Artistic Non-Inertial Tracer (ANT): an Educational Kit for a 3-Link Origami Slithering Robot

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Abstract

The abundance of connections between art and engineering are opportunities to engage artistically inclined students who may not think of themselves as interested in robotics, and to inspire engineering-inclined students to express themselves artistically. This work presents a tool kit and lesson plan for a hands-on introductory robotics activity centering how art and engineering influence each other. The Artistic Non-Inertial Tracer (ANT) is a three-link robot made of origami, which contacts the ground through markers that trace patterns as it slithers around. The design is capable of forward, turning, backward, and diagonal motion. Using origami for the body highlights the influence of art on engineering, and the gait traces are a visually interesting output of the engineering. The kit uses inexpensive components totaling about $26/robot USD (servos, origami, and an Arduino Nano) common in hobbyist communities so that learning how to use these components can empower further exploration of actuated art. Our associated lesson plan engages participants in the assembly and control of ANT and contextualizes it within a broader overview of robot system components and the use of origami in engineering. We successfully ran the lesson as a 3-hour outreach workshop at a local arts organization.

1 Introduction

The emerging use of origami in robotics [1] is based on how it enables interesting relationships between 2D patterns and 3D structure, which is also the foundation of origami's artistic expressivity. This presents an opportunity for highlighting relationships between art and engineering to engage artistically inclined audiences in STEAM. We aim to create a hands-on activity for participants to explore this relationship, whether in the classroom, after-school programs, makerspaces, or outreach workshops. Although we developed this activity in the context of a specific outreach workshop aiming to engage adult artists and creatives for potential future collaboration with our engineering lab, our activity development goals are also applicable to other contexts. Table 1 summarizes these goals and how we interpreted them into corresponding design goals for a robot kit.

To meet these goals we present the Artistic Non-Inertial Tracer (ANT), an easy-to-build robot kit and corresponding lesson plan. ANT, shown in Figure 1, is a simple snake-like robot formed from an origami tube with 3 links and 2 joints. It contacts the ground via markers attached to the sides of the links, so as it slithers on paper the markers trace interesting cyclic patterns (Figure 2).

Educational/Engagement Goal	Robot Design Goal
Highlight the multi-directional relationship between art and engineering.	Use origami to make a robot, and use the robot to create visually interesting patterns.
Engage participants' creativity and communicate that this is important in STEAM.	Make the robot controllable to adjust the patterns it creates.
Cultivate participants' sense that they can build functional machines, and familiarize them with components that can be a platform for other actuated art projects.	Have participants construct the robot themselves (especially folding the origami themselves). Actuate and control the robot with common hobbyist electronics.
Require no technical background to construct or operate the robot, and ensure the activity takes at most 3 hours total.	Design kit parts to connect intuitively, by hand or with screwdrivers. Encapsulate the control code in a one-line function call based on a few interpretable parameters.
Encourage participants to build on the base kit to continue their exploration.	Use affordable parts and materials (ended up about $26/robot USD), potentially allowing participants to keep their completed robot.

Table 1: Educational and engagement goals for our activity plan, and corresponding design goals for our robot kit.

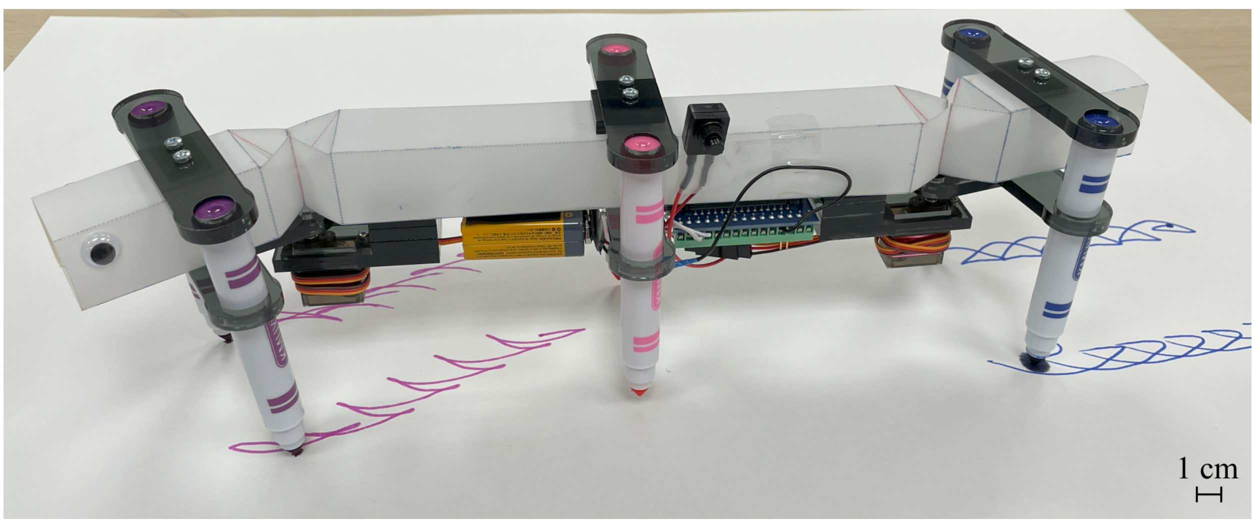


Figure 1: The Artistic Non-Inertial Tracer (ANT) leaving a marker trace of its gait on paper.

The basic underlying concept of this robot kit is motivated by a number of studies that have investigated the positive effect of origami in STEM education. Origami-based activities were associated with improved spatial reasoning scores in a variety of primary and secondary education groups [2],[3],[4],[5], though another study found more mixed results [6]. Student subjects across these studies overwhelmingly reported that they found the origami activities fun [6],[2],[3] and believed the activities helped them learn [6],[2].

Using origami to develop spatial reasoning is based on its versatility in mapping relationships between 2D and 3D forms. This same feature also leads to a variety of engineering advantages

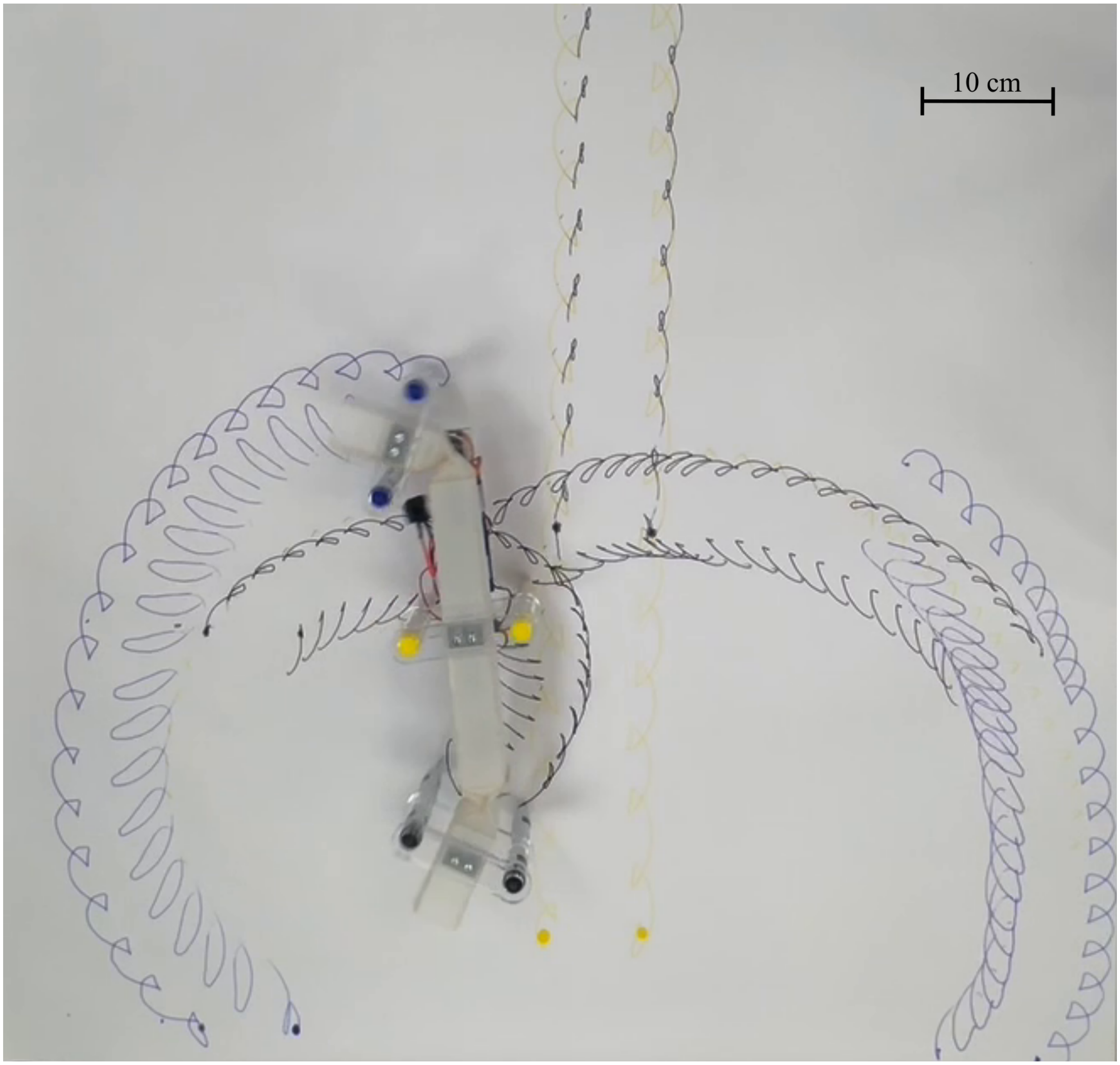


Figure 2: The robot performing a gait which moves forward while rotating clockwise, alongside marker traces from this gait as well as a forward-counterclockwise gait and a straight forward gait (the latter having been performed with a different arrangement of marker colors).

making it an emerging platform for robot design [1]. These advantages include the ability to parameterize patterns to tune properties such as trajectory [7] or stiffness [8],[9],[10], high strength-to-weight ratios [11], potential for multistable reconfigurabilty [12],[13], and access to rapid planar fabrication techniques [14] potentially augmented with electronics embedding [15],[16] and self-assembly via self-folding [17],[18],[19]. Origami robots have successfully demonstrated a wide variety of motions and tasks such as legged locomotion [14],[17],[20], jumping [21],[22],[23], swimming [24],[25], continuum manipulation [26],[27], and gripping [28],[29],[7],[13].

Our robot's body structure is generated using our code from [30] based on joint and link patterns from our *Kinegami* system presented in [10]. This system consists of an algorithm to design serial chain mechanisms with arbitrary kinematics out of tubular origami, based on a modular catalog of patterns including revolute and prismatic joints, static twists, and static bends.

At a higher level of design, the body structure and gaits were inspired by Purcell's 3-link "swimmer" [31] and subsequent study of geometric mechanics of simple snake-like robots [32],[33], though our robot interacts with the ground in a way not modeled in that literature (because it has limited contact through only the front and back markers). A closer analogue to our design is an online video, presented without mechanical analysis, of a "table-top Purcell's swimmer" which only contacts the table at the inner sides of the outer links [34].

There are a variety of established and commercially available robotics education kits [35],[36],[37]. For origami robotics specifically, a few educational resources exist. Oribokit [38], based on [39], is a commercially available kit for an origami flower that opens and closes using a servo and microcontroller. The (unrelated) OriBot system [40] has a hardware kit and software platform designed to guide young children through designing and making origami robots in the figure of animal characters which locomote using servos and interact via sensors. [41] is a lesson plan where students create a foldable gripper actuated by hand. [42] is a lesson plan having students read about [19], a research article about origami exoskeletons allowing different behaviors when the core cube is manipulated by an external magnetic field, and then make a solenoid like those used to control such robots.

Compared to these resources, our goals (Table 1) focus on showcasing how the relationship between art and engineering flows in both directions. In our activity, origami is used to make a robot, which in turn is used to draw interesting patterns. The robot is capable of a variety of gaits (forward, backward, steering, and diagonal), enabling users to express creativity by controlling the shapes traced. The visual trace of the gaits also helps intuitively explain how the robot works, motivating and guiding self-driven experimentation with gaits.

The lesson plan is designed for a 3-hour workshop, although it can also be modified to span a longer or shorter timeframe or distributed over several shorter sessions. The plan presents background about origami robotics (10 minutes) and then has students fold and assemble the robot (1 hour and 45 minutes), followed by presentation about and experimentation with gaits (50 minutes), totaling 2 hours and 45 minutes, leaving some time for small breaks or on-the-fly pacing corrections. It requires no technical background for participants. The kit materials cost about $26/robot (USD). Fabricating the kit components (which our lesson plan assumes the instructor prepares in advance) involves soldering, 3D printing, laser cutting, and gluing. Then the assembly within the lesson plan involves minimal tool usage (just screwdrivers), and all fabricated components from disassembled robots are re-usable except for the origami pattern itself. Our activity materials (including fabrication files, gait code, lesson slides, and a folding video) are available on our project webpage: https://sung.seas.upenn.edu/research/ant/.

The remainder of this paper is organized as follows. Section 2 presents the design of the robot. Section 3 explains the gaits by which it moves around and draws patterns. Section 4 gives instructions for fabricating the kit components and assembling the robot. Section 5 presents the lesson plan with timing estimates based on our experience preparing for and running the workshop, and Section 6 discusses our experience running the workshop and feedback from participants. Section 7 concludes by discussing considerations for using this in other contexts and potential for alteration or expansion of the kit and activity.

2 Robot Design

The robot body is an origami square prism with two revolute joints folded into it, with downwards-facing markers mounted to the sides and contacting the ground. The joints are actuated by servo motors attached underneath the joints: moving them in appropriate gait cycles (see Section 3) causes the robot to move around in slithering-like patterns. Figure 1 shows an assembled robot, and Figure 3 shows how the parts fit together. Seven of the parts attach with the help of custom-designed nut stabilizers, pieces into which M3 hex nuts are recessed and glued to make it easier to hold them in place while inserting bolts.

The body crease pattern, depicted in Figure 4, is based on our lab's origami tubular kinematic chain patterns from [10] and generated via our code from [30]. One face of the prism is duplicated to adhere together (with double-sided tape). The body has screw holes to attach other parts.

2.1 Marker Mounting

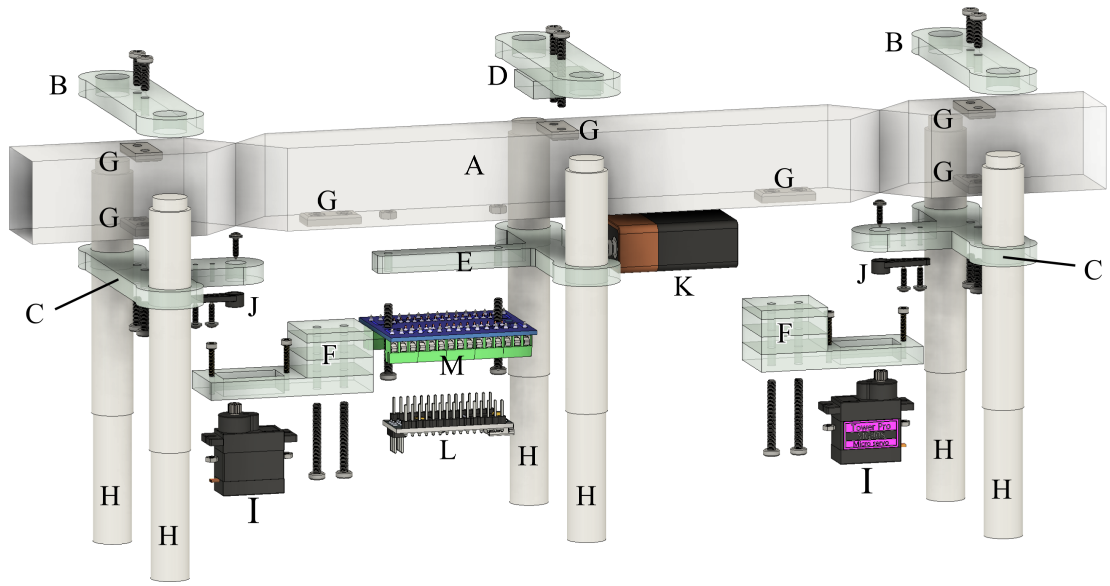
The robot has 6 washable markers, in pairs at each link, mounted with the drawing tip down. The front and back pairs are always in contact with the ground, while the middle pair's mount is raised upwards so that the center markers only contact the ground occasionally to prevent tipping over (like raised training wheels on a bicycle).

Markers are mounted via bars with holes on each end to friction-fit the marker tops and screw holes in the center to connect to the top of the robot body. These bars are laser cut from 6 mm acrylic. The central marker mount is raised upwards by an additional piece of 6 mm acrylic at its center.

To remain vertically stable, makers pass though holes in stabilizer pieces directly underneath the robot body. For the front and back marker pairs, this piece is attached to the servo horn and also serves to connect the servo horn to the outer links. For the central marker pair, the stabilizer piece attaches between the Nano expansion board and the robot body: this is necessary because solder nubs on the expansion board preventing it from lying directly flush to the robot body.

2.2 Electronics

The robot is controlled by an Arduino Nano (or equivalent third-party clone) and powered by a 9V battery. The Nano plugs in to an expansion board: this has screw holes to connect it to the robot body. The power input (ports GND to VIN) connects to a 9V battery connector and a switch wired in series, observing polarity on the battery connector. We use a push-on-push-off button for the switch. The servos each plug in to servo extension receptacle wires, which have their respective power components joined together to plug into the GND and 5V ports, and data wires connected to separate digital pins (we use D9 and D10). Figure 5 depicts the wiring connectivity.



A. Folded Body Sheet
B. End Marker Mount
C. Servo Horn Attachment
D. Central Marker Mount
E. Central Marker Stabilizer
F. Servo Mount
G. Nut Stabilizer
H. Marker
I. Servo
J. Servo Horn
K. 9V Battery
L. Arduino Nano Clone
M. Nano Expansion Board

Figure 3: Exploded view of the robot design, showing the major components and how they attach.

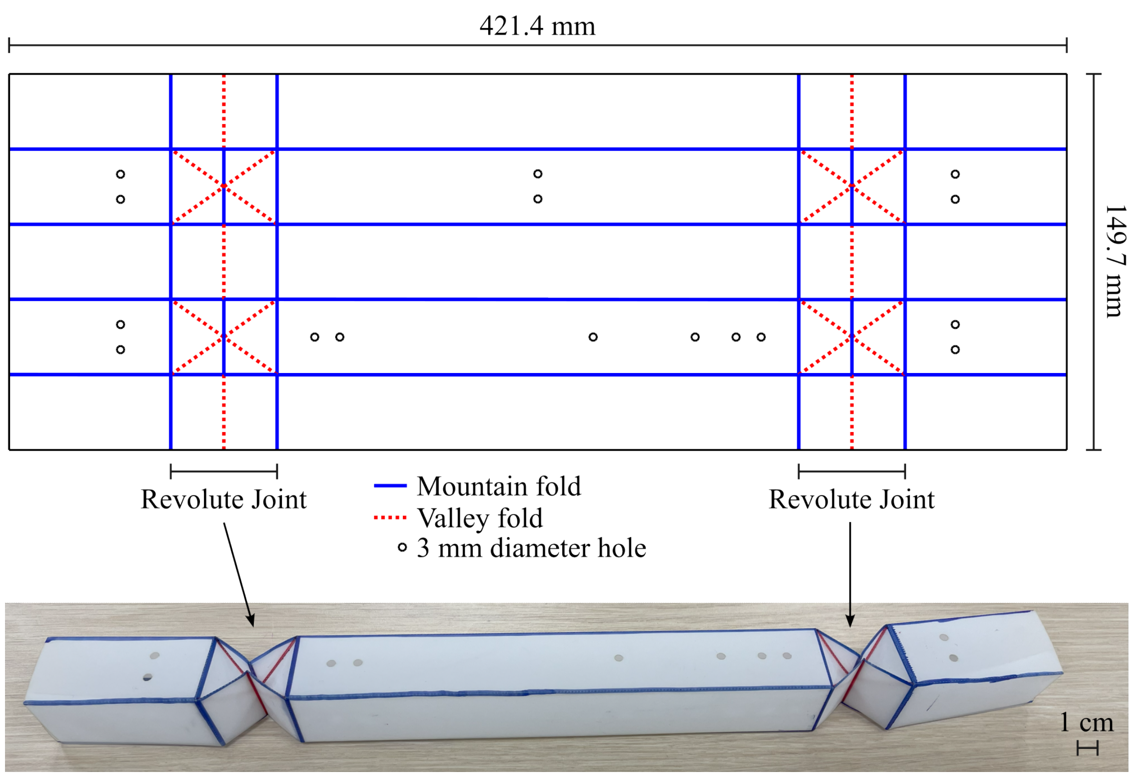


Figure 4: The origami crease pattern for the robot body, and a photograph of it folded up.

(a)

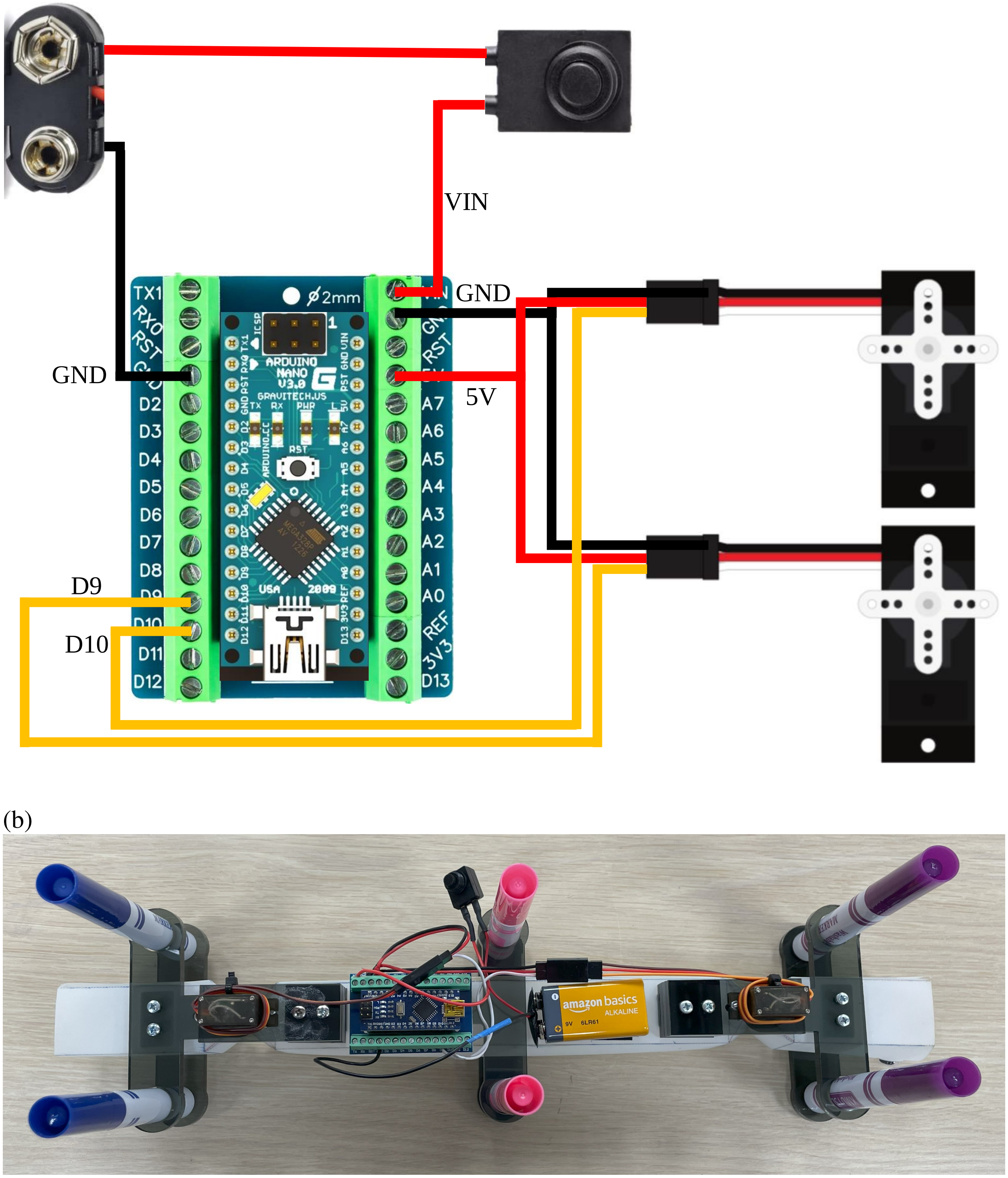


Figure 5: The electrical wiring, shown via (a) the connectivity diagram and (b) a photograph of the underside of the robot.

3 Gaits

The robot moves by simultaneously oscillating the angle of each servomotor in offset waves. Specifically, the servo angles θ_1, θ_2 are functions of time as

$$\theta_1(t) = a \cos\left(\frac{2\pi}{d} t\right) + c_1 \tag{1}$$

$$\theta_2(t) = a \sin\left(\frac{2\pi}{d} t\right) + c_2 \tag{2}$$

where $a \in [0°, 90°]$ is the amplitude, d is the cycle duration (period) in seconds, and $c_1, c_2 \in [0°, 180°]$ are the centers of each wave. A *gait* is defined by a specification (a, c_1, c_2, d) of these parameters, subject to constraints

$$0° \leq c_1 - a \tag{3}$$

$$0° \leq c_2 - a \tag{4}$$

$$c_1 + a \leq 180° \tag{5}$$

$$c_2 + a \leq 180° \tag{6}$$

ensuring that the servo angles stay in valid range $[0°, 180°]$. Note that we did not define d as inherently positive: negating d negates the terms inside the $\cos$ and $\sin$, corresponding to traversing the same wave in reverse; this reverses the gait's direction. Arduino code implementing the gaits, and videos of a variety of gaits, are available on our project webpage.

This way of classifying gaits is drawn from the literature on geometric mechanics for planar 3-link robots [32],[33], but we have not done the friction analysis of how the markers contact the ground to find the *height functions* that would theoretically predict the detailed relationship between servo rotation and robot motion. Instead, we observe the following general relationships empirically.

The cycle duration scales the robot's speed while keeping displacement per cycle approximately constant (hence the "non-inertial" in ANT's name). The amplitude of the gait scales how much it moves in each cycle, and the wave centers control the sideways bias of each joint (which can be balanced to keep the robot facing forward, or imbalanced to rotate the robot). For example (assuming $d > 0$, where the opposite reverses the gait):

1. Gaits with $c_1 = c_2 = 90°$ move straight forward (Figure 6).
2. Gaits with $c_1 > 90°$ and $c_2 < 90°$ and $c_1 + c_2 = 180°$ will rotate right while moving forward, with more rotation the farther the values move apart. For example we show tests with $c_1 = 120°, c_2 = 60°$ (Figure 7) and $c_1 = 105°, c_2 = 75°$ (Figure 10(d)).
3. Symmetrically, gaits with $c_1 < 90°$ and $c_2 > 90°$ and $c_1 + c_2 = 180°$ will rotate left while moving forward, with more rotation the farther the values move apart. For example we show tests with $c_1 = 60°, c_2 = 120°$ (Figure 8) and $c_1 = 75°, c_2 = 105°$ (Figure 10(c)).
4. Gaits with $c_1 = c_2 \neq 90°$ move diagonally without rotating much. For example, we show $c_1 = 120°, c_2 = 120°$ moving diagonally forward-left in Figure 10(a) and $c_1 = 60°, c_2 = 60°$ moving diagonally forward-right in Figure 10(b).

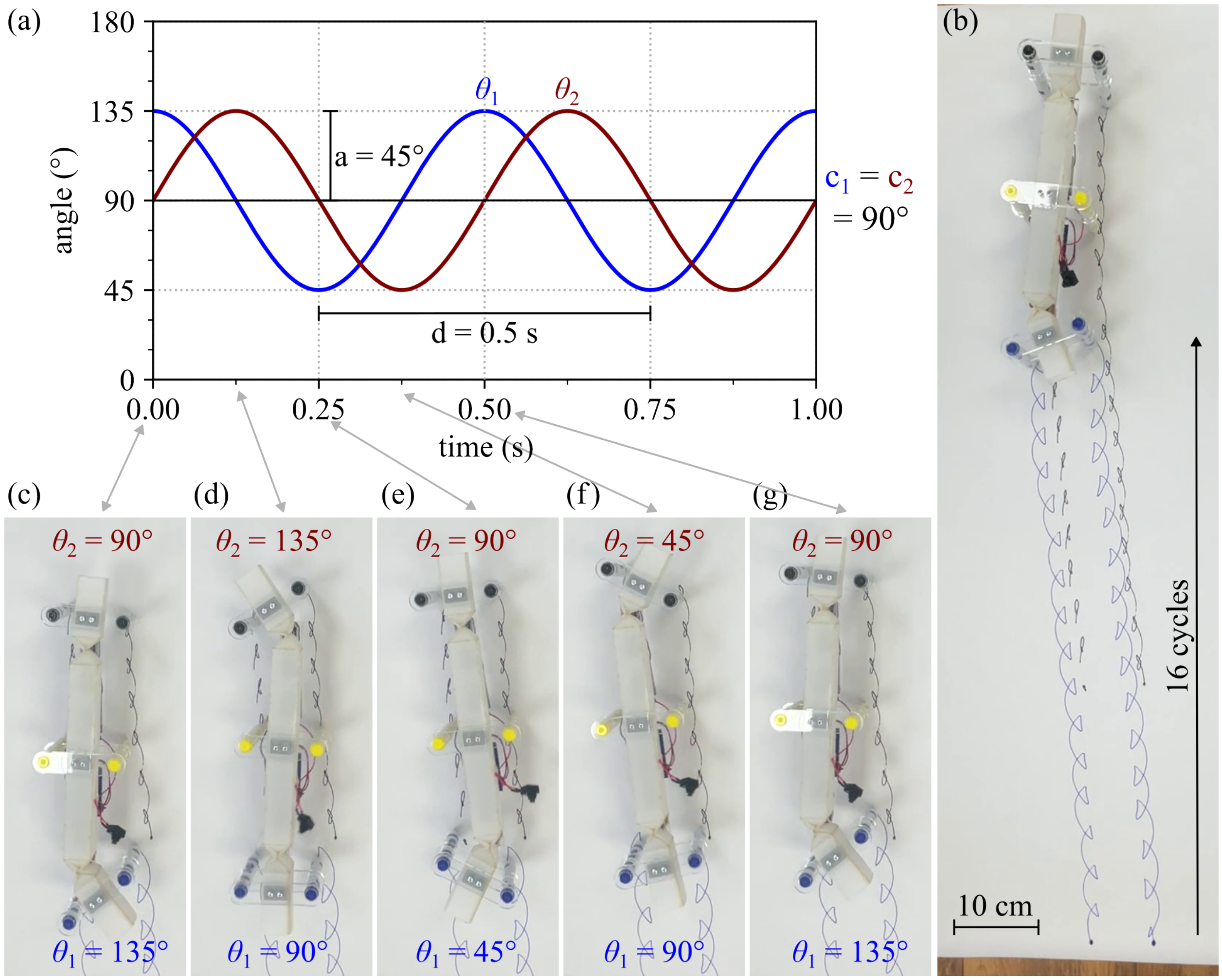


Figure 6: The gait $(a = 45°, c_1 = 90°, c_2 = 90°, d = 0.5)$. (a) Plot of 2 cycles of the servo angles θ_1, θ_2. (b) Robot position and marker trace at the end of 16 cycles. (c–g) A sequence of frames corresponding to one cycle.

For four key gaits, we measure mean motion per cycle by manually extracting the robot's center and heading from video frames:

1. $(a = 45°, c_1 = 90°, c_2 = 90°, d = 0.5)$ moves forward. Figure 6 depicts a trial which measures forward motion of 5.1 cm/cycle, with sideways drift 0.8 cm/cycle leftward and rotation $0.0°$/cycle.

2. $(a = 45°, c_1 = 120°, c_2 = 60°, d = 0.5)$ rotates clockwise (right) while moving forward. Figure 7 depicts a trial which measures 2.1 cm/cycle forward, 0.7 cm/cycle leftward, and $8.4°$/cycle clockwise.

3. $(a = 45°, c_1 = 60°, c_2 = 120°, d = 0.5)$ rotates counterclockwise (left) while moving forward. Figure 8 depicts a trial which measures 2.1 cm/cycle forward, 0.0 cm/cycle sideways, and $5.8°$/cycle counterclockwise.

4. $(a = 45°, c_1 = 90°, c_2 = 90°, d = -0.5)$, moves backward. Figure 9 depicts a trial which measures backward motion of 4.7 cm/cycle, with sideways drift 0.5 cm/cycle rightward and rotation $-0.1°$/cycle.

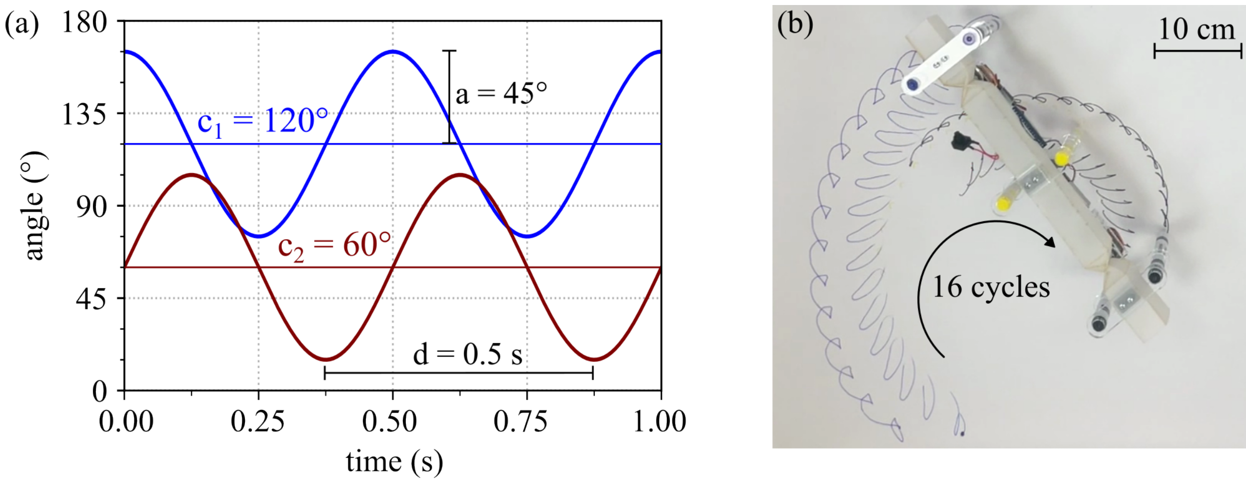


Figure 7: The gait $(a = 45°, c_1 = 120°, c_2 = 60°, d = 0.5)$. (a) Plot of 2 cycles of the servo angles θ_1, θ_2. (b) Robot position and marker trace at the end of 16 cycles.

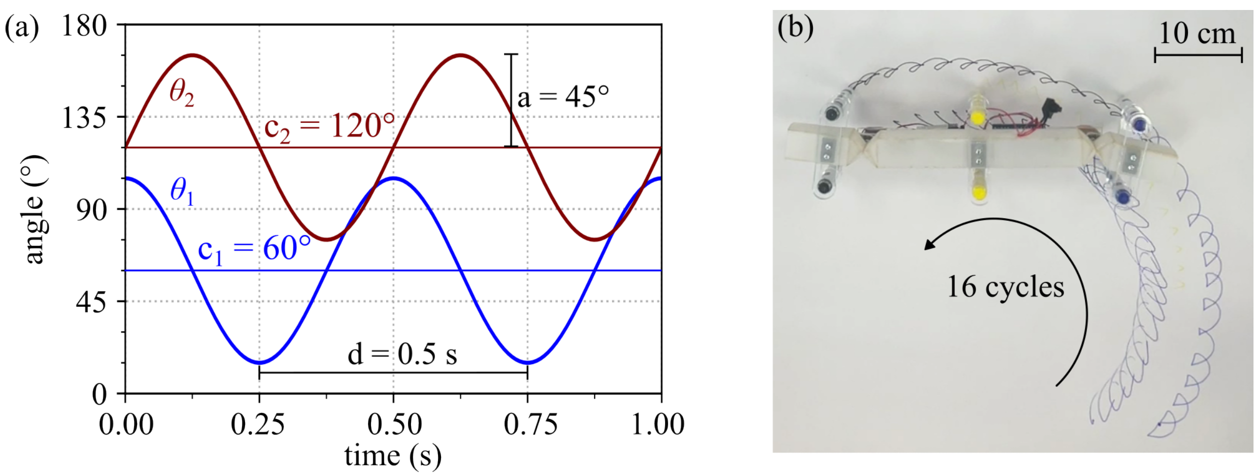


Figure 8: The gait $(a = 45°, c_1 = 60°, c_2 = 120°, d = 0.5)$. (a) Plot of 2 cycles of the servo angles θ_1, θ_2. (b) Robot position and marker trace at the end of 16 cycles.

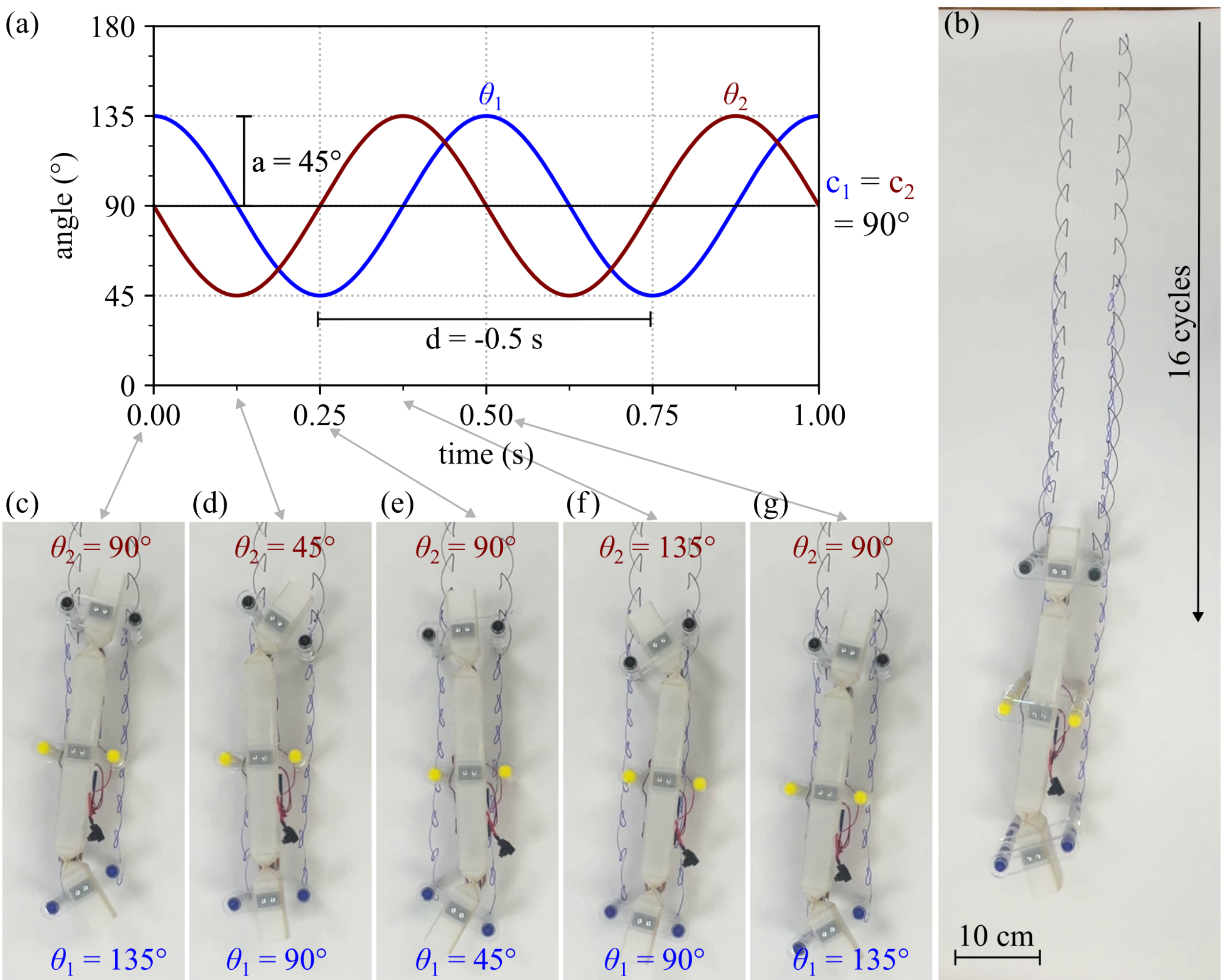


Figure 9: The gait $(a = 45°, c_1 = 90°, c_2 = 90°, d = -0.5)$. (a) Plot of 2 cycles of the servo angles θ_1, θ_2. (b) Robot position and marker trace at the end of 16 cycles. (c–g) A sequence of frames corresponding to one cycle.

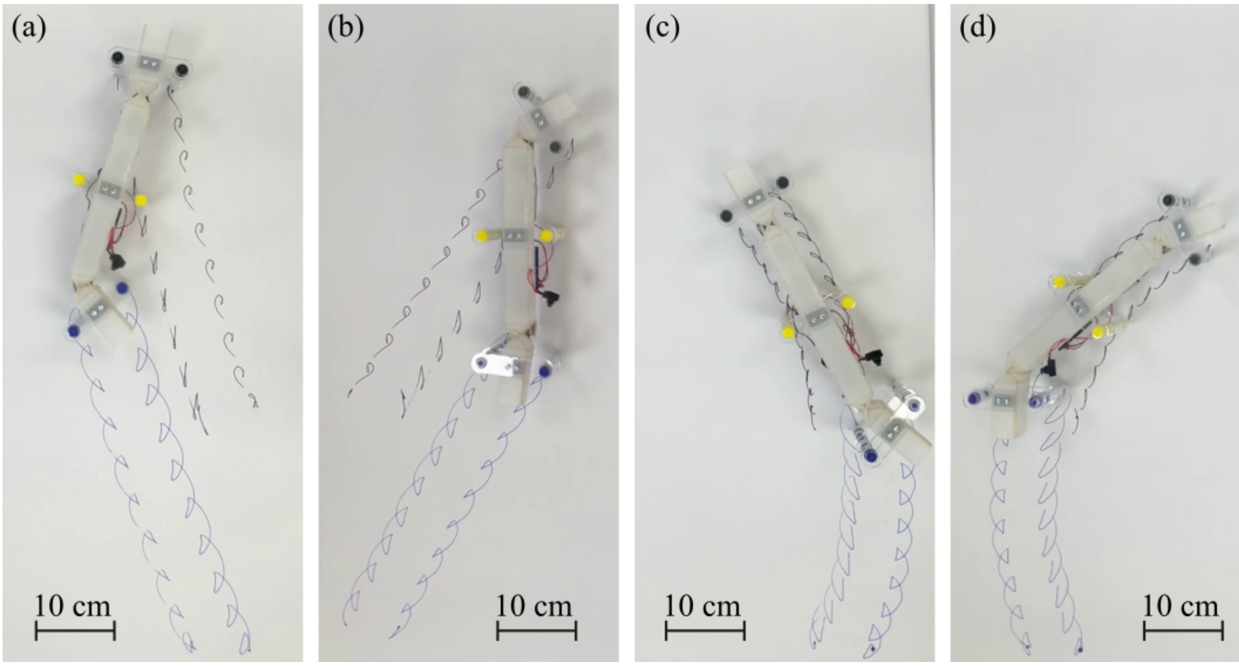


Figure 10: 10 cycles each of several gaits with $a = 45°$, $d = 0.5$ seconds, and various angles for c_1 and c_2: (a) $(c_1 = 120°, c_2 = 120°)$, (b) $(c_1 = 60°, c_2 = 60°)$, (c) $(c_1 = 75°, c_2 = 105°)$, and (d) $(c_1 = 105°, c_2 = 75°)$.

4 Fabrication and Assembly

The robot is fabricated from a combination of off-the-shelf components and custom parts that can be laser cut or 3D printed. Table 2 in the Appendix is the bill of materials. Unit costs are based on prices from January 2025 and order sizes sufficient for 24 robots, assuming access to a laser cutter with bed size 18 in.$\times 24$ in. Table 3 in the Appendix lists the robot components and how we fabricate each, if applicable.

Fabrication and assembly requires the following equipment and tools:

1. Laser cutter: we use a PLS4.75 CO_2 laser cutter, which has an 18 in.$\times 24$ in. bed.
2. 3D printer: we use a Prusa Mini and print in PLA.
3. Soldering equipment: soldering iron, solder, wire strippers, heat shrink. Optional: multimeter to verify successful connections.
4. Phillips head screwdriver: 3-4 mm head, for M2 and M3 bolts.
5. Flat head screwdriver: 2 mm head, for wire terminals in Nano expansion board.

4.1 Manufacturing Preparation in Advance

Fabrication files are provided on our project webpage. Before manufacturing parts for participants, we recommend the instructor begin by making a full test robot: this will uncover if any tolerances need to be adjusted based on differences in fabrication equipment, and serve as a reference example for participants.

Preparing the kit components includes laser-cutting the origami pattern into the body sheet, laser-cutting acrylic parts and then gluing some of them together in stacks, 3D printing the nut stabilizers and gluing the nuts into them, soldering wires and plugging some into the expansion board, attaching the servo horn (with the servos set to $90°$) and connecting the servo to its mount and the horn to its attached piece, and ensuring the Arduinos have appropriate pin setup and starting gait code pre-uploaded. Section 9 (in the Appendix) provides detailed instructions.

4.2 Assembly

The assembly steps are designed to be simple enough for participants with minimal hands-on building and folding experience to be able to follow. Associated time estimates are based on our experience at the workshop to make sure every participant finishes the step. Instructional slides with photos and diagrams (to be presented and/or printed out), and a video of the folding, are included in our instructional materials on our project webpage.

1. **Pre-crease the origami (30 minutes):** Fold the origami pattern to the full tube, then unfold it. This pre-creases all the folds, making it easier to re-fold after attaching the parts. It is crucial to define creases sharply. One body sheet.
2. **Attach the central marker stabilizer piece and the expansion board (15 minutes).** Two 25mm M3 bolts, two M3 hex nuts.
3. **Attach the central marker mount (10 minutes).** One central marker mount, one nut stabilizer.
4. **Attach the servo assemblies (15 minutes)** to the holes in the middle link. Two servos and associated parts pre-attached, two nut stabilizers, four 25 mm M3 bolts.
5. **Re-fold the body (15 minutes)** and secure the tubular wraparound with double-sided tape.
6. **Attach the outer (servo horn side) of the servo assemblies (5 minutes)** to the corresponding holes on the front and back links. Two nut stabilizers, four 10 mm M3 bolts.
7. **Attach the end marker mounts (5 minutes)** to the corresponding holes on the front and back links. Two nut stabilizers, four 10 mm M3 bolts.
8. **Insert the markers into the marker mounts (2 minutes).** Six markers.
9. **Attach the Arduino and battery (5 minutes).** Plug the Arduino Nano board into the breakout board, making sure corresponding ports match. With the servos *not* connected to their extension wires, plug the battery into its connector, obeying polarity. If the switch is on (i.e. if the Arduino power light turns on), turn it off. Velcro the battery in place under the body tube. One battery, velcro.
10. **Complete the wiring (8 minutes).** Plug servos into the extension wire headers. Tape the switch's wire to the body top or side such that the switch is easily accessible, and secure all other loose wires with tape or zip ties.

5 Activity Plan

The activity plan is as follows. The presentation slides and a folding video are available on our project webpage.

1. **Introductory slides** (10 minutes): discuss the use of origami in robotics and the kinegami project background [10] from which the kit's origami pattern is generated.

2. **Pre-crease the origami pattern** (30 minutes): Show the difference between mountain and valley folds. Demonstrate step by step how to fold the origami pattern, showing the crease pattern and circulating fully-folded examples so participants can proceed ahead independently (an experienced folder could complete this in under 10 minutes). The trickiest step is forming the joints: this will likely require repeated demonstration.

3. **Attach parts** (75 minutes): show the associated slides and demonstrate the steps (see Section 4.2). When adding servos, briefly explain the difference between servos and standard motors and mention that there are many other types of actuators used for robots. When adding the Arduino, point out the chip on it and explain that it is a tiny computer connected to the ports via wires etched onto the board, some of which are for power and some for signals representing numbers. Before moving on, check every robot for safe wire management and easy switch access.

4. **Present about gaits** (15 minutes): present the slides explaining the gait parameters, then show the code in the Arduino IDE and walk through how to make a call to the gait function.

5. **Experiment with gaits** (35 minutes, or more as desired): Tape down paper covering large areas of the floor, e.g. from wide rolls. Have participants run their robots on the paper. Circulate with a computer and cable to let participants edit the setup code to try different gaits from those commented out, adjust gait parameters directly, or sequence multiple gaits.

6 Outreach Workshop

We ran this activity as an outreach workshop at a local community arts organization, in combination with an informational session recruiting applicants for an artist in residence program in our lab. The workshop was advertised through the arts organization's email list and flyer board, the social media of both the arts organization and our university school of engineering, and personal networks with artists. Promotional materials presented the event as an opportunity to build a robot out of origami and learn about our lab's upcoming artist in residency program; these also specified that "no robotics expertise is required", "enthusiastic folders are encouraged", and "we'll cover origami patterns and how to attach electronics and motors." The RSVP form stated that "The workshop is intended for artists and creatives interested in learning about robotics and about the residency program. It's theoretically open to all ages but the activity is not designed for children."[1]

[1]As a result of this goal, the introductory slides differed from those we provide in our lesson plan materials: the overview of origami robotics focused more on our own lab's work, and the introduction also included information about ourselves and the residency.

There were 20 participants: 16 adults and 4 minors. For the assembly process, 6 people circulated to demonstrate steps and assist participants in keeping up. During the experimentation with gaits, 4 of us circulated with computers to let participants adjust and re-upload the code.

All participants successfully built a working robot within the scheduled time period. They generally seemed to find it exciting and engaging, and in fact it was several participants' suggestion that we look into publishing about the kit.[2]

To gather additional feedback about participants' experience in our workshop, we sent a follow-up survey to adult participants whose email we had. Our email stated that "both positive and negative feedback is welcome and constructive." The survey consisted of a single question with free text response:

> "Please tell us briefly about your experience at our Origami Robotics workshop. For example, you could comment on what you enjoyed and/or disliked about the experience, what you learned from it, or how it could be improved. Please do not include your name or any other information that would identify who you are."

We received four responses, which we present verbatim because this is too few responses for summaries or thematic analysis to be meaningful or assumed to be representative:

- "I enjoyed the workshop very much. But didn't learn how to use/attach the motor without help, and I don't know how to code the arduino programming. The class seemed geared to student age participants."
- "Loved the detailed explanation of how you arrived at the design and the hands on aspect of making our own. Fun and informative and gave insights into the process. Loved having the people from the lab available to answer additional questions. The integration of art of origami with tech is a great and unexpected combination."
- "The workshop was very well planned out and organized. I loved how the plans were laid out and everything was prepped to follow along. This experience was great"
- "I found this workshop very insightful and informative. I was able to learn about how origami can be implemented in robotics to save time, money, and materials. I do not believe there is anything that could be improved on as it was a very effective workshop that successfully introduced origami robotics to a group of people."

7 Conclusion

Our kit and activity showcase the intersection of art and engineering via robots made out of origami that trace visually interesting patterns as they move. We believe it could be an engaging lesson plan in contexts such as secondary education classrooms, after-school programs, and outreach workshops. The kits cost about $26/robot (USD), and all components except for the crease pattern sheet can be used repeatedly. The activity plan requires no technical background or hazardous tools, and has been verified in an outreach workshop aimed at connecting with adult

[2] We had not been considering this before, which is why we did not gather any data at the workshop about participants or outcomes.

artists. Participants gained hands on experience folding kinegami joints, an opportunity to work with code to change the robot's gaits, and first hand experience to see how robotics can be used to make art.

The largest barrier we foresee to classroom adoption is the required time and equipment to pre-fabricate all the parts. Since 3D printers are more widespread than laser cutters, the parts that we laser cut from acrylic could instead be 3D printed (though this would be slower and would use a lot of filament). The other laser-cut part is the origami pattern, which could instead potentially be etched with a vinyl cutter or ink-printed onto thick paper (cutting out the bolt holes with a 3 mm hole puncher). Meanwhile, for both 3D printing and laser cutting there are widespread commercial suppliers, though this would increase cost. Whatever one's fabrication approach, it is important to figure out all required tolerances and settings by making a complete robot before manufacturing additional kits for participants.

Another way to limit fabrication cost and time is to have students share robots in small groups, which could also ensure students can help each other stay on track with steps. Every participant in our workshop built their own robot because this was a one-time activity where we wanted them to take the robot home to continue exploration. However, keeping all participants on track with assembly steps required several "instructors" circulating to help, at a ratio of one helper per four participants. Since participants varied in progress speed, we suspect that working in groups would support time management in classroom settings with one instructor.

Looking towards the future, we believe that the kit could serve as a launching platform for more in-depth educational and exploratory exercises to expose students to not only robotics, but also fundamental skills in manual dexterity, patience, logic, physics, and more. Of course, in order to have this impact, some additional developments are needed such as expanding the kit and activity to support additional learning goals. To learn about fabrication (laser cutting, 3D printing, and soldering), students could be involved in manufacturing the components. On the artistic end, students could decorate the robot or sequence gaits to have it trace specific intended patterns. To learn more about robotics, an expanded kit could incorporate a sensor (e.g. an ultrasonic distance sensor) to explore closed-loop control, add additional joints to explore more complex gaits, or experiment with different types of ground interaction.

Finally, there is room remaining for future work modeling the robot's gait. The overall gait idea draws from geometric mechanics modeling of 3-link planar robots, most directly from [32]. That literature features *height functions* which model the relationship between changes in joint angles and changes in link directions in ways that enable prediction and optimization of gait behavior. However, the modes of environmental interaction covered by this literature involve all 3 links interacting with the environment, which our robot does not normally have. With all 3 links in contact, achieving net displacement requires some form of directional asymmetry in friction [32] such as as immersion in a damping environment [31],[43], having wheels on each link [32],[44], or continuous contact along a robot underside with directionally asymmetric friction (akin to snake scales) [45]. This is why our robot staggers the central markers upwards so they only contact the ground when necessary to prevent tipping over: we tried putting them in direct ground contact, and the robot could turn but not move forward. This difference requires new analysis to calculate height functions, after which one could do more principled prediction of gait behavior and incorporate that into a lesson plan in a more mathematically advanced context.

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9 Appendix: Components and Manufacturing Details

Our lesson plan assumes the following steps are performed in advance by the instructor to manufacture and prepare the kit components:

1. **Prepare body sheet.** Laser-cut the pattern into the sheet. Optionally, color-code or otherwise distinguish the mountain vs valley folds with a pen or marker (we make mountain folds blue and valley folds red).

2. **Laser cut acrylic parts.** An 18×24 in sheet can fit all the 6 mm thick acrylic parts for 8 robots. Each robot also uses 2 25×25 mm parts of 3 mm thick acrylic, which serve as spacers in the servo mounts.

3. **Glue stacked acrylic parts.** The servo mounts and the central marker mount each feature stacked layers of acrylic. While these layers do not need to be adhered together to function, doing so in advance makes parts easier to handle and helps guarantee layer alignment. When adhering the central marker mount, check if the marker friction fit works better on one side (due to the conical shape of the cutting laser): if so, attach the spacer rectangle on the side where the markers fit better. Keep the adhesive away from the screw holes. We have successfully used either superglue or acrylic adhesive.

4. **Prepare nut stabilizers.** 3D print the hex nut stabilizers: we print these from polyactide (PLA). Place a tiny dot of superglue on the side of the M3 nuts, insert them into the recess, and wait for the glue to set. Be careful to avoid getting any glue in the nut threading.

5. **Solder wires.** Cut the servo extension wires, leaving most wire connected to the receptacle header. Take a pair of extension wires and solder the corresponding power cables together in Y shapes (see Figure 5). Meanwhile, solder the switch in series with the 9V battery connector. Ensure the wires connecting to the switch are at least 10 cm long, to allow enough slack for the switch to be taped to the top or side of the robot for easy access.

6. **Plug wires into expansion board.** Doing this in advance saves instructional time and reduces risk of paricipants making polarity errors that could destroy parts. Following Figure 5, plug the joined power wires of the servo extension wires into their corresponding ports (GND for ground, 5V for voltage). Plug the data wires of the servo extension port into separate digital pins (we use D9 and D10, but you could use others if you edit the code accordingly).

7. **Connect parts to the servos.** Use M2 10 mm bolts and nuts to screw the servo into the servo mount, with the bolt head on the mount side. Separately, screw the the servo horn to its acrylic attachment (use the screws that come with the servo). Then use an arduino to set each servo to $90°$, place the servo horn on the servo facing straight outwards, unplug the servo so it is no longer powered, and screw the servo horn into the servo (a screw for this comes with the servo).

8. **Ensure pin rows are soldered to the sides of the Arduino Mini** such that they can plug into the expansion board (many suppliers of Arduino Mini or equivalent clones provide them this way).

9. **Upload gait code** onto each Arduino Mini. Varying the gaits between Arduinos can allow participants to see different gaits in action even before connecting to computers to tinker with the gait code.

Part/Material	**Quantity/robot**	**Unit cost (USD)**	**Cost/robot (USD)**
LAFVIN Nano V3.0 (Arduino Nano clone)	1	6.66	6.66
Nano V3.0 Screw Controller Terminal Adapter Expansion Board Shield	1	1.62	1.62
Miuzei MG90S 9G Micro Servo Motor Metal Geared	2	2.80	5.60
0.127 mm PET Film, 20 in $\times$ 25 ft roll	10x20 in	60.28/roll	2.01
6 mm Acrylic, 18 $\times$ 24 in sheet	Parts for 8 robots fit on a sheet	24.95/sheet	3.12
3 mm Acrylic, 18 $\times$ 24 in sheet	Parts for 195 robots fit on a sheet	13.95/sheet	0.07
PLA filament	7 g	0.02/g	0.14
Adhesive Hook&Loop, 1 in width	2 in	9.99 for 30 ft roll	0.06
KMUYSL Washable Markers	6	0.22	1.32
Servo Extension Cables	2	0.35	0.70
Push-on push-off switch 12V wired	1	2	2
10mm M3 Bolts	10	0.05	0.50
25mm M3 Bolts	4	0.06	0.24
M3 Nuts	16	0.02	0.32
10mm M2 Bolts	4	0.05	0.2
M2 Nuts	4	0.02	0.08
Total			**$25.15 USD**

Table 2: Bill of materials for the robot kit, not including the glue for adhering certain parts and tape for wire management.

Component	Fabrication Approach	Count
Body Sheet	Laser cut from 0.127mm polyethylene terephthalate (PET) sheets, with folds etched at 20 perforations per inch. Optionally, use a pen or marker to color-code or otherwise distinguish mountain vs valley folds.	1
End Marker Mount	Laser cut from 6mm acrylic	2
Servo Horn Attachment	Laser cut from 6mm acrylic	2
Center Marker Mount	2 pieces of laser-cut 6mm acrylic glued in a stack	1
Central Marker Stabilizer	Laser cut from 6mm acrylic	1
Servo Mount	4 pieces of laser-cut acrylic (3 6mm thick pieces, 1 3mm thick piece) glued in a stack	2
Nut Stabilizer	3D printed from PLA, with 2 M3 hex nuts inset and fixed in place with superglue (use tiny dots of glue on the nut outside to avoid getting glue in threading)	7
Markers	Purchased (KMUYSL Washable Markers)	6
9G Micro Servo Metal Geared	Purchased (Miuzei MG90S)	2
Servo Horn	Comes with purchased servo	
9V Battery	Purchased, attached to body with velcro (or tape)	1
9V Battery Connector	Purchased, then soldered in series with the toggle switch (see wiring diagram)	1
Toggle Switch	Purchased, then soldered in series with the 9V battery connector (see wiring diagram)	1
Servo Receptacle Wire	Purchased, then respective power components joined via soldering (see wiring diagram)	2
Arduino Nano Clone	Purchased	1
Nano Expansion Board	Purchased	1
10mm M3 Bolt	Purchased	10
25mm M3 Bolt	Purchased	4
10mm M2 Bolt	Purchased	4
M3 Hex Nut	Purchased, then glued into nut stabilizers	16
M2 Hex Nut	Purchased, used for Arduino mount	4
Servo Horn Screws	Comes with purchased servo	6
Velcro (or Tape)	Purchased, used to attach battery	
Tape	Purchased, used for wire management	
Double-sided tape	Purchased, used to adhere duplicated body face	
Superglue	Used to attach nuts to stabilizers.	
Acrylic Adhesive	Optional (could use superglue instead): used to adhere layered acrylic parts.	

Table 3: List of robot components.