Title

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EXTENDING AND BENDING ROBOTIC LIMBS USING TAPE SPRINGS FOR MOBILITY AND MANIPULATION: PRELIMINARY INVESTIGATIONS

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ABSTRACT

Conventional mobile robots have difficulty navigating highly unstructured spaces such as caves. In these environments, an extendable/retractable mechanism could be useful for deploying hooks to climb over terrain, or for reaching hard-to-access sites for sample collection. Spooled tape spring mechanisms offer long reach in a compact package, but have not been widely explored for use in mobility and manipulation tasks. This paper proposes a new form of multimodal mobile robot that utilizes a novel tape spring limb named EEMMMa (Elastic Extending Mechanism for Mobility and Manipulation). For mobility, the limb can extend prismatically to deploy grappling hook anchors to suspend and transport the main body, or even serve as legs. For manipulation, the limb can morph its shape to bend around or over obstacles and extend to reach into tight spaces. This can allow the limb to retrieve distant objects, position cameras around corners, or place grappling anchors above an overhang such as a table or cliff. The EEMMMa-1 prototype detailed in this paper can climb ladders and shelves, and exhibit shape morphing to bend over obstacles. The extendable limb uses a simple braking function as a mechanical multiplexer, which can change the limb's kinematics to control a second rotational DOF using only a single motor. The paper concludes by detailing potential applications and configurations of future EEMMMa robotic systems.

Keywords: Tape Springs, Mobile Robots, Compliant Mechanisms, Shell Mechanisms, Robot Design, Multimodal, Rough Terrain, Nonlinear Phenomena, Soft Robots, Exploration

NOMENCLATURE

- R Transverse radius (when straight), Fig. 2a
- l Tape spring length, Fig. 2a
- t Tape spring thickness, Fig. 2a
- α Subtending angle of arc swept by tape, Fig. 2a
- R_f Longitudinal radius of localized fold, Fig. 2a
- M Applied external moments, Fig. 2b
- θ Bending angle of fold, Fig. 2b

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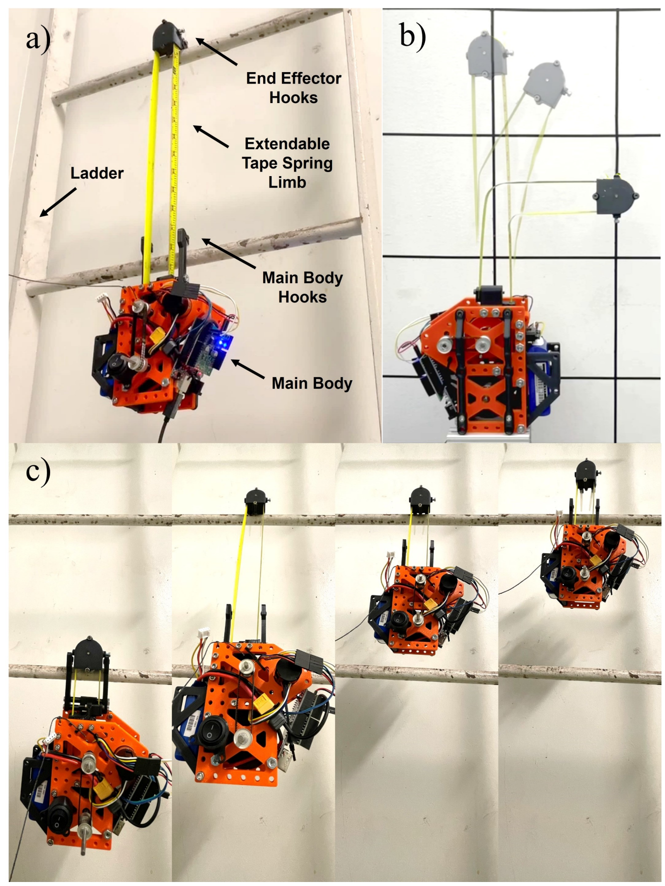

FIGURE 1: A) EEMMMA-1 OVERVIEW, WITH MAIN BODY AND TAPE SPRING LIMB. THE LIMB CAN EXTEND TO PLACE THE END EFFECTOR HOOKS ON THE NEXT LADDER RUNG, ALLOWING IT TO CLIMB VERTICALLY. B) THE LIMB CAN BOTH EXTEND AND BEND USING A SINGLE MOTOR, ACHIEVING 2-DOF WITH A FORM OF MECHANICAL MULTIPLEXING. C) SNAPSHOTS OF THE CLIMBING SEQUENCE, WHICH CAN BE REPEATED TO SCALE THE ENTIRE LADDER.

1. INTRODUCTION

Robots remotely deployed in highly unstructured spaces such as caves face numerous challenges for both mobility and manipulation tasks. In these environments, hazards can vary widely in scale, from tightly confined tunnels to large cliffs with vertical walls that are extremely difficult to traverse for traditional robots. Additionally, interacting with the environment for inspection or sample collection is also challenging since the robot may be unable to navigate to the desired location due to ground obstacles, or otherwise reach the point of interest with typical bulky industrial robot manipulator arms. In these scenarios, an extendable/retractable mechanism could be useful for deploying hooks to climb over terrain, or for reaching hard-to-access sites for sample collection.

Retractable mechanisms can provide a very long reach in a small package, which involves deploying a spooled material. A common retractable mechanism is the tape spring, the primary mechanism in household tape measures. These curved thin shells have the ability to elastically deform and transition between a straight configuration and a folded configuration as depicted in Fig. 2a. In this way, localized folds serve as revolute joints, while unfolded straight segments can serve as links that can withstand significant forces in tension, as well as limited compression forces and bending moments. The rigidity exhibited by unfolded segments can be attributed to their transverse curvature, which increases the energetic cost of bending longitudinally [1] [2].

The benefits of tape spring mechanisms have been previously explored in a variety of fields, but there has been little prior work on utilizing the long range of such mechanisms for mobility or manipulation. Tape springs are used in deployable space structures, including extendable booms [3], automatically deploying solar reflectors [4] [5], and large closed-loop structures [6]. A notable example is a planar 3 DOF manipulator for UAVs, which utilizes the long reach of the tape to deploy an end effector below a UAV. This design utilizes a mechanical node that travels along the tape's length to "pinch" and induce a fold to control the bend location and angle [7]. Other applications focus on shape morphing by controlling the locations of the folds and rigid segments. One example utilizes a closed-loop tape to form a 4-bar linkage, utilizing shape memory alloys as actuators [8]. A final example is a cylindrical mobile robot that uses closed-loop tapes to move like an amoeba by everting its compliant body [9].

This paper proposes a novel form of multimodal mobile robot that uses extendable tape spring mechanisms for both mobility and manipulation tasks named EEMMMa (Elastic Extending Mechanism for Mobility and Manipulation). EEMMMa utilizes the directional stiffness of tape springs to serve as a versatile, lightweight, long-reach limb. For mobility, the limb can extend prismatically to deploy grappling hook anchors to suspend and transport the main body, or even serve as legs. For manipulation, the limb can morph its shape to bend around or over obstacles and extend to reach into tight spaces. This can allow the limb to retrieve distant objects, position cameras around corners, or place grappling anchors above an overhang such as a table or cliff. Additionally, the tape's elastic properties enable it to self-correct from perturbations for tasks that require alignment. The limb is also safe to use for manipulation tasks since it can simply

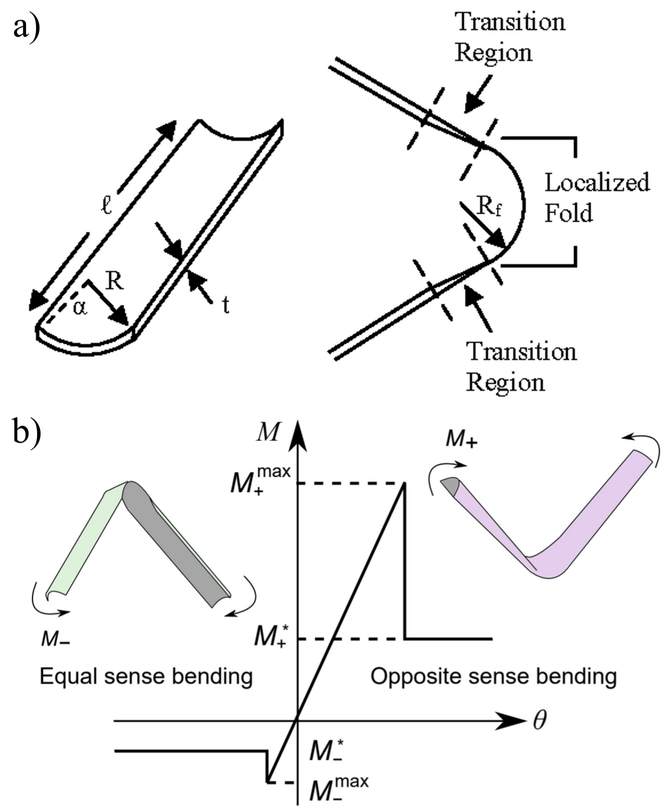

FIGURE 2: A) GEOMETRIC PARAMETERS THAT DEFINE TAPE SPRINGS. AN UNFOLDED TAPE SEGMENT IS SHOWN ON THE LEFT, WITH A LOCALLY FOLDED SEGMENT ON THE RIGHT. [8] B) MOMENT-ROTATION CHARACTERISTICS OF 2D FOLDING. [7]

elastically deform during a collision or if a target is missed.

Figure 1a shows the EEMMMa-1 prototype, a lightweight multimodal single degree of freedom (DOF) robot that uses an extendable tape spring mechanism to demonstrate promising mobility and manipulation capabilities. EEMMMa-1 can climb shelves and ladders using compliant hooks, and can ascend rough vertical walls when equipped with microspines. The extendable limb can also morph its shape with a form of mechanical multiplexing. Using a simple braking function, the limb's kinematics can be changed to control a second rotational DOF using a single motor, allowing the limb to bend as seen in Fig. 1b. A summary video of its capabilities is available in Appendix A.

Section II outlines the overall design and operation of the prototype. Section III displays demonstrations of these tasks, and Section IV analyzes the kinematic and elastic properties of the tape during climbing and bending. Section V summarizes the implications of this system and outlines future concepts that can utilize EEMMMa.

2. DESIGN AND IMPLEMENTATION

EEMMMa-1's design will be broken down into five main parts: 1) background information, 2) an overview of operations, 3) the tape spring which forms the main structure of the extendable limb, 4) a main body containing the motorized spool, tension management subsystems, and electronics, and 5) an end effector

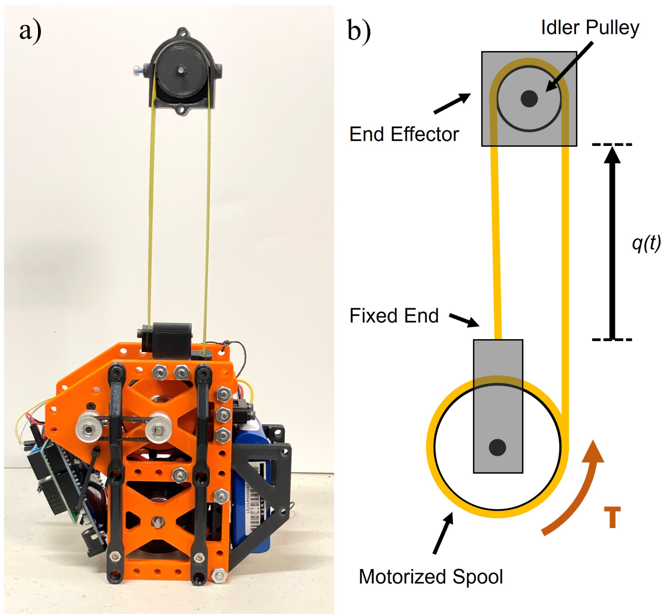

FIGURE 3: OVERVIEW OF EEMMMA-1'S TAPE MECHANISM. A) THE PROTOTYPE IN BASIC PRISMATIC CONFIGURATION, WITH END EFFECTOR CASING REMOVED TO SHOW THE CONTINUOUS U-SHAPED TAPE PATH. B) DIAGRAM OF THE TAPE PATH, WITH THE EXTENDED LENGTH $q(t)$ AS THE INPUT VARIABLE.

that serves as the end of the limb, and has a braking function for shape morphing.

2.1 Background

Tape springs exhibit several useful features for serving as flexible or structural members. When a moment is applied, tape spring segments will not fold until a peak moment is reached. As depicted in Fig. 2a, this localized fold exhibits zero transverse curvature and a uniform longitudinal curvature. If the peak moment is exceeded, the tape spring will exhibit a snap-through buckling behavior with a sudden change in stiffness properties at the fold as it is formed. Additionally, because of the directionality of the tape's curvature, the value of the peak moment changes depending on the direction of the applied moment. As depicted in Fig. 2b, tapes subjected to "equal-sense" bending will fold much more easily than for "opposite-sensed" bending [10]. The development and propagation of folds is highly dependent on the loading and boundary conditions present at the end sections of the tape spring [11]. Tape springs also exhibit a level of self-actuation due to their spring properties, which will cause the tape to elastically return to its unfolded neutral state when bent or twisted [12].

2.2 Overview of Operations

Designed primarily to demonstrate climbing on shelves and ladders, EEMMMa-1 is equipped with two sets of compliant hooks to climb successive levels, as can be seen in Fig. 1c. The first set of hooks is located on the main body and serve to anchor the main body at the current shelf or ladder rung. The second set of hooks is attached to the end effector.

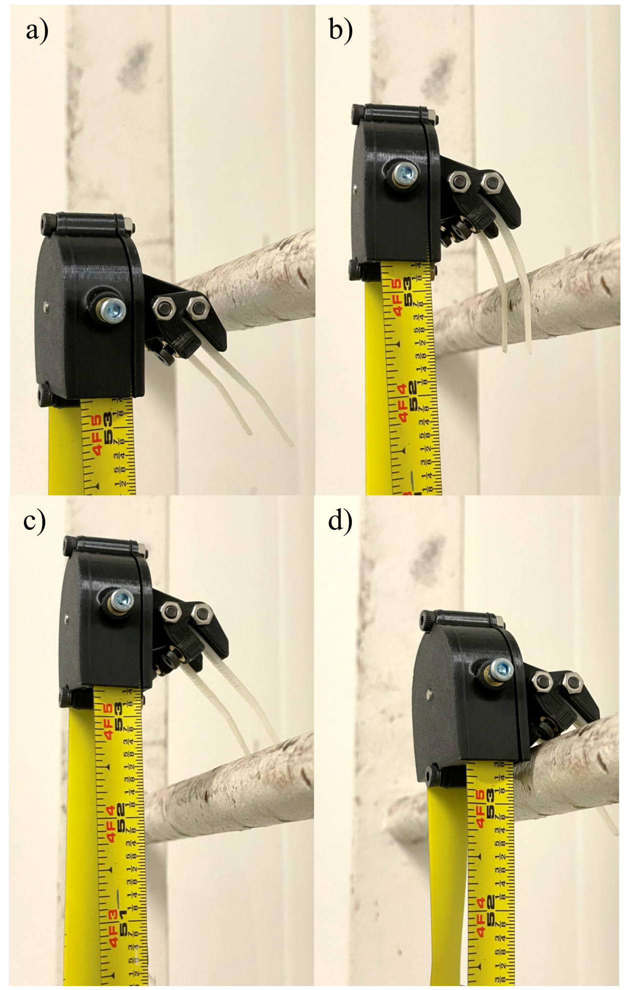

FIGURE 4: SEQUENCE OF OPERATIONS FOR THE COMPLIANT HOOKS. A) THE HOOKS APPROACH THE UNDERSIDE OF THE RUNG. B) THE HOOKS CONTACT THE RUNG AND BEGIN DEFORMING AS THEY CONTINUE TO RISE. C) THE HOOKS PASS THE RUNG, AND THE COMPLIANT TIPS SPRING TO THEIR ORIGINAL SHAPES. D) THE HOOKS ARE LOWERED ONTO THE RUNG. THE REACTION FORCE FROM THE ANGLED SURFACE PULLS THE ASSEMBLY TOWARDS THE RUNG UNTIL IT SETTLES AT THE ROOT OF THE HOOK, CREATING A STURDY ANCHOR POINT.

The hook engaging sequence can be seen in Fig. 4. As the tape extends vertically, the end effector hooks gently deform to allow them to pass above the next level. The hooks then spring back to their original positions after they clear the level, resulting in a one-way locking effect. As the main body reels itself upwards, the sloped hooks passively guide the shelf or ladder rung onto the load-bearing back portion of the hook, establishing a new anchor point. Once the main body hooks pass the next level and establish stable contact, this grappling and anchoring sequence can be repeated.

EEMMMa-1 can initiate shape morphing using a form of mechanical multiplexing to bend the limb, depicted in Fig. 5. By activating a braking function at the end effector, the system can switch its kinematic mode. The brake locks the end effector relative to the tape's surface by pressing a small rubber pad, creating

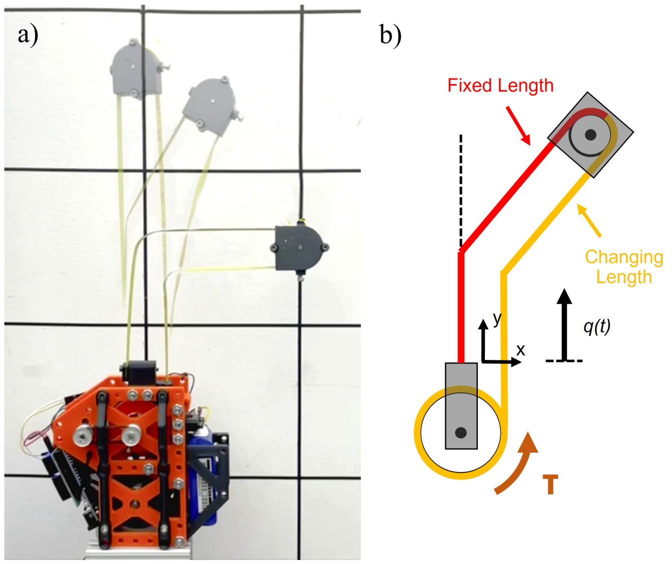

FIGURE 5: A) OVERLAID SNAPSHOTS OF THE BENDING SEQUENCE, DEPLOYED VERTICALLY AND BENDING IN THE Z-AXIS. B) DIAGRAM OF THE INTERNAL TAPE PATH IN "BRAKE" MODE. THE INPUT $q(t)$ NOW CONTROLS ONLY ONE SIDE OF THE TAPE, AND THE RESULTING DIFFERENCE IN SEGMENT LENGTHS CAUSES THE LIMB TO ROTATE UNTIL A FOLD IS GENERATED.

a local "fixed" boundary condition. Since one segment is "fixed", it will not change length, while the other actuated segment will decrease in length. The disparity in lengths causes the upper half of the assembly to rotate until folds are generated, which serve as revolute joints. This simple on-off braking function allows EEMMMa-1 to bend with minimal added weight, effectively granting the arm 2-DOF capabilities with only a single main motor, although it cannot be actuated in 2-DOF simultaneously.

The overall weight of the system is 685 grams, consisting of a 640 g main body, 35 g end effector assembly equipped with hooks, and 10 g of steel tape. Much of this weight comes from excess fasteners and components included for adjustability and modularity that can be removed in future designs.

2.3 Tape Spring Limb

The tape provides the main structure for the limb, and is stored in a spool in the main body. It is folded into a U-shape, with the transverse curvature pointing outward. The U-shape has one end connected to the spool, with the other end fixed to the main body. This layout essentially creates three tape regions: two unfolded segments placed back-to-back, and a folded segment connecting them at the base of the U. When tape springs are placed back-to-back, the overall structure exhibits significantly improved stiffness, since one of the tapes is subjected to opposite sense bending regardless of bend direction [13] [14] [15]. EEMMMa-1 utilizes this advantageous property while only requiring actuation of a single continuous tape. Additionally, the elastic spring properties of the tape assist with maintaining the orientation of the hooks during extension and engagement, resulting in robust climbing capabilities.

The material used is a uniform segment of pre-stressed steel tape cut from a Pittsburgh brand 12 ft. x ½ in. tape measure, with a 0.006 in. thickness. This tape width of ½ in. is relatively small when compared to 1-¼ in. used in other projects [7] [16]. This results in reduced bending stiffness and limb rigidity, but also lighter weight and easier shape morphing since the peak moment required to induce folds is lower. Since this prototype was designed for climbing, the reduced bending stiffness is inconsequential since the tape is almost always loaded in tension. The tape's total length is 1m, allowing the limb to extend 50 cm away from the main body. This distance was chosen specifically for climbing ladders, which commonly have rungs with 4 cm diameter, spaced 30 cm apart. Both ends of the tape have 3 mm holes drilled in their centers to rigidly connect to the spool or frame.

2.4 Main Body

The main body forms the primary structure that houses the motorized spool, tension management subsystem, and electronics. These components are placed in specific locations to make the center of mass close to vertically aligned with the tape axis. This is to reduce pitching moments that can disrupt hook alignment while climbing or cause the system to fall [17]. The frame is primarily composed of 3D printed PLA and steel fasteners, and measures 130 x 140 x 95 mm.

The 40 mm diameter spool is surrounded by an outer casing with a small exit hole to confine the coiled tape loops, which will unwind themselves or push out of plane due to instabilities while coiled [18]. The inside of the spool casing is lined with a strip of nylon to reduce friction.

After leaving the spool, the tape enters the tension management subsystem. An output roller covered with non-slip rubberized surface (neoprene) grips the tape as it exits to maintain a tension force inside of the tape that keeps the tape properly coiled around the spool. The spool and roller have the same diameter and are geared 1:1 to ensure the tape deploys smoothly. While this is sufficient for shorter lengths, longer lengths of spooled tape will result in the spool diameter decreasing as more tape is deployed, which may cause tensioning issues for future prototypes.

Finally, the tape exits the main body at the output hole, which has a curved shape that follows the tape's transverse curvature. This is to ensure the tape deploys in an unfolded state for maximum rigidity. When there are disturbances from forces at the end effector, the output hole's curved surfaces reduce the likelihood of a stress concentration which may result in an unwanted fold.

2.5 End Effector

The end effector assembly provides a structure at the end of the limb for mounting any additional mechanisms that interact with the environment such as hooks or cameras. The end effector contains an idler pulley that passively follows the traveling fold at the "end" of the limb as seen in Fig. 3b. The idler pulley is wrapped in rubberized tape and is 29mm in diameter; folded tapes exhibit a characteristic longitudinal curvature based on the tape's manufacture, which is 29 mm for this tape. The idler and the U-shaped tape form a pulley system that provides mechanical advantage that halves the torque required to lift the main body while climbing.

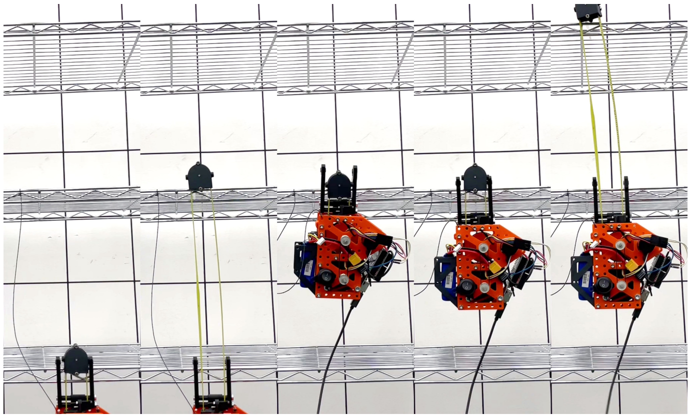

FIGURE 6: SNAPSHOTS OF SHELF CLIMBING DEMONSTRATION.

An outer casing surrounds the idler and tape. The inside of the casing contains a small nylon pad at the tip of the fold, which allows the end effector to transfer loads to the tape in both tension and compression with minimal friction. The casing also prevents the traveling fold from splitting into two separate folds when loads are applied.

3. DEMONSTRATIONS

In the following demonstrations, EEMMMa-1 shows its effectiveness as a multimodal platform for both mobility and manipulation in a lightweight, compact package. By leveraging the tape spring's unique properties, EEMMMa-1 can demonstrate climbing, bending, pushing, and pulling. These tasks require only two parameters to be controlled: the length change of the tape, and the on/off of the end effector brake.

3.1 Climbing

To verify the limb's ability to handle loads in tension, EEMMMa-1 was subjected to climbing trials in three scenarios: climbing a shelf, a ladder, and a rough vertical wall. Trials were first conducted on wire-frame shelves made of 5 mm diameter wire, seen in Fig. 6. Shelves had a thickness of 22 mm and were spaced 254 mm apart for a total of 276 mm to ascend per level. EEMMMa-1 can ascend at 7.5 in/s (19 cm/s), traversing a level at top speed in about 2 seconds. For ladder climbing trials, straight vertical ladders were used, which are commonly seen in industrial or mechanical environments such as factories, buildings, and ships. The ladder chosen had cylindrical rungs with 2 cm diameter, spaced 28 cm apart for a total of 30 cm to ascend per level. The larger diameter of the ladder rungs caused more significant perturbations from the compliant hooks. When climbing at top speed, these perturbations caused hook alignment issues during multiple climbs in succession, although trials at slower speeds were successful.

For the wall scaling trials, the end effector compliant hooks were swapped with a small microspine array, seen in Fig. 7. This microspine array is composed of four small steel hooks, with sharp points that engage in asperities on the rough surface. Outer housings and rubber bands provide rotational and translational compliance for engagement and load sharing. EEMMMa-1 could

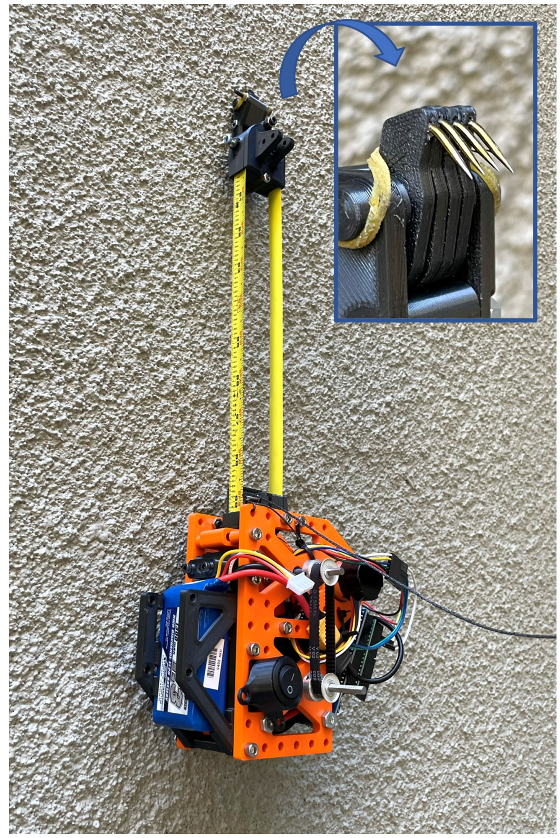

FIGURE 7: SNAPSHOT OF EEMMMA-1 CLIMBING A ROUGH VERTICAL WALL. THE END EFFECTOR'S SMALL MICROSPINE ARRAY GRIPS INTO ASPERITIES IN THE ROCKY SURFACE.

successfully cling to the wall and ascend small distances. However, this prototype was unable to perform multiple grappling and anchoring sequences in succession due to two main effects. First, the main body's center of mass being slightly off center caused the body to pitch and the limb to extend at an angle. At large extensions, this caused the end effector microspines to be too far away from the wall to engage the surface properly. Additionally, the microspine array footprint was small enough to be approximated as a point contact, which sometimes caused the anchor to twist off the surface during perturbations. A future body redesign and microspine array upgrade could alleviate these issues.

For all climbing trials, the elastic spring properties of the tape proved to be beneficial for resisting unwanted forces or moments at the end effector. Hooks require directional engagement, and they must approach the grappling features at a specific orientation to be effective. This is especially important for microspines, which can peel away or fail to engage if they are not properly aligned with the gripping surface. These experiments were performed with simple open-loop control and manual input. Because correctional forces are passively supplied by the tape's spring properties, the climbing sequence is robust and simple to control. However, future designs with larger extension lengths and heavier end effectors may experience additional difficulties since the end effector may oscillate over long periods and require long settling times to passively re-establish alignment without added stiffness or damping. These trials demonstrate EEMMMA-1's ability to

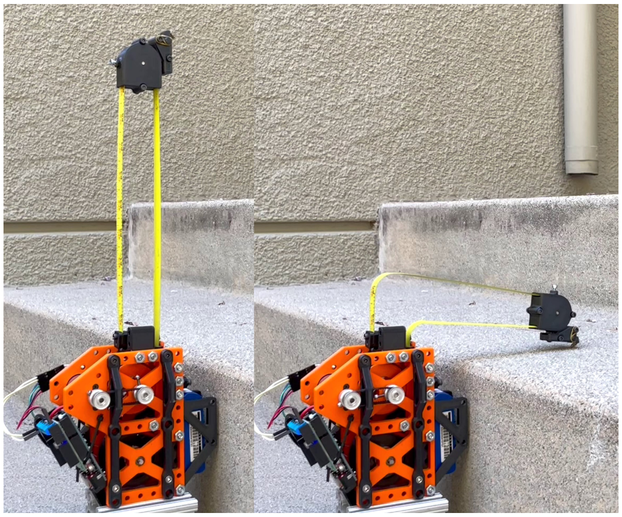

FIGURE 8: SNAPSHOTS OF EEMMMA-1 BENDING TO PLACE A MICROSPINE ANCHOR ON THE TOP SURFACE OF A STEP.

pull loads against gravity, which is vital for suspending the main body in midair from above, or for retrieving samples from below.

3.2 Bending

Robotic manipulation tasks commonly require reaching a target in space, so the next set of tests were devised to demonstrate EEMMMa-1's ability to reach a desired location on a plane using controlled bending. Since it is trivial to reach any single point along the 1-DOF linear path, trials involved reaching two points on the plane, seen in Fig. 5a. For the first set of trials, the limb was pointed vertically, extending in the direction opposite gravity. This was selected as the most relevant scenario for this system, since climbing actions generally involve vertical movement, and bending would be advantageous for reaching above tables or steps. For the first test, the limb was first extended to point A located 20 cm above the main body at coordinates (0,20) cm. Next, the end effector braking system was engaged, allowing the motor to initiate limb bending. Actuation was applied slowly until a fold was created in both tape segments, essentially serving as a new revolute joint. After rotating 90 degrees, the end effector successfully reached point B located at (10,10) cm. Video footage was taken on a gridded background to verify repeatability. The tape's bending kinematics and behavior will be discussed in more detail in Section IV.

Subsequent bending trials to other points in the plane revealed additional phenomena. Angling the revolute joint more than 90 degrees resulted in the folds suddenly migrating towards the main body, causing the limb to collapse. Limb collapse also occurred when extending the spool to reach most points in the -X direction (see Fig. 5b). This is due to the fixed segment being loaded in equal-sense bending rather than opposite-sense bending, which will cause buckling under a much lower peak moment. It was also found that the location of the fold could be controlled through dynamic inputs, which will be discussed more in Section IV.

As a test application for bending, EEMMMa-1 was placed on a stone staircase to demonstrate anchoring to steps with microspines, shown in Fig. 8. The limb was extended vertically above the next step, and a fold was induced to angle the end effector until the spines contacted the surface. The tape was then retracted slowly, allowing the spines to fully engage and pull the body in. The tape's natural spring properties assist with maintaining the proper spine orientation during all phases of movement, including approach, engagement, and retracting. These tests demonstrate the potential for EEMMMa to serve as a long reach, low complexity manipulator arm that can bend around or over obstacles to position grippers, cameras, or other instruments in difficult to reach places.

FIGURE 9: EEMMMA-1 STANDING DEMONSTRATION. THE LIMB IS DEPLOYED DOWNWARD, WITH THE END EFFECTOR SECURED IN A VICE. THE WEIGHT OF THE MAIN BODY LOADS THE LIMB IN COMPRESSION, SIMILAR TO A WEIGHT-BEARING LEG.

3.3 Standing

A simple "standing" test was performed as a demonstration of the limb's ability to handle loads in compression by serving as an extendable prismatic leg, as seen in Fig. 9. First, the end effector was placed in a vice with the main body carefully positioned directly above. The limb was extended and the main body was released, with its weight creating a compressive load on the limb. These static loading tests were successful up to 20 cm of limb extension. Beyond this point, the limb's rigidity was insufficient to prevent small perturbations from causing the body's center of mass to shift, which resulted in a collapse. Dynamically

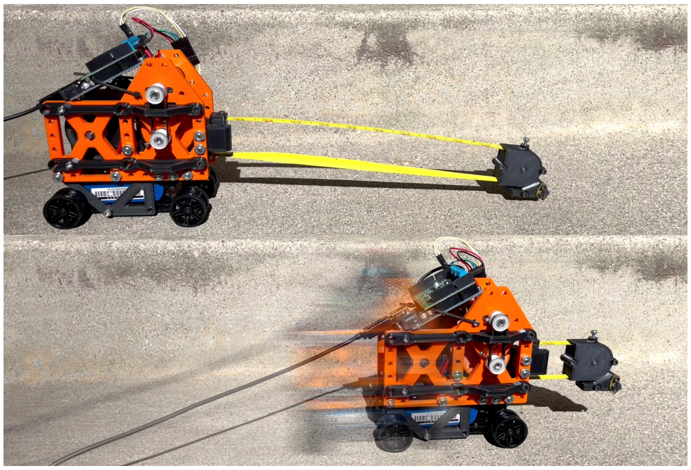

FIGURE 10: SNAPSHOTS OF EEMMMA-1 CRAWLING DEMONSTRATION, EQUIPPED WITH PASSIVE WHEELS.

extending the limb also caused collapses at longer lengths, since reaction moments at the main body resulted in the center of mass shifting and would cause the system to topple over.

These tests demonstrate the end effector's effectiveness at allowing the limb to handle compressive loads. Because the tape is a single continuous U-shape, loads can be transferred evenly between the two opposing segments. The end effector housing effectively confines the U-shaped tape fold without it splitting or propagating, which would result in a greatly reduced ability to handle loads as a manipulator. The ability to successfully handle compressive loads is promising for future EEMMMa designs, which will feature multiple limbs and not exhibit the same collapsing issues due to load sharing between the limbs.

3.4 Crawling

As an additional test for mobility, EEMMMa-1 was equipped with passive wheels on the underside of the main body to demonstrate 1-DOF crawling along the floor, depicted in Fig. 10. The end effector was equipped with the microspine attachment and the limb was extended. When outstretched, gravity causes the limb to sag slightly, allowing the end effector microspines to contact the floor. The tape was retracted slowly to engage the microspines, then a fast retraction pulled the body forward. The main body would then coast linearly on the floor, carried by momentum. As the body approaches the end effector, the microspines would naturally disengage due to the changing angle of engagement. This demonstrates EEMMMa's ability to be used with other mobility schemes, and operate with them in combinations for various effects.

4. ANALYSIS AND DISCUSSION

4.1 Bending Behavior

The limb's ability to extend and bend in a controlled, repeatable fashion can be explained by analyzing the tape's properties. From previous work, the bending stiffness of a tape segment can be characterized by its material and four geometric parameters: its unstressed radius of curvature R, thickness t, subtended angle α, and length ℓ, as previously depicted in Fig. 2a.

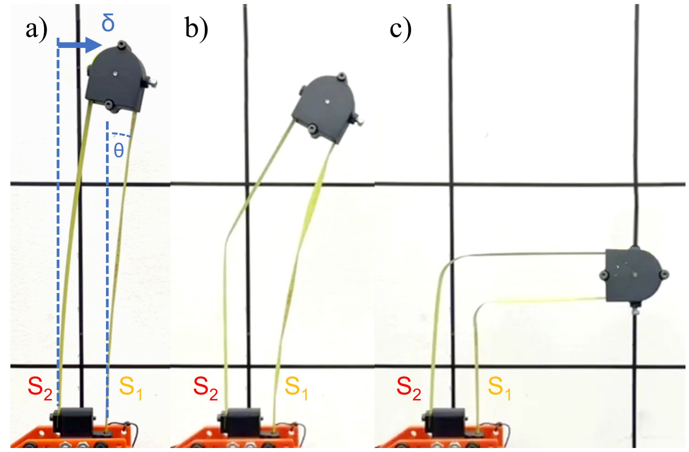

FIGURE 11: THREE STATES OF BEHAVIOR FOR BENDING. A) FOR SMALL ANGLES ($0° < \theta < 10°$), BOTH SEGMENTS ARE UNFOLDED, AND DISPLACE SOME DISTANCE δ. B) FOR MEDIUM ANGLES ($10° < \theta < 40°$), S_2 HAS A FOLD WHILE S_1 IS UNFOLDED, BUT EXPERIENCES COMBINED TWISTING AND BENDING. C) FOR LARGE ANGLES ($40° < \theta < 90°$), BOTH SEGMENTS ARE FOLDED, CREATING TWO COMBINED REVOLUTE JOINTS.

Snapshots from the bending trials are shown in Fig. 11 displays three states of behavior that the limb exhibits as it bends from 0° to 90°. Under normal 1-DOF operation, the tape operates as a single continuous piece of material, moving the end effector as the idler pulley rolls along the tape's length. Activating the brake at the end effector functionally separates the tape into two segments, S_1 and S_2. The actuated segment S_1 on the right is attached to the spool, and has a variable length that can be changed by actuating the motor. The segment S_2 on the left now has a fixed length due to its end attachment to the main body. By retracting the tape, S_1's length is reduced, and the end effector begins to rotate due to the disparity in lengths. The tape's bending behavior becomes dominated by geometric constraints.

In the first bending state depicted in Fig. 11a, both tape segments exhibit small horizontal displacement. S_2 is subjected to opposite-sense bending, and we can treat it as a single flexible beam until buckling occurs. By treating this case as a beam deflection, the applied moment can be calculated:

$$M = \frac{2\delta EI}{S_2^2} \tag{1}$$

where δ is the tip displacement of S_2, E is the elastic modulus of the tape material, I is the second moment of area of the cross section. For an unfolded tape, I can be found using the geometry of the curved cross section:

$$I_u = \frac{R^3 t}{2\alpha}[\alpha^2 - 4(1 - cos(\alpha)) + \alpha sin(\alpha)] \tag{2}$$

S_2 exhibits linear behavior until the applied moment exceeds the peak moment M_+^{max} and a fold is created (see Fig. 2b). Meanwhile, S_1 is subjected to equal-sense bending, and will bend and twist simultaneously until the negative peak moment M_-^{max} is reached and a coherent fold is formed. While this flexural-torsional deformation mode is difficult to capture mathematically, equations governing this behavior and peak moments can be found in Seffen's work [13]:

$$M_{+}^{max} = (1 + \nu)D\alpha \quad (3)$$

$$M_{-}^{max} = (1 - \nu)D\alpha \quad (4)$$

$$D = \frac{Et^3}{12(1-\nu)} \quad (5)$$

where ν is Poisson's ratio of the tape material.

In the second bending state depicted in Fig. 11b, the fixed segment S_2 has folded while the actuated segment S_1 has not, but continues to experience combined bending and twisting. When folded, the curve flattens and the cross section becomes rectangular. The required applied bending moment of the flattened tape is:

$$M = EI_f\kappa = ER\alpha\frac{t^3}{12}\kappa \quad (6)$$

$$I_f = R\alpha\frac{t^3}{12} \quad (7)$$

where κ is the longitudinal beam curvature and I_f is the second moment of inertia for the folded tape. Note that the formulation of I changes significantly due to the change in cross section, which now exhibits a much lower stiffness for rotations about the Z axis.

Folds will generally occur at the midpoint of segments, since the loads at the ends are equal and opposite. Due to this symmetry, the fold will not propagate or travel along the tape's length, assuming minimal effects from external forces. Since the fold is symmetric and located away from endpoints, it can be modeled as a point hinge [10]. In this state, S_2 behaves as two rigid segments connected by a revolute joint, while S_1's behaves nonlinearly as a beam undergoing large deflection, with higher flexural-torsional deformation that can be characterized using Mansfield's equations [19].

In the third bending state depicted in Fig. 11c, both segments have folded at their centers, essentially creating a new revolute joint for the limb. The limb can easily be returned to the straight prismatic configuration by equalizing the lengths. This is partially assisted by the tape itself, which will attempt to straighten in order to relieve the accumulated strain energy from bending [10].

4.2 Two Dimensional Bending Kinematics

Figure 12 shows the parameters that define the 2D kinematics for this vertically deployed limb at large bending angles. The forward kinematics of the end effector at point C can be defined in terms of virtual link length L and bending angle θ:

$$x = -Lsin(\theta) \quad (8)$$

$$y = L + Lcos(\theta) \quad (9)$$

The limb consists of two virtual links: the first link goes from the midpoint of the base A to the center point between the two tape folds B, and the second goes from point B to the center of the pulley C. Since end loads of the two tape segments are symmetric about point B, both of their bends will occur at the midpoint of the segments. Thus, both links AB and BC have equal length L,

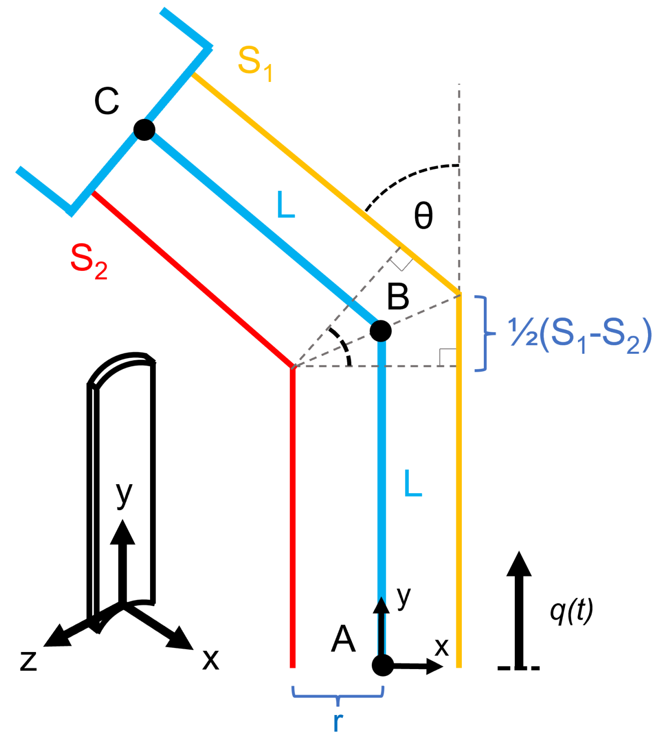

FIGURE 12: LIMB BENDING KINEMATICS. THE STATE OF THE TWO OPPOSING SEGMENTS OF TAPE S_1 AND S_2 DETERMINE THE STATE OF THE VIRTUAL LINKS L IN BLUE THAT APPROXIMATE THE OVERALL LIMB.

which is dependent on the lengths of the right actuated segment S_1 and left fixed segment S_2. The bending angle theta is defined as the angle between the two virtual links, which is dependent on the difference between S_1 and S_2. The two tapes are parallel and offset by a distance r from the centerline, which is the radius of the end effector idler pulley (and also characteristic bending radius of the tape). Since L is located at the center between the two tapes, we can use triangle similarity rules to draw two conclusions:

$$L = \frac{1}{4}(S_1 + S_2) \quad (10)$$

$$tan(\frac{\theta}{2}) = \frac{\frac{1}{2}(S_1 - S_2)}{2r} \quad (11)$$

Both of these values are dependent on S_1 and S_2, which are determined by our single control variable $q(t)$, which is the length of tape extended/retracted from the base. However, the braking function gives us two modes for formulating S_1 and S_2. In "free" mode, the braking function is off, a change of $\dot{q}(t)$ will result in S_1 and S_2 changing lengths equally. In this case, lengths $S_1(t)$ and $S_2(t)$ are given by:

$$\begin{bmatrix} S_1 \\ S_2 \end{bmatrix} = \begin{bmatrix} \frac{1}{2} \\ \frac{1}{2} \end{bmatrix} q(t) + \begin{bmatrix} S_1(0) \\ S_2(0) \end{bmatrix} \quad (12)$$

where $S_1(0)$ and $S_2(0)$ are the lengths of the tape segments at time $t = 0$. However, when in "brake" mode, only S_1 changes

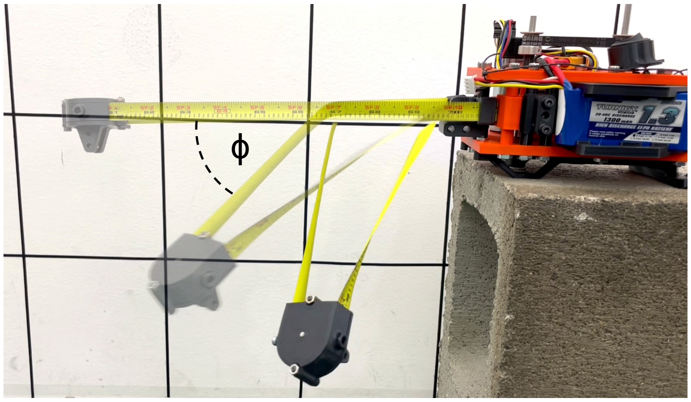

FIGURE 13: DEMONSTRATION OF OUT-OF-PLANE BENDING, WHERE THE APPLIED BENDING MOMENT IS PERPENDICULAR TO THE MOMENT FROM THE END EFFECTOR'S WEIGHT.

length while S_2 remains fixed at its initial length.

$$\begin{bmatrix} S_1 \\ S_2 \end{bmatrix} = \begin{bmatrix} 1 \\ 0 \end{bmatrix} q(t) + \begin{bmatrix} S_1(0) \\ S_2(0) \end{bmatrix} \tag{13}$$

It can be observed that the two kinematic modes determine how theta is formulated. In the "free" mode, computing the $S_1 - S_2$ term results in $q(t)$ canceling out. This means that the theta is not dependent on $q(t)$ and will be unaffected by extending/retracting the tape. However, in "brake" mode, the $q(t)$ term reappears in theta and can now be controlled by inputs. Substituting either of these Equations into Equation 1 yields the system:

$$\begin{bmatrix} x \\ y \end{bmatrix} = \frac{1}{4} \begin{bmatrix} -sin(\theta) \\ 1 + cos(\theta) \end{bmatrix} q(t) + \frac{1}{4} \begin{bmatrix} -sin(\theta) \\ 1 + cos(\theta) \end{bmatrix} [S_1(0) + S_2(0)]$$

While the model is accurate for small displacement, static loading conditions, it does not take into account effects from external forces such as gravity, as well as dynamic effects from oscillations caused by the spring properties of the tape.

4.3 3D Bending and Dynamic Input Investigations

The formulation above assumes negligible effects from external forces, but in practice there are several additional factors to include if a holistic model is desired in future work. When gravity is included, the weights of the extended tape and the end effector now contribute additional torques to the system. This can have significant or insignificant effects on motion depending on the orientation of the tape. In the above configuration, actuating the spool applies a bending torque about the Z-axis, and the weight of the end effector generates a torque that is also about the Z-axis. Thus, the addition of gravity only causes θ to deviate slightly, and the system remains in 2D.

However, when the tape is deployed horizontally as depicted in Fig. 13, inducing a fold can cause the limb to bend out of plane, resulting in a 3D fold. This is because actuating the spool applies a torque about the Y-axis, but the moment arm from the weight of the end effector also causes a rotation about the Z-axis. In this case, the fold will exhibit both bending and twisting in θ and ϕ. Since ϕ is a function of the Z-axis moment, it can be controlled by extending the tape to increase the moment arm. This can be used to control the end effector's out-of-plane displacement until the peak moment is reached and the limb collapses. This can potentially be used in future versions of EEMMMa to grant the limb 3-DOF, taking advantage of gravity to achieve out-of-plane movement.

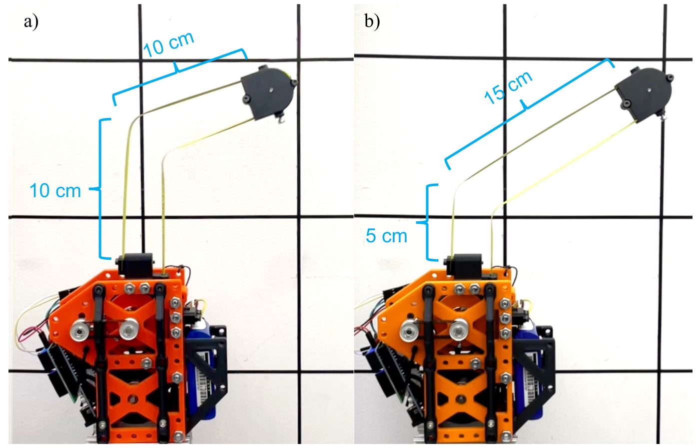

FIGURE 14: EXAMPLE OF THE FOLD LOCATION CHANGING FROM DYNAMIC INPUT. A) BASE CASE WHERE SLOWLY ACTUATING CAUSES THE FOLD TO OCCUR AT THE TAPE MIDPOINTS. B) DYNAMIC CASE WHERE ACTUATING IN DYNAMIC BURSTS CAUSES THE FOLD TO OCCUR AT A DIFFERENT LOCATION.

Additional properties can be controlled if inputs are applied dynamically. In preliminary tests, the actuated tape was retracted in short bursts, resulting in oscillations at the end effector. If the tape was retracted again before the oscillations settled, the fold location could be altered depending on the state of the end effector, depicted in Fig. 14. The timing of these actuation bursts can also potentially be used to minimize oscillations at the end effector by cancelling out vibrations with well-timed retractions. This phenomenon has been observed in previous tape spring studies where the fold travels due to impulse-momentum interactions [10] where the tape is modeled as a traveling hinge with hinge position and rotation angle as two independent degrees of freedom.

While analyzing and controlling these additional degrees of freedom are outside the scope of this paper, these phenomena are important to note for their potential to enhance EEMMMa's available workspace and manipulation capabilities in the future.

5. CONCLUSION AND FUTURE WORK

This paper introduced the novel concept of utilizing tape spring mechanisms for robotic limbs that can serve for dual mobility and manipulation tasks. Tape springs exhibit unique characteristics that can be valuable for a robotic limb, such as compact retractability, long reach, light weight, simple construction, elastic self-correcting, and safety. The EEMMMa-1 prototype presented in this paper demonstrates the powerful versatility of a single EEMMMa limb, providing key functions such as climbing and bending with only one actuator.

Future mobile robots can utilize combinations of EEMMMa limb configurations and end effectors to achieve a wide range of mobility schemes. The EEMMMa-C series of climbing robots are currently under development. EEMMMa-C2 will be a two-

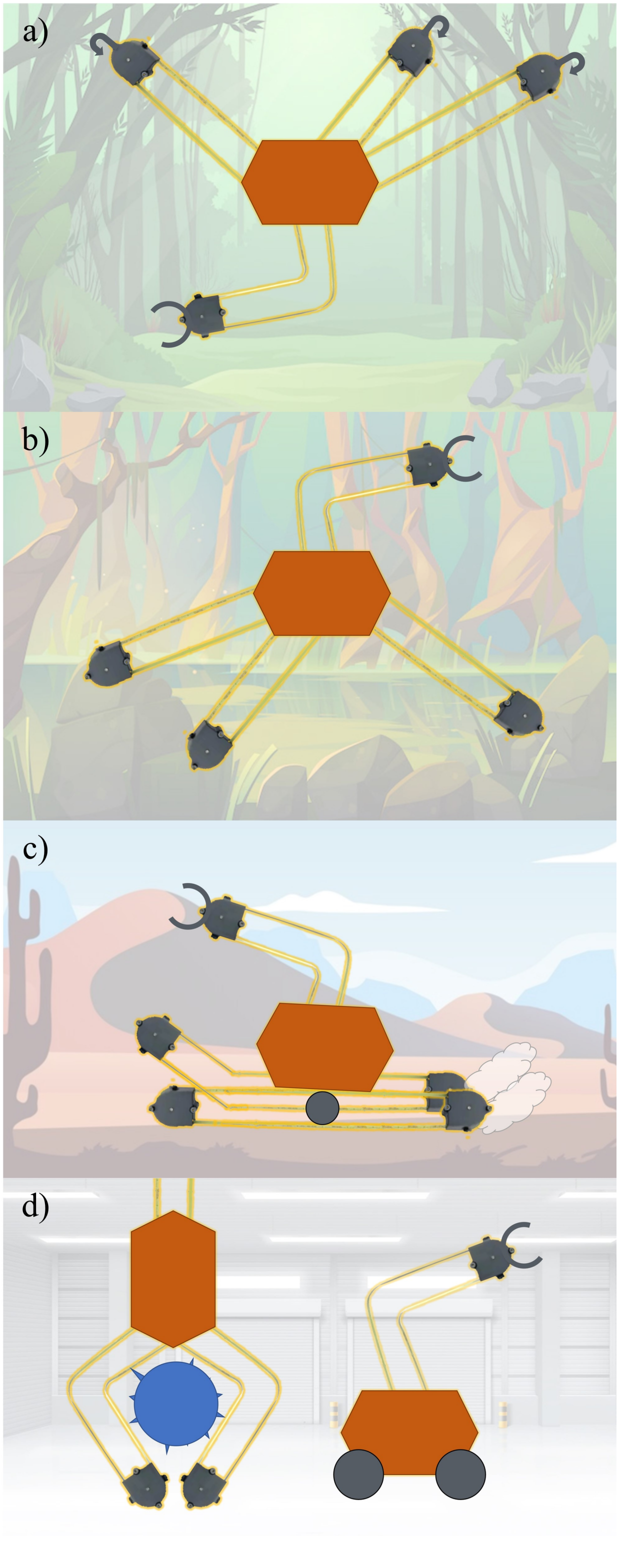

FIGURE 15: CONCEPT ART OF POTENTIAL EEMMMA CONFIGURATIONS. MANY CONCEPTS HAVE REDUNDANT LIMBS THAT CAN BE REPURPOSED FOR INSPECTION OR MANIPULATION TASKS. A) SUSPENDED ROBOT THAT DEPLOYS ANCHORS TO TREES. B) QUADRUPED WITH TELESCOPIC POINT FEET. C) TREAD MORPHING CLOSED-LOOP TAPE TANK ROBOT. D) MANIPULATION FOCUSED ROBOTS.

limbed, 3-DOF planar manipulator equipped with microspines for anchoring into rough walls. EEMMMa-C2 will be able to grasp parallel walls to suspend itself in midair by aiming and deploying anchors, then simultaneously reeling in both limbs.

The long term goal envisioned for this project is a lightweight three or four-limbed robot that can move in 3D space by aiming and anchoring onto different locations with its extendable limbs, depicted in Fig. 15a. From its suspended position, it can then reel itself in or even swing to transport itself quickly. Since this mobility scheme only requires three anchor points for safe motion, this system would be excellent for navigating through caves or dense forests where terrain is highly unstructured and there are large vertical structures for anchoring and climbing. For a three-limbed system, since only two limbs are needed to suspend the body, the third limb could be used to deploy a camera or retrieve a sample from below. For a four-limbed system, the multimodal nature of each limb grants the system built-in redundancy for both mobility and manipulation tasks. Even if a limb is damaged, the system can continue functioning by simply repurposing the remaining limbs.

Beyond climbing robots, there are many other mobility schemes that can be explored. Legged locomotion could use EEMMMa extendable legs for a quadrupedal system, depicted in Fig. 15b. This could be highly advantageous for stepping over obstacles rather than traveling around them. In environments that feature wide-spanning hazards like water and mud, such as swamps, this would make path planning much easier and safer. For manipulation tasks, the quadruped could establish three stable points of contact with the floor and use the fourth limb as a bendable arm for tasks such as reaching submerged objects.

The principles explored in EEMMMa could also be used to improve platforms that focus purely on either mobility or manipulation. EEMMMa's morphability could be used for a closed-loop continuous tape as a tank tread for movement, utilizing the pulley-brake mechanism to morph the shape of the treads to move over obstacles, as seen in Fig. 15c. EEMMMa could also serve as fingers for a compliant gripper that morphs its shape to conform around objects. The tape's steel construction could be favorable for conforming to shapes with sharp corners that could damage other soft robotic shape-morphing manipulators.

The limitations of tape spring limbs can be explored in future work as well. Deploying the limb at long lengths decreases the limb's ability to handle transverse and compressive loads due to increasing moment arms. Longer lengths also increases the limb's sensitivity to external forces and the severity of vibrations, which can limit its usefulness as a manipulator. The presence of gravity greatly affects the characteristics of the limb and can limit deployment in certain directions. Additionally, the maximum length deployable is physically limited by the tape's geometric properties. Finally, while the limb is generally protected from accidents since it can deform elastically, there is risk of plastic deformation if the tape loop gets caught or bent excessively, which would permanently affect its deployment characteristics or cause the limb to be unable to retract. Examining these limitations will help enhance EEMMMa's potential to enable a wide variety of long-reach manipulators and locomotion schemes for future mobile robots.

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APPENDIX A. SUMMARY VIDEO

Link: https://www.youtube.com/watch?v=Ou8liYu03RA

