Transforming Everyday Objects into Dynamic Interfaces using Smart Flat-Foldable Structures

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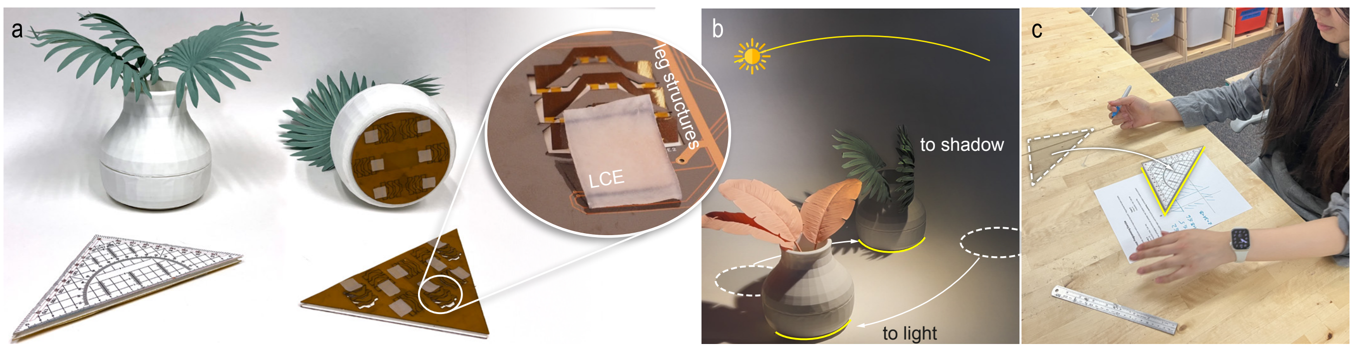

Figure 1: We present an actuation system that allows users to transform existing physical objects into dynamic physical user interfaces. (a) We design it as a self-contained flat locomotion layer that is steered by compliant leg structures actuated by liquid crystal elastomers. We aim to give typically stationary objects the ability to move, e.g., (b) plant pots seeking or avoiding direct sun, or (c) a ruler helping students with assignments.

ABSTRACT

Dynamic physical interfaces are often dedicated devices designed to adapt their physical properties to user needs. In this paper, we present an actuation system that allows users to transform their existing objects into dynamic physical user interfaces. We design our actuation system to integrate as a *self-contained locomotion* layer into *existing objects* that are small-scale, i.e., hand-size rather than furniture-size. We envision that such objects can act as collaborators: as a studio assistant in a painter's palette, as tutors in a student's ruler, or as caretakers for plants evading direct sunlight. The key idea is to decompose the actuation into (1) energy input and (2) steering to achieve a flat form factor. The energy input is provided by simple vibration. We implement steering through differential friction controlled by flat-foldable compliant structures that can be activated electrically. We study the mechanism and its performance, and show its application scenarios enabling dynamic interactions with objects.

CCS CONCEPTS

• **Human-centered computing → Human computer interaction (HCI)**.

KEYWORDS

Physical Interfaces, Robotic Objects, Compliant Structures, Kirigami

ACM Reference Format:
Violet Yinuo Han, Amber Yinglei Chen, Mason Zadan, Jesse T. Gonzalez, Dinesh K. Patel, Wendy Fangwen Yu, Carmel Majidi, and Alexandra Ion. 2025. Transforming Everyday Objects into Dynamic Interfaces using Smart Flat-Foldable Structures. In *The 38th Annual ACM Symposium on User Interface Software and Technology (UIST '25), September 28-October 1, 2025, Busan, Republic of Korea.* ACM, New York, NY, USA, 15 pages. https://doi.org/10.1145/3746059.3747720

UIST '25, September 28-October 1, 2025, Busan, Republic of Korea

ACM ISBN 979-8-4007-2037-6/2025/09.
https://doi.org/10.1145/3746059.3747720

1 INTRODUCTION

In our day-to-day lives, we use dozens of physical objects that are for the most part non-reactive. Unlike our phones and laptops, whose screens can adapt to different contexts and applications, physical interfaces are generally fixed, only moving or changing when touched by an outside actor. If a person needs to find a file on their computer, the monitor adapts to display the relevant information. But if that same person is searching for a screwdriver amidst a messy workbench, the tool can't move itself into view—it just sits motionless, waiting to be found.

The primary roadblock to realizing these dynamic objects is not necessarily a problem of computation. Wireless microcontrollers, after all, are increasingly pervasive in everyday life. Rather, a major hurdle is *actuation*; we may know where we want an object to move, and we may be able to calculate the preferred trajectory, but how do we actually *move* it?

Current approaches to this problem fall under two major categories. One solution is to employ collections of helper robots, e.g., swarm interfaces that can roam along tabletops [19], clothing [6], and other surfaces [54, 56], grabbing or pushing objects along the way. These robots are often built at the centimeter scale (larger than a coin, but smaller than a hand). While they are effective at object manipulation, and can even produce playful motions [27], these systems can risk cluttering spaces if not designed carefully.

A more streamlined option is to modify the environment around the objects. Drawing from visions of "programmable matter" [9], researchers have crafted specialized surfaces that can change shape in order to convey information or interact with passive objects. These robotic devices exist at various scales, often taking the form of tables [7], walls [10], and floors [15]. However, while neatly integrated in their surroundings, object manipulation is only possible within the confines of these specialized surfaces.

If we want physical objects to move, is there perhaps a way to augment these objects themselves? This is sometimes explored by attaching wheels [2, 38] or rails [3], but the additional bulk can significantly alter the affordances and characteristics of our already-familiar items.

Instead of relying on outside systems or additional robots, we consider the question: *'What if any of my personal things could move?'* Is there an unobtrusive way to integrate such actuation into the object materials themselves? There has been growing interest in making everyday objects move with integrated actuation. Investigating diverse actuation systems is crucial to enable different movement capabilities for various objects: Sticky Actuator [29] animates paper objects with pneumatic pouches, Vibkinesis [50] moves a phone using vibration motors, fiber-based actuators [17] actuate wearable and fabric objects, and shape-memory alloy actuators enable integrated morphing interfaces [30].

Among various approaches, thin flat locomotion systems are particularly promising for integration with tabletop objects to enable dynamic interaction scenarios where objects can move and reorient themselves while maintaining familiarity. CARDinality [33] presents a thin flat locomotion system for card objects using vibration-based locomotion and learning-based control, demonstrating effective omnidirectional movements for lightweight card objects. Complementary to this, we explore how thin flat locomotion can be extended to move heavier tabletop objects of different weights (up to 1.2kg in our evaluation), shapes, and sizes, broadening the range of everyday objects that can locomote.

In this paper, we address the technical challenge of creating a *thin, self-contained locomotion system* that can be integrated with existing tabletop objects of different sizes, shapes, and weights. By doing so, we transform these formerly static objects into dynamic interfaces that can move.

Though end users can employ our system to augment their existing objects, we also leverage mature fabrication techniques (i.e., flexible printed circuit board (PCB) assembly) that make it feasible for manufacturers to incorporate these structures earlier in the design process. We focus particularly on small, common objects (i.e., tabletop items rather than furniture).

1.1 Augmenting Objects With Motion Through an Actuation Layer

As we illustrate in our walkthrough (Figure 1), we introduce a flat layer that can be added to existing objects, augmenting them with movement capabilities. These newly mobile objects can interact with users in multiple ways: communicating information, affect, or help with physical tasks. The benefits of such interactions have been well established in prior research [1]. We aim to bring these benefits into users' everyday objects. The key technical challenge lies in achieving controlled movement while maintaining a minimal form factor. The key benefit of our approach is enabling locomoting objects of varying masses, while maintaining objects' familiarity by integrating our locomotion layer into their bottom surfaces. We design our motion layer *LayMo* to be integrated with a variety of objects and to operate on horizontal surfaces by applying it to their bottom side.

Our proposed motion layer, shown in Figure 2, is self-contained and untethered to make the integration with objects simple. To allow for controllable motion while keeping the layer flat, we decompose the actuation into (1) energy input and (2) steering.

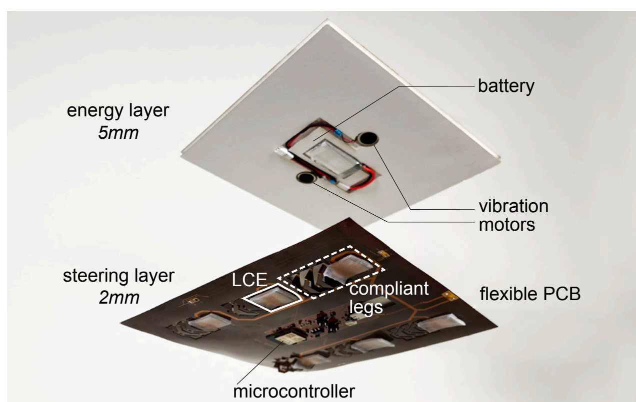

Figure 2: Our actuation system uses two flat layers to augment objects with locomotion: the steering layer that contains many flat-foldable smart structures and the simple energy layer to propel the object using simple vibration.

The *energy layer* is simple; it holds a battery and vibration motors that introduce energy into the system. Vibration alone can make objects move [50], but the trajectory is difficult to control.

For controlled movement, we introduce our *steering layer*. It consists of flat-foldable compliant structures that can be activated electrically. We use active materials (here, liquid crystal elastomers [55]) that contract when heated (using Joule heating) to pull the structures out, forming little legs. The legs reduce the friction in, e.g., the forward direction while increasing friction in the backward direction. We can fold these legs out in different spatial patterns to create local friction differentials and control the movement direction. The structures and the active material are compliant, which keeps the layer thin and easy to adapt.

1.2 Contributions

Our work contributes to the larger space of programmable matter by making the following specific contributions:

(1) A design for a self-contained motion layer that can be applied to many everyday objects.
(2) A layered fabrication method that can be adapted to fit a variety of objects.
(3) Technical evaluations of the system's steerability, trajectory following, and weight capacity.
(4) An exploration of the application space enabled by integrating the motion layer into different objects.

2 RELATED WORK

Our work is related to previous HCI explorations of interacting with dynamic interfaces and locomoting objects. We further draw inspirations from friction-based locomotion in robotics and advancements in active materials to inform the design and implementation of LayMo.

2.1 Interaction With Dynamic Interfaces

HCI has long envisioned interweaving computing into everyday life, as proposed by Weiser and Ishii [14, 49]. Researchers have explored physical dynamic interfaces as a means to integrate computing into daily environments. These interfaces convey digital information by forming shape-changing displays [7], deliver encounter-type haptics via distributed robotic systems [39], and assist users' tasks through configurable functionalities [5]. They bring in dedicated devices to highlight interaction benefits of dynamic interfaces. Another approach is to transform objects themselves into dynamic interfaces that can output local shape-changes. This offers opportunities for expressive interactions with everyday objects. For example, MoLux [36] is a shape-changing lamp that negotiates control through its form, while the Thrifty Faucet [42] demonstrates using shape-change to communicate its use. With more focus on output mechanisms, Robiot [21] introduced actuating passive objects' mechanisms with 3D printed attachments along with motor actuation. Sticky Actuator [29] showed using air pouches to actuate lightweight objects, such as a paper box's folding mechanism. Along this line of work that animate passive objects, PINOKY [37] presents a ring that animates plush toys, and [46] utilizes a multi-robot system to manipulate passive objects. We follow these works in transforming objects themselves into dynamic interfaces, and focus on creating global output capabilities (i.e., locomotion).

2.2 Locomotion of Objects

As locomoting passive objects could bring interaction benefits, previous research in HCI has demonstrated different ways of moving passive objects. Actuated Tangible User Interfaces [26] and swarm robots [19, 40] have been introduced to help move users' desktop objects around. They can be distributed to move several objects for complex tasks [22]. Other works focused on building dynamic actuation into surfaces and stationary furniture in the environment. Transform [44] shows a shape-changing display fitting into users' environments as a tabletop that enables passive objects' movement upon. Gonzalez et al. [10] further explored building actuation into architectural surfaces (i.e., walls, floors, ceilings) to augment users' daily tasks with moving their things when needed. Another approach that has been proposed is attaching mechanical parts such as wheels and 3D-printed mechanisms onto objects [12, 21] to give objects themselves movement capabilities. As some objects such as smartphones already have vibration motors built-in, researchers have [50] also used readily-available vibration motors within these devices to create locomotion. Our work builds upon insights from previous works on locomoting objects. We introduce integrating a self-contained locomotion layer into objects, which can give objects controllable and environmentally-independent movements when combined with a vibrational force.

2.3 Friction-Based Locomotion

Friction-based locomotion has been demonstrated as a promising way of producing movement in robotics. It is especially robust for small or lightweight robots [52] to locomote themselves without adding many additional mechanical parts onboard. Origami and kirigami surface patterns have been developed to propel crawling robots [4]. Folding in and out these geometric patterns manages friction in different directions to help the robots propel. Integration of passive arrayed legs is an approach to create friction-based locomotion. For example, Ta et al. [41] showed the differential friction created by passive arrayed legs capable of replacing wheels when given an actuation force. Yan et al. [51] combined vibrational force with arrayed legs to allow a small robot to move across various substrates. We take inspiration from this line of work, designing *flat-foldable* structures that can be integrated into objects' surfaces. Our structures *become* arrayed legs when actuated, creating friction-based locomotion when combined with vibrational energy.

2.4 Active Materials

Active materials are engineered substances that respond to external inputs such as heat [20, 34], electric fields [47], light, and so on, often with altering their physical properties such as expansion or contraction. This output can be used as actuation. They offer more integrated and lightweight forms of actuation compared to traditional mechanical systems. Active materials have been employed in HCI research focusing on physical actuation with small and integrated factors. Lin et al. [23] incorporated shape memory alloy into a small modular actuator; Zhong et al. [57] demonstrated shape memory materials as an approach to morphing interfaces;

FiberRobo [8] presents liquid crystal elastomers (LCE) in a fiber form to be integrated into textile interfaces for shaping-changing behaviors. We are especially interested in LCE due to its large power density [16] and flexibility in shape [18], allowing for robust actuation and flat-form factor for our structures. LCE literature also shows future potential for wireless actuation [45], integration of heating [43], and self-healability [48]. We believe that such advancements show future possibilities to improve our structure for, e.g., wireless steering, integration into ultra-thin layers, enhanced durability, and so on.

3 IMPLEMENTATION

In this section, we detail the implementation details of LayMo, presenting its geometry, actuation, and control specifications. We describe the actuation and control of our motion layer in its smallest configuration, i.e., with only one structure to fold out, before expanding to a fully actuated surface. Figure 3 shows an overview of one such reduced configuration: it consists of leg structures that are folded out by an active material; we use liquid crystal elastomers (LCE). A film heater, controlled by a microcontroller, heats up the LCE, such that it contracts and folds out the leg structures to modulate the friction between the object and the surface it is moving on.

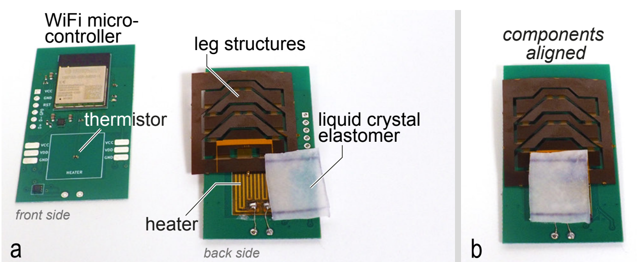

Figure 3: Overview of a single LayMo structure. The leg structures are folded out by heating a liquid crystal elastomer, which shrinks. A WiFi microcontroller controls the heater.

3.1 Leg Geometry

We illustrate the base geometry of a LayMo unit in Figure 4a. It consists of trapezoidal legs and linkages connected by compliant hinges. Our novel design allows for efficient fabrication of our structures in thin sheets. It also enables efficient actuation of multiple linked legs with a single actuator, and maintains a flat-foldable form factor that allows the structures to become various objects' bottom surfaces. As shown in Figure 4b, we define several geometry constraints. Specifically, the height of the inner hinge within a leg (as compared to its base hinges) must be equal to the height of the shoulder hinges of the same leg (also as compared to its base hinges). This is to ensure consistent actuation angles among all linked legs. Also, inner hinge placement within a leg should be greater than or equal to half of the leg's tip height to account for efficient actuation.

Our compliant linkage mechanism also allows designers to vary the legs in size, height, or layout to adapt to different objects. In our prototypes, we use trapezoid-shaped tips for biasing friction,

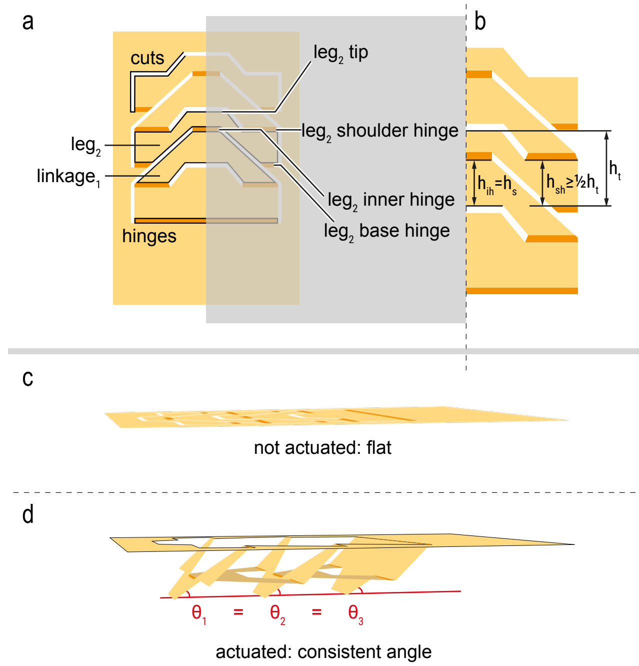

Figure 4: Illustrations of a base geometry design. (a) Components of the flat structure, and (b) its parameters in the actuated state. (c) The leg structures lay flat when not actuated, and (d) fold out to form inclined angles when actuated.

consistent with [32]. Other tip geometries could be a subject of interest for future research. Our leg geometry design is inspired by kirigami-based soft robots [32]. Building on those principles to create a thin system to integrate with existing objects instead of, e.g., building dedicated robots [32]. Our fabrication process is related to Smart Composite Microstructure (SCM) fabrication techniques.

3.2 Actuating the Legs Using LCEs

To actuate LayMo's legs, while still maintaining a flat form factor when it is not actuated, we choose to use active sheet materials that can be directly integrated with the base geometry layer. Such flat actuators also have the benefit that they can be laminated with the leg layer to enable large scale fabrication. We use liquid crystal elastomers (LCEs) as our actuators because they have high power density [16] and their geometry can be manipulated easily [28] (i.e., they can be custom-made into various shapes, sizes, and thicknesses), making them suitable for our case.

We mount a 15 × 15 × 1 mm LCE actuator on the first leg structure to actuate the entire unit. A film heater is used to actuate the LCE actuator with joule heating. The heater is fully adhered to the PCB or fabricated with the PCB. We glue the LCE actuator at its top and bottom to the PCB, as highlighted in Figure 5a. We use 407 silicon glue adhesive, and apply it on the top and bottom (approx. 2 mm) of the LCE actuator. The LCE contracts approximately. 40% linearly when it is activated through joule heating to pull the first leg structure out-of-plane, which in turn pulls the other legs up. When the LCE contracts, the heater bends and forms a small gap

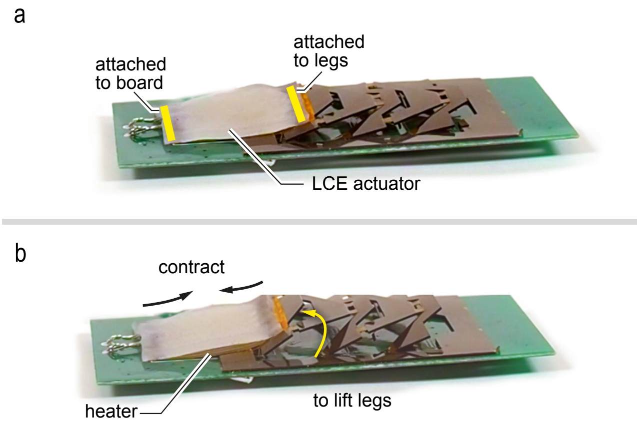

Figure 5: We make custom LCE actuators (a) that we attach to the board and legs at their two ends. An LCE actuator acts as a muscle for our structure , (b) lifting the legs with a contraction force.

between it and the LCE, as seen in Figure 5b. The linkages in the structure actuate all connected legs, while ensuring they maintain nearly the same actuation angle (Figure 4d). We include fabrication steps in supplementary materials for replicability.

Our LCE actuator's actuation temperature is 60°C. In our experiments, 3V and 0.6A fully actuate an LCE actuator in approx. 45 seconds. Increasing the voltage will heat the heater faster, thereby actuating the LCE faster.

3.2.1 Spatial Programming of LCE Actuators. LCE actuators are the artificial muscles in our actuation system that contract to lift the legs. We follow the procedure reported in [55] closely to make custom spatially programmed LCE actuators tailored for our actuation system. We illustrate the process in Figure 6. To do this, we 3D print a mold with external dimensions of 10.2 × 66 × 77.6 mm and inner dimensions of 2.2 × 50 × 60.2 mm, using a stereolithography (SLA) printer. After steps of mixing the chemicals, we pour the mixture into the mold and leave the mold in a fume hood at room temperature for 12 hours, followed by another 12 hours in a vacuum oven. After this, we remove the LCE sheet from the mold and stretch it to 180% of its original length with a stretcher. We then expose it to high-power UV light for a short time (15 - 30min). This step programs LCE sheets to remember this elongated state. They contract to be 60% of this length when activated and return to this elongated state on their own. We refer interested readers to "6 Experimental Section" in [55] for chemical compositions and replicable details of the LCE fabrication process.

Different from the fabrication process in [55], we leverage the spatial controllability in this step for fabricating enduring LCE actuators for the needs of our structures: an LCE actuator should form strong attachments at its two ends with the board and the legs, while exhibiting a large contract stroke between the attachment sites.

To achieve this effect, we explore the idea of spatially programming regions of the LCE during the UV crosslinking stage. We illustrate this process in Figure 6. We make custom stretchers that stretch alternating sections of an LCE sheet, while firmly holding down the in-between sections not to stretch, to eventually become sites for attachment. We refer interested readers to our supplementary materials for our design files, a step-by-step fabrication process, and fabrication files.

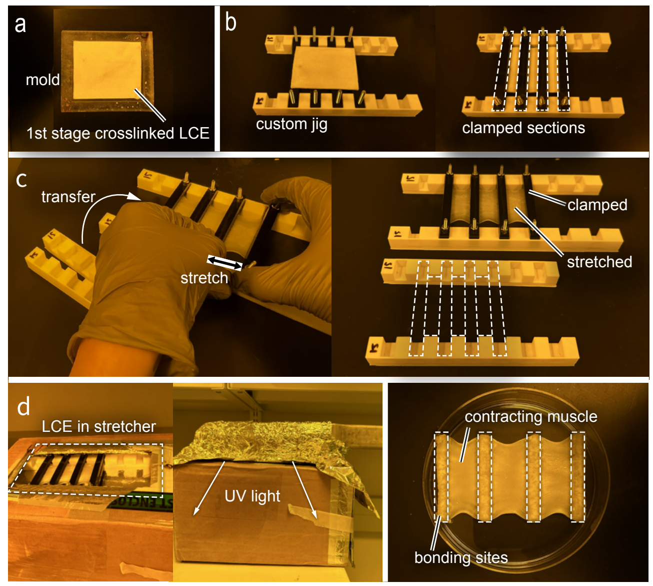

Figure 6: We show the process of making custom liquid crystal elastomer actuators. We 3D print (a) a custom mold and (b) jig. (c) We transfer the LCE onto the jig and stretch it in 4 sections by clamping it down. (d) We UV cure it, resulting in an LCE with 3 contracting regions with non-contracting regions in between for bonding.

3.3 Integrating Control Circuit

Since an LCE actuator acts as the muscle for the structure, we implement a circuit to Joule heat the LCE and monitor its temperature. In the smallest configuration, each modular structure includes a microcontroller in its printed circuit board (PCB) layer for modular control. We show our simple control circuit for just one unit structure in Figure 7. We designed a custom PCB with a Wifi microcontroller (ESP32) for controlling the heating. The top side of the board holds the microcontroller, a thermistor for temperature control, and other voltage-regulating circuitry. On the bottom side, we apply our flexible leg structures, the film heater, and the LCE. We employ a simple bang-bang control for heat regulation. In addition to Joule heating, we can drive the vibration motor(s) using our control circuit.

Our modules each have their own microcontroller to give us flexibility for our research prototypes. As we show in Figure 8a, one microcontroller can control multiple leg structures. Furthermore, all electronic components needed for the steering layer can be integrated into one layer and manufactured as a flexible PCB. We show one example in Figure 8b that consists of 6 leg structures,

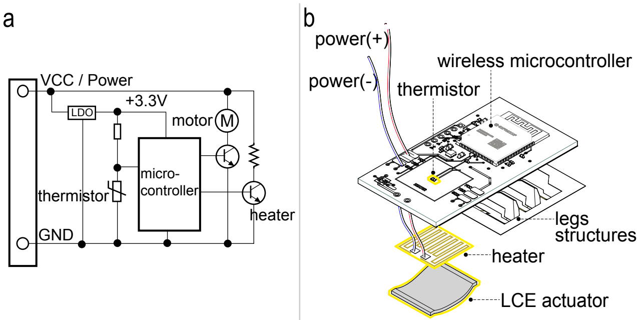

Figure 7: (a) To control one leg structure, we use a film heater, a thermistor for temperature control, and a microcontroller. (b) We show the assembly and how we laminate the leg structures, the heater, and the LCE on the back of the PCB.

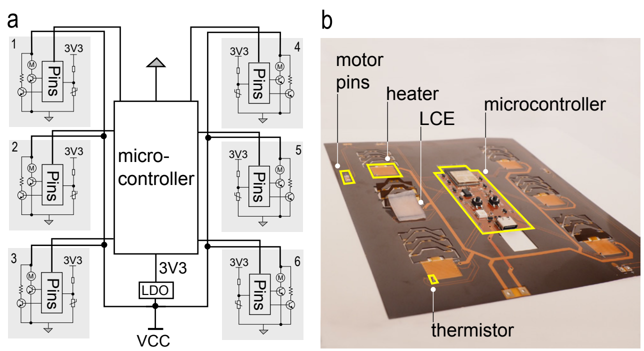

Figure 8: (a) We show the circuit to control multiple structures with one microcontroller. (b) Such a flexible PCB can be manufactured with multiple leg structures, an onboard microcontroller, and film heaters.

has integrated film heaters and thermistors for each, and a microcontroller shared between all structures. Only the LCEs need to be applied to this self-contained steering layer. The energy layer will provide power and control the vibration motors, which can also be controlled by our steering layer.

Manufacturing the steering layer as a fully integrated flexible PCB offers several advantages, in that the manufacturing quality is high, miniaturization is easy, and customization is enabled through digital design. When active materials become more mainstream, future manufacturers may even expand their catalog to embed them in their assembly pipeline.

4 MOVEMENT PRINCIPLE

Our movement principle is simple. The leg structures are designed to remain inclined after being folded out by the LCE. As we show in Figure 9a, the structures inclined towards the back result in a forward motion. That is because the directionality in contact with the ground surface creates different friction. To rotate the object, we can use leg structures that point in opposite directions, as shown in Figure 9b.

The inclined structures alone would not move the object forward. To do so, we need to insert energy, for which we use vibration motors. The vibration force should be directed towards the ground, as opposed to being parallel to the ground, as regular pancake vibration motors would produce. We use linear resonant actuators for this purpose.

Figure 9: Our movement principle is based on friction differential. (a) The inclined legs determine the movement direction. (b) Combining legs in opposing directions makes the object rotate.

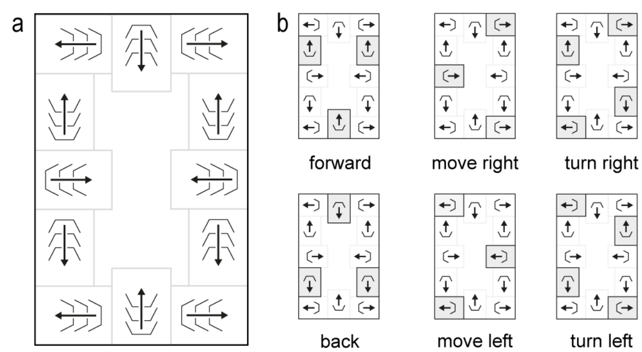

Figure 10: (a) We design a layout of 12 leg structures to cover (b) 6 canonical movements, while keeping a stable base.

These two motion principles, i.e., moving forward with leg structures pointing in the same direction and turning with leg structures in opposite directions, are the core principles. We use these to devise a spatial layout of leg structures that allow an object to perform all possible movements. We show this layout in Figure 10. We orient the legs to (1) always actuate at least 3 leg structures distributed in a triangle for stability and to (2) be a tileable pattern. We show how our leg layout incorporates 6 canonical movements, i.e., move forward and backward, move sideways to the left and to the right, and rotate clockwise and counterclockwise (i.e., turning left and right). Note that for rotations, any combination of 3 modules among the 4 highlighted modules would produce the rotations. For heavier objects, all 4 modules can be actuated to help balance the distribution of weight during rotations.

This generic layout is tileable to stretch over larger objects as well if needed. For actuating smaller objects, the leg structure can either be manufactured in a smaller size, or users can design a custom layout.

5 TECHNICAL EVALUATION

We conducted technical evaluations on LayMo's movement capabilities. We first evaluate simple movements in a comparative study. Validating that our system can produce canonical movement is the prerequisite for following trajectories that are compounds of multiple simple movements, which we validate in a second experiment. Finally, we evaluate LayMo's weight-bearing capacity, testing both its initial lifting capability and ability to maintain steerable movements under load.

5.1 Simple Movement Evaluation

We aim to evaluate how our system can perform simple movements, i.e., move forward, backward, left and right, and turn left and right. We compare the performance of our system in three conditions: (1) a *baseline* condition [50] producing steering movements using only vibration motors, (2) using LayMo's *energy layer only* (i.e., without leg structures) to study the impact of our steering layer, and (3) our complete *LayMo* system with steering layer and energy layer. We expect our system to be able to produce more types and more accurate movements compared to the vibration-only conditions.

Setup. We show our tracking setup in Figure 11a-c. We used white cardboard with an acrylic sheet overlay as the test surface. For each trial, we placed the test object on the surface and tracked its movement. We stopped the trial if the object exited the surface's boundaries, moved slowly exceeding one minute, or stopped moving on its own. We added colored markers on our test devices, which we used to track the motion paths using a top-mounted camera. We tested all three conditions on this setup.

We implemented Vibkinesis [50] as our *Baseline* condition. The authors of that work used coin vibration motors placed in the four cardinal directions of the device. We replicate their setup of 8 coin vibration motors (Vybronics Inc VC1434B002U, 3.7V, 9000 RPM, 2G), as shown in Figure 11. We note that the authors mentioned doubling the motors from originally 4 to 8 motors due to their device's weight. We tested both implementations, and while our baseline implementation was significantly lighter (approx. 40g compared to their 231g), we still achieved considerably better results with 8 motors and decided to report the better results. We tested steering left and right only, including translations and turns, since Vibkinesis indicates that the system is not able to produce forward motion. Instead, they would frequently steer left and right to aggregate a forward directional path. We adapt the vibration motor actuation patterns they reported for steering this baseline condition. We used 5 mm foam core board to build test objects for all three conditions.

To test the effectiveness of the steering layer, we isolate LayMo's energy layer in the *Energy-Only* condition. Inspired by recent work on moving lightweight cards across tables using cylindrical (rather than coin-type) vibration motors [33], we align the eccentric masses of our motors and balance their rotation directions, as illustrated in Figure 11. We used cylindrical ERM motors (BestTong Eccentric Rotating Mass Vibration Motors, 3V, 14000 RPM) and actuated only one at a time according to its rotation direction.

In our *LayMo* condition, we used the energy layer described in *Energy-Only* along with our generic steering layer layout with 12 leg structures that we previously introduced in Figure 10. We used a passive steering layer since we only tested one single movement in each trial. We manually folded the appropriate leg structures out, then turned the vibration motors on, and set it down in the starting position. We cut small bistable structures into the steering layer to keep the legs folded out during the trial, imitating the LCEs holding force. While we left all 4 motors on the layer, we only activated 2 of them across all trials to allow our steering layer to steer.

Results. Overall, the results shown in Figure 11d indicate that *LayMo* is able to produce more types of movements as well as more reliable steering than the *Baseline* and *Energy-Only* conditions.

The *Baseline* condition relied only on the location of the vibration motors for directional control. While this approach achieved steering functionality, its performance seems largely influenced by the clockwise rotation direction of the motors. Due to this, the *Baseline* condition is not able to produce forward nor backward movement. This is discussed in the Vibkinesis paper [50] where frequent steering of turning motion is used for the device to go forward. The influence of the motors' rotation direction is also evident in the better performance of right turns in comparison to left turns, and that *Baseline* exhibited a tendency to initiate unintended turns or stop when moving left and right.

The *Energy-Only* condition relied on the motors' rotation directions for steering. It was unable to produce turns, despite being able to translate in cardinal directions. Since we aligned the motors eccentric masses along horizontal and vertical axes, this implementation can produce reliable movements in forward and side directions, as shown in Figure 11. Surprisingly, we observe barely any movement going backward. This may be due to a potentially worn-out motor.

In contrast, our *LayMo* condition achieved more types of movements and more reliable directional control through its decoupled steering and energy layers' design. While *Baseline* was unable to produce forward and backward motion, LayMo's locomotion can steer forward or backward for about 50 cm.

While the *Energy-Only* condition was unable to produce turns, *LayMo* achieved both left and right turns. We observe that even though the steering layer is the main actor for steering, vibration motors may still influence the movement. In Figure 11, there are small noticeable patterns in the movements. For example, right turns appear wider than left turns, and backward movements are slightly angled towards the left. We attribute these effects to the different vibration energy exhibited by the motors. As mentioned above, the bottom motor appears to be weaker. Despite minor effects, the steering layer in LayMo was still able to produce all 6 test movements reliably, demonstrating the effectiveness of our layered design approach.

Recent work [33] proposed learning-based control for omnidirectional locomotion with vibration. This is not currently implemented in our comparison, but is interesting future work to integrate advanced control into our actuation system.

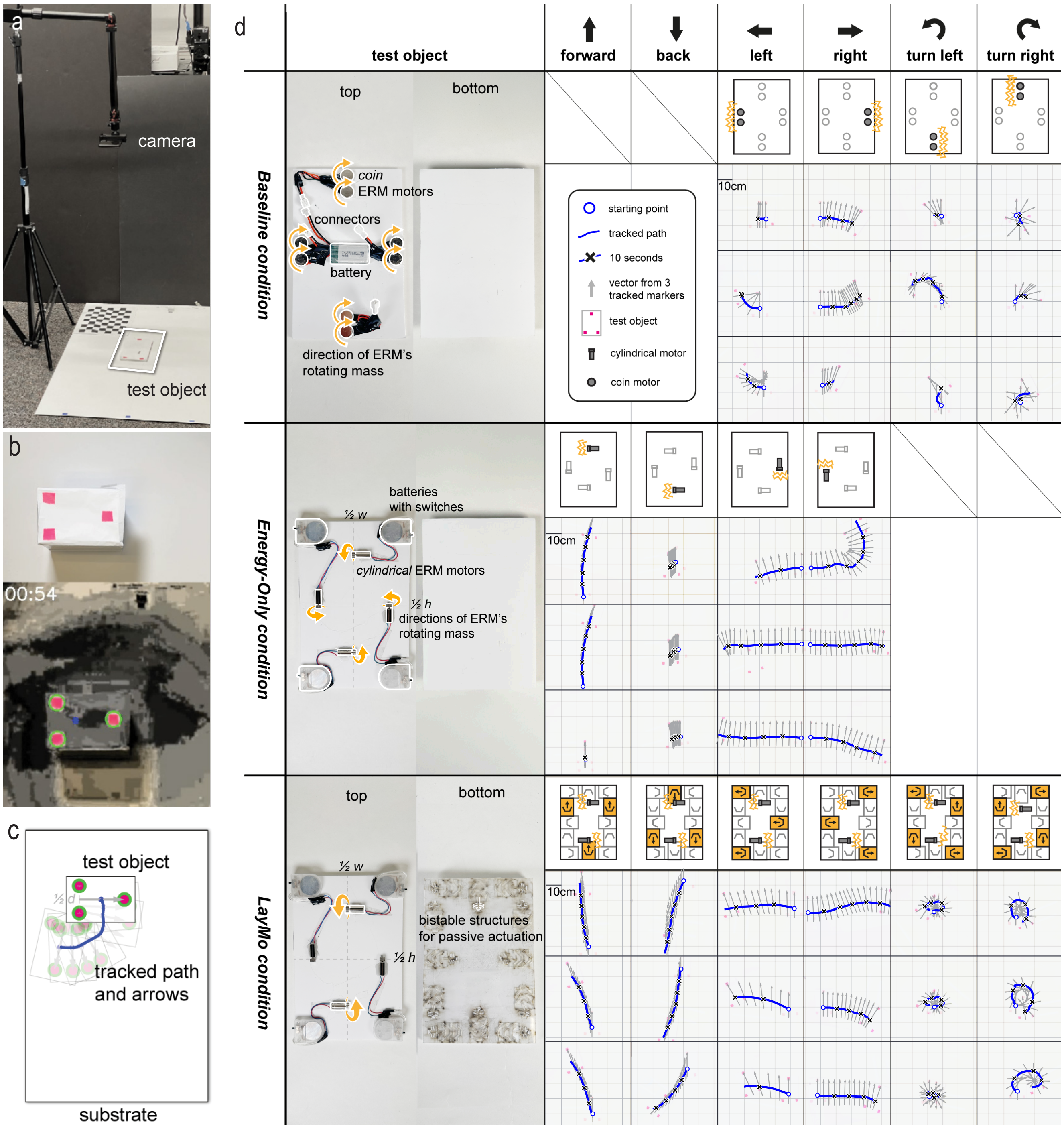

Figure 11: We tested three conditions for six different movements. We use (a) an overhead camera to track (b) test objects with three red markers, and use (c) a custom tracking program to produce reliable tracking results throughout our evaluation. (d) We plot the trajectories. The grid labels the distance and the × on the trajectories mark time to indicate speed.

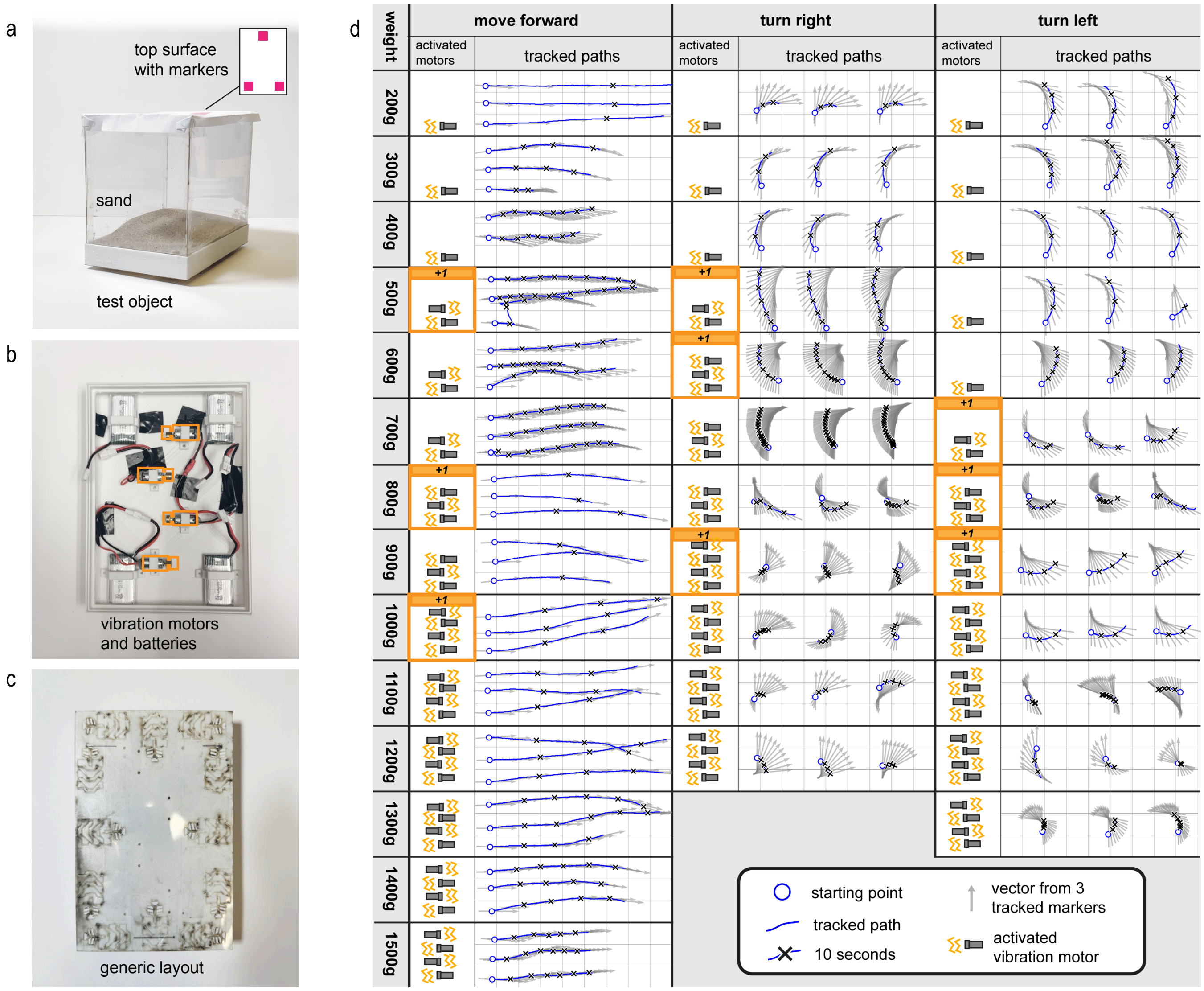

Figure 12: We show our test object with (a) tracking markers on its lid and a mounted container for sand to increment weight, (b) 4 vibration motors and batteries, and (c) a generic layout at its bottom. (d) We show the results of steering loads up to 1200g under weight. More active motors help move heavier objects.

5.2 Movement Under Load

Since LayMo is designed to augment objects, which will have their own mass, we proceed to evaluate its canonical movement capabilities under load. To do so, we use the same passive 12-module generic layout as in the previous experiment and pair it with 4 new eccentric rotating mass vibration motors (NFP-FF-M20SA-07170), as shown in Figure 12a-c. We vary the number of activated vibration motors and the weight being moved using sand. We employed a staircase method, i.e., progressively adding weight in increments of 100g until the test device failed to move. Upon failure, we incremented the number of active motors by 1 and resumed testing from the last weight. We tested 3 basic movement types: moving straight, turning right, and turning left.

Results. The trajectory tracking results in Figure 12d indicate that the LayMo prototype can steer objects of up to 1200g in weight. This makes it appropriate to actuate desktop objects, such as smartphones (~200g), hardcover A5 notebooks (~230g), or coffee mugs (~400g).

The '×' in each tracked path indicates the movement performed in 10 seconds, illustrating speed. The results are largely consistent with our expectation that heavier loads decrease actuation speeds and introduce variations to the movements. We notice outliers, e.g., increasing the load from 700g to 800g in the turn right condition increases the speed. We hypothesize that due to fabrication differences in our hand-made research prototypes, heavier loads may help LayMo's legs establish more uniform contact with the ground. Validating this interpretation would require further studies.

5.3 Lifting Capacity

To steer objects with mass, LayMo's leg structures need to be able to actuate, which means that the object needs to be lifted. We evaluated LayMo's lifting capacity based on a similar staircase method as in the previous experiment. We use a prototype with 12 active modules that measures 15 × 20 cm, and weighs about 100g. We started by activating 3 modules and added sand in increments of 100g until the system failed to lift. In that case, we incremented the number of actuated modules by 3 and resumed testing from the last weight. We proceeded until we activated all 12 modules.

We show our setup in Figure 13a-b. We varied the number of activated leg structures using a custom control web interface. Both the WiFi control and the Joule heating of the LCE actuators were powered by an external power supply. Our 12-module LayMo uses a 10 mm × 10 mm × 1.5 mm LCE actuator for each module. This prototype is used in the next experiment as well; we show the LCE arrangement in Figure 14.

Results. Our results (shown in Figure 13) indicate that a 12-module LayMo can lift up to 800g of weight. Consistent with our expectations, more actuated modules allow for larger weight-lifting capacity. This means that heavier objects can be moved if they have a larger area to add more active modules. In other words, small heavy objects may not be suitable for LayMo, but larger heavier objects may be. At the same time, there are also trade-offs between the weight being lifted by the system, the power consumption, and actuation time: since heavier weights require more actuated modules, they also consume more power and take longer to be lifted.

During our evaluation, our LayMo was powered by a 5V supply with a 9A current limit. On average, actuating 3 modules to lift a 400g object required about 29 – 42W for heating the modules for about 23 – 32 seconds, consuming about 0.2Wh. For context, a standard portable phone charger (e.g., 10000 mAh at 3.7V, or 37Wh) could support about 194 actuations of our system (= 37Wh/0.19Wh). This number decreases as the number of LCEs increases. Note that the power consumption shown in Figure 13 does not persist over the entire duration of the test, since the power consumption fluctuates due to our pulse width modulation (PWM). We use LayMo's onboard thermistor to control the LCE's temperature using PWM to prevent overheating and maintain 55 – 70°C during the LCE's actuated duration.

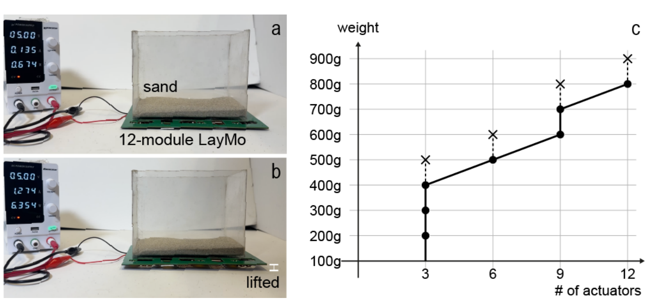

Figure 13: (a-b) We use a 12-module LayMo to lift an increasing load adjusted with sand. (c) Results indicate that a 12-module layout can lift up to 800g of load.

5.4 Following Trajectories

Next, we evaluated how well LayMo can follow target trajectories. We tested 4 different trajectories, shown in Figure 14, each consisting of 2 or 3 canonical movements. We used our active steering layer with 12 actuated leg structures laid out in our generic pattern and 2 vibration motors (Figure 10). We use an external power supply tethered to the test object. This supplies power for both the WiFi MCU onboard to establish a connection for control, and for joule heating the LCE actuators to fold the respective leg structures out. We use long wires and hang them overhead to minimize impact on the locomotion trajectory.

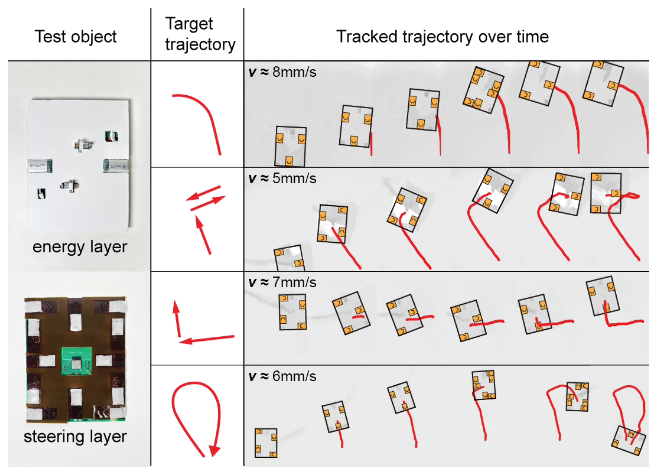

Figure 14: Our results show how our system approximates distinct trajectories, such as (a) a granular angle shift, (b) a loop motion, (c) an angle turn, and (d) sharp angle changes.

We use the same overhead tracking setup as in our previous experiment and show our raw tracking results in Figure 14. Such qualitative visual comparisons are commonly used in soft robotics (e.g., [35]).

We show the motion paths we captured in Figure 14. For each target trajectory, we show the device's movement in 6 subsections each. We annotate the leg structures that are active in each subsection to illustrate our steering patterns. Overall, our test device can approximate the 4 distinct trajectories well. We note that the main features of the trajectories are clearly visible, i.e., curvature direction, curvature degree, change in direction, or sections that are straight. This indicates that LayMo can support interactions similar to the application examples we present in Section 6. These initial results look promising for steering along more complex trajectories with closed-loop control in future implementations. Speeds for following different trajectories vary. This is due to turns slowing the motion down, as LCEs need to actuate or cool down.

6 APPLICATIONS

We present example applications to illustrate how transforming everyday objects into dynamic entities with movement enabled by LayMo can enable new interaction for users. Since in this paper we focus on how to augment objects with *actuation*, we utilize predefined movement patterns to illustrate how such dynamic interfaces can assist users. To fully realize these scenarios in the future, we will discuss additional sensing and control systems in the following section. Our motion layer is most suitable for hand-sized objects and works on horizontal surfaces.

6.1 Studio Assistant to an Artist

Figure 15 shows an artist in their studio. To assist with their painting process, they augment their (a) color palette and a tissue box with our structures. While the artist is laying down an initial layer of paint, (b) their augmented palette moves itself closer to the artist, (c) for them to access all the paints on the palette. (d) Having painted the initial scene of a fall forest, the artist takes a step back to contemplate which color to use to capture the special lighting condition they have in their mind. To assist with the color choice, the palette rotates itself to suggest a yellow-toned color; a physical instantiation of suggestive interfaces [13, 24]. (e) For the final touches, the artist uses tissues for smudging and blending colors, for which the tissue box approaches them. As the artist takes a break, the palette pushes the dirty tissues over the table into the trash bin to help maintain a clean and organized working environment.

Our prototype implementation uses a color palette-shaped LayMo layer with 12 modules arranged in different directions based on the movement principles from Figure 10. We implement the energy layer using two vibration motors and a LiPo battery. A researcher controls structure actuation via open-loop control to generate the demonstrated movements, using actuation patterns informed by Figure 10 and confirmed by our evaluations.

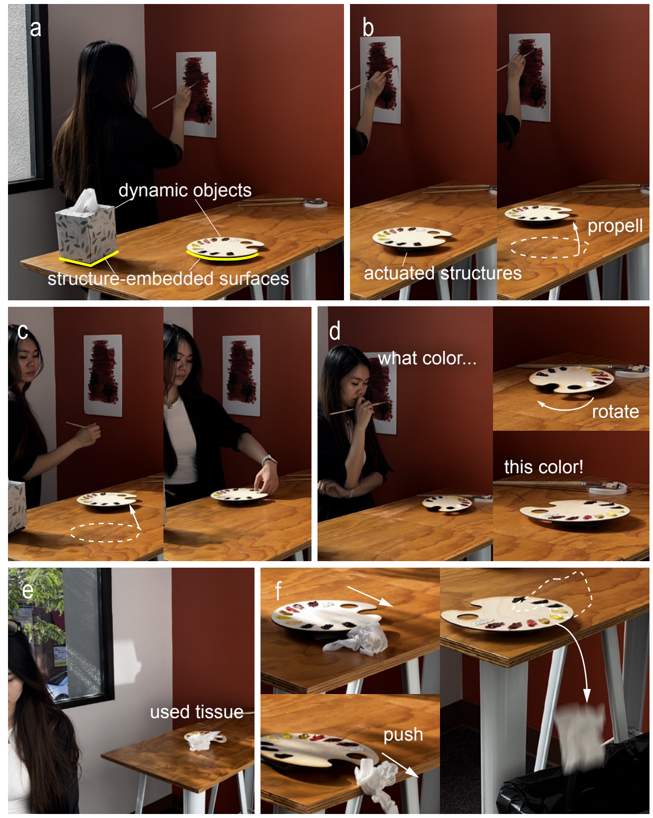

Figure 15: (a) An artist uses our system to make their (b) palette dynamic, which (c) moves to them and (c) suggests new colors by rotating itself. (e) After the artist leaves (f) the palette cleans up.

6.2 Moving Plants

In addition to augmenting objects that interact directly with users, we also envision our LayMo to enable other objects to move. While currently not implemented, additional sensing and control systems may enable autonomous motion in the future. We show in Figure 16a two plant pots that are augmented with motion, as both plant pots integrate LayMo layers at their bottom surfaces. As we show in Figure 1, each surface consists of 6 modules and 2 vibration motors. The integration of LayMo allows the plant pots to move and turn to produce compound trajectories as shown in our evaluation Figure 14.

For example, (b) the green plant prefers indirect sunlight, while the pink plant thrives in direct sun. In the future, with additional sensing and control as described in previous application examples, LayMo allows the plants to take care of themselves by moving away or into the light, depending on the weather and position of the sun over the course of the day, while the owner is not home to take care of them.

The illustrated scenario suggests the possibility of plants caring for themselves. Future plant care systems can combine motion capabilities from LayMo with plant-specific sensors [25], to create autonomous plant care systems.

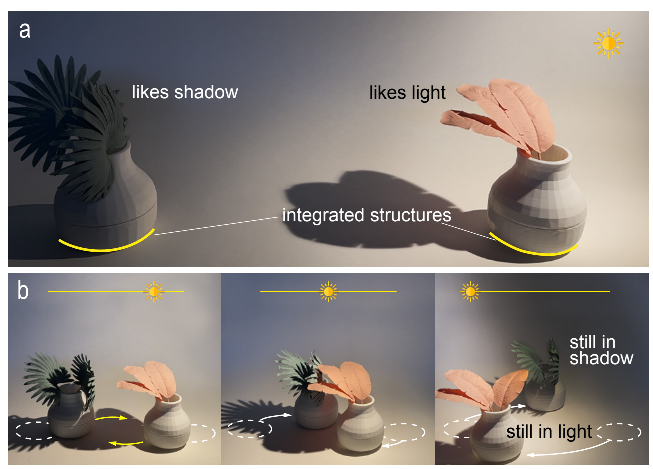

Figure 16: (a) Our system also augments plants in that it enables them to move to (b) stay in the sun or in the shadow as the sun changes position.

6.3 Math Tutor in a Ruler

We envision that moving objects can serve as tutors to students by integrating movement into items they are familiar with. Figure 17 shows a student working on a linear programming problem. (a) Their geometry ruler is integrated with a LayMo layer with 8 modules, 2 vibration motors, and a battery for untethered demonstration (see Figure 1). We illustrate this envisioned interaction scenario in Figure 17. (b) After writing down the constraints of their optimization problem, the student gets stuck on how to visualize the feasible area on the diagram. (c) To help, their ruler moves onto the coordinate system and rotates itself to indicate how to draw the line. This helps the student unblock and proceed with their homework. (d) Next, the student draws a line to visualize the objective function, but can't remember how to maximize it. (e) Again, their dynamic geometry ruler gives them a hint by moving towards their linear ruler on the desk. (f) This reminds the students to use the other ruler to parallel shift their previously drawn objective function up to maximize the area and solve their homework. Our current implementation enables the ruler to move across the student's work area. To expand it into a closed-loop tutoring system would require adding optical character recognition, precise position tracking, and mathematical reasoning capabilities.

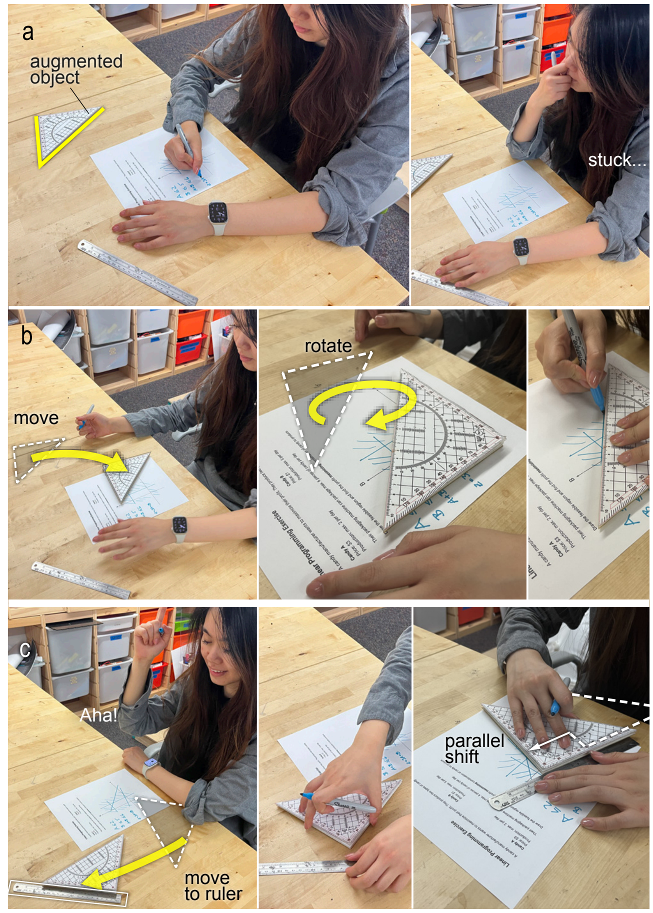

Figure 17: (a) A student uses our system to augment their geometry ruler. (b) As the student is stuck on their homework, the ruler moves and places itself onto the coordinate system, indicating the correct line. (c) The ruler moves towards the other ruler on the table, hinting at using it to parallel-shift the function.

7 DISCUSSION & LIMITATIONS

Our paper focuses on an actuation design that is flat and can be integrated with existing objects that users are already familiar with. There is room for follow-up research and exploration going beyond actuation alone and towards interaction.

7.1 Sensing and User Intent

While our motion layer augments objects with movement capabilities, our current prototypes should be extended with sensing capabilities as well. One obvious reason to add sensing is for closed-loop control of the movements (e.g., using IMUs, sound-based localization, or similar).

Beyond control on the device, we are interested in expanding this concept into a system where objects can react to users at any time. To do so, we are interested in using sensor data embedded into our object augmentation layer (e.g., touch, proximity, gestures) to potentially sense users' gaze or biosignals in an instrumented environment to predict user intent. In our 'math tutor in a ruler' example, we describe a scenario where the student tries to solve the assignment on their own, without the ruler's interference. Only as the ruler would sense that the student is stuck, it would interfere and show them the next step. Beyond tutoring and our other application examples, such dynamic physical interfaces could assist users in ways that current objects often don't; e.g., they could assist users with disabilities by moving into their reach, or remind users to take them along if they would have forgotten. Since LayMo is integrated with the object, users can just grab the object and go once notified, which is often not possible with other notification systems (e.g., swarm robots).

Predicting user needs to facilitate these types of interactions is very challenging and outlines a longer roadmap towards such intelligent materials in our daily lives. Recent advances in multimodal large language models (LLMs) [53] show promise for developing intelligent control systems that can determine appropriate actions for dynamic materials and objects. Recent work [31] demonstrated using an LLM for interacting with a shape-changing interface. More recently, *Object Agents* [11] showed how an LLM-based system can proactively initiate assistance from robotic objects in everyday scenarios. A similar approach could be extended to establish appropriate control of objects integrated with LayMo.

7.2 Heat and Noise Management

Our current prototypes actuate at low speeds (approx. 25s for heating and approx. 1 min for cooling down). Powering the device with high voltage allows for faster heating, but risks overheating the LCE actuators. This is in line with the emerging field of active materials, morphing matter, 4D printing, or soft robotics, with rates of actuation spanning from seconds to hours. For faster actuation speeds, we may consider additional engineering efforts that go beyond the research question and scope of this paper. For example, using Peltier elements for heating and cooling, along with efficient heat management, can speed up the actuation time, which can reduce the power consumption accordingly. Additionally, improvements in heat management may retain the heat better to reduce the power needed to sustain the actuation. For instance, in our current module prototype, a small gap exists between the film heater and the LCE. Adding thin enclosure layers or heat conductive material could better conduct heat from the heater to the LCE and speed up the actuation process. We also observe continuous advances in material science promising efficient active materials as actuators in the future.

Additionally, the vibration motors produce audible noise, which may be distracting to users. In our research prototypes, the energy layer consists of a foam core board holding the motors and batteries. Product engineers may consider using sound-damping materials instead of the simple foam core board to dampen the sound waves.

7.3 Durability and Power Consumption

In this paper, we present the design and implementation, and investigate the movement capabilities of LayMo. During our experiments, we saw LCEs slightly shrinking after many actuations, causing the structure to remain slightly deformed in its non-actuated state (Figure 5a). Future production-ready systems should conduct fatigue and lifetime testing for LayMo's LCE actuators and leg structures under thermal and mechanical cycles. While the current power consumption is relatively high, it can be optimized with better heat management, as discussed in subsection 7.2. Such future investigations have the potential to balance the tradeoffs between durability, actuation speed, and power consumption, allowing LayMo to be more durable and actuated faster with less power consumption.

7.4 Outlook for Small Scale and 3D Integration

We are also interested in exploring the integration of such actuation into different objects and on 3D surfaces. Our layer-based manufacturing using flexible PCB designs make our structures miniaturized, easy to customize the leg structures' layout and shapes, and flexible to wrap onto other objects. This may allow us to go beyond movement and provide haptic feedback as well.

8 CONCLUSION

We present LayMo, a self-contained motion layer that can be applied to users' everyday objects. In this paper, we explore a scalable design for an actuation system that takes existing stationary physical objects and gives them the ability to move through that physical space on their own. With this augmentation, our aim is to blur the lines between stationary and robotic objects that move. Beyond the actuation system in this paper, we are interested in exploring such everyday objects as intelligent physical companions in the future.

ACKNOWLEDGMENTS

We thank Judy Wang for help with shipping research materials, Michael Vinciguerra for wet lab training, Yunzhi Li for lending his phone, Yuyu Lin for insightful discussions, and Lea Albaugh for proofreading.

The work in this paper was supported in part by the National Science Foundation under Award No. IIS-2443190.

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