, the distance between two vertices, is 180 mm and can increase by 7.5%, which is constrained to 6.7% when two edges are fully extended due to a minimum vertex angle of 55.9°. The overall thickness of the robot is 12 mm. One fully assembled module, consisting of three edges and all functional and electronic components, weighs 237 g.

The rotary component of the coupling is driven by a DC motor with a reduction of 256:1, Maxon DCX 8 M and GPX 8, connected to a custom Aluminium gearbox consisting of two stages of 28:12, resulting in an overall reduction of 1393.8:1. The actuation system is used to both fold two connected modules, with a range of angles between them of $\pi-\delta=\pm120°$, and drive a single module or collection of modules across flat surfaces. The wheels incorporated into the rotary part of the coupling have a diameter 15 mm with a silicone insert, moulded out of Smooth-Sil 960, slightly protruding the device's thickness. The control method for driving is described in Methods and depicted in Fig. S4

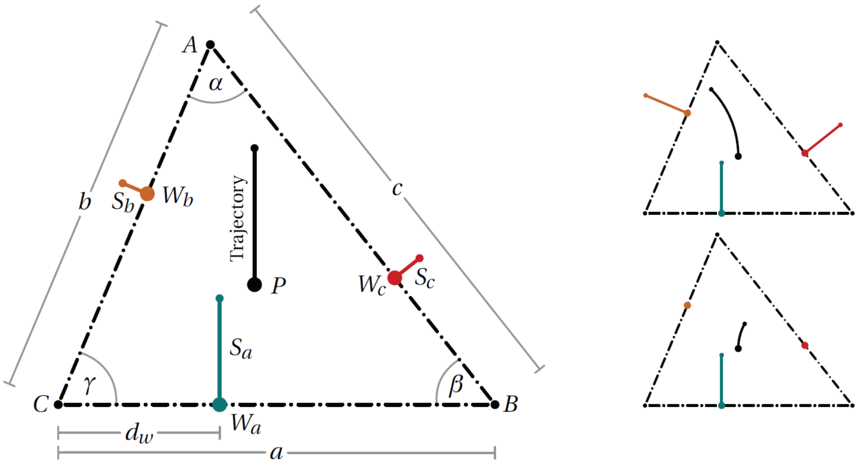

Fig. S4. Notations used in the friction-based driving model for a single module. Left: the curved trajectory of a module, perpendicular to edge $\boldsymbol{a}$ at point $\boldsymbol{P}$, is determined by a combination of relative rotational speeds $\boldsymbol{S}$ of the three wheels as well as the shape of the polygon. Right: maximum curvatures to the left and to the right.

The coupling mechanism consists of a linearly-retracting element and the wheel, both of which have the same self-centring, radial tooth profile. The mechanism is actuated by a shape-memory-alloy (SMA) spring, which is activated via Joule heating, and a passive spring ensures the coupling is normally closed. The underlying mechanism is described in detail in (25).

Electronic design

Each module holds a total of 24 individual printed circuit boards (PCBs) connected by 81 wires and 17 physical contacts. The main electronics consist of two stacked PCBs that are located in the centre of a module, suspended by six extension springs. The bottom board contains motor, SMA, and LED drivers, a DAC, the solder connections for all cables the main micro-controller, and a 16-bit Microchip dsPIC33EP512GM604, responsible for coordinating all functions of a module. The three Maxon motors are driven by two Texas Instruments (TI) DRV8834 chips with the maximum current output set by a TI DAC5574. The three extension motors are driven by two TI DRV8836. The coupling SMAs are activated by an LED driver, TI TLC59208F, which also sets the colour and brightness of the six RGB LEDs located on both faces of a module. The top board is plugged into the bottom one with nine connections and contains the power and wireless communication electronics. A single cell, 150 mAh lithium-polymer battery plugs into the top board resulting in a standby time of roughly 1.2 h and runtimes of around 25 m and 10 m under medium and maximum loads respectively. The battery provides a nominal 3.7V directly to the SMAs and the extension motors. A TI TPS61030 boost converter supplies 5V to the three Maxon motors. A MaxLinear SPX3819 regulates the 3.3V logic level. An Espressif ESP8266EX adds wireless communication and high-level control to each module.

To account for a modular control architecture, several communication streams have been included in the design of the robotic platform that address the challenges associated with controlling and synchronising modules. Using the wireless chip, each module can communicate directly with another, as well as external computers providing global commands. In addition to this, electronic connections have been embedded in the coupling system. Spring-loaded pogo-pins in the centre of the rotary coupling element make contact with two rings on the sliding element of another module. As the rotary element can spin continuously, two spring-loaded levers are in turn used to connect it to the main body. They provide a ground connection shared by all modules and direct serial communication between neighbouring modules. Through a custom communication protocol, each module can interpret the commands directly, or pass them on until they reach the addressed module as instructed. These physical connections are also used to synchronise the actuation of the DoF shared by two neighbouring modules.

The extension of each edge is measured by a linear potentiometer, ALPS RDC1014A09, coupled to one of the linear shafts. The angle between two connected modules is measured by an absolute magnetic encoder, AMS AS5048B, sensing the magnetic field of a permanent magnet on the coupled module. The matching sensor and sensing source are separated such that the sensing source on one module is detected by the sensor on the neighbouring module. This allows for absolute measurement of the angle between modules, regardless of the initial angle during coupling. The two sets of three values for the extension and the angle are actively controlled by PID-loops running at 20 Hz and 100 Hz respectively. An accelerometer, NXP MMA8452Q, aligned to one of the edges, provides the static, spatial orientation of a module.

Mori3 etymology

Mori is a portmanteau of ‘modularity’ and ‘origami’, two areas of reconfigurable robotics that have influenced our work, while also serving as a reference to the roboticist Prof. Masahiro Mori. The number 3 refers to the many multiples of three that are present in the robot including three edges of a triangle, three of most components in each module, and three linear and three rotational degrees of freedom. It also refers to this being the third robotic system we have developed around the concepts of reconfigurability, modularity, and origami.