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A LIGHTWEIGHT MOBILE ROBOT FOR CLIMBING STEEL STRUCTURES WITH AN EXTENDING AND BENDING TAPE SPRING LIMB

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ABSTRACT

This paper details the design and preliminary demonstrations for a compact climbing robot named EEWOC (Extended-reach Enhanced Wheeled Orb for Climbing). This novel platform utilizes the EEMMMa limb (Elastic Extending Mechanism for Mobility and Manipulation), detailed in previous work. This highly extendable and bendable robotic limb utilizes a unique tape spring structure for long reach in a small, lightweight package. EEWOC combines this limb with additional degrees of freedom and two magnetic grippers to allow it to ascend vertical metal surfaces by consecutively extending and gripping. It is also equipped with wheels for horizontal mobility. A key advantage of this system is EEWOC's ability to bend to place its grippers around obstacles or corners and above ledges. The prototype is small and lightweight, with a profile of 25x30x30 cm and weight of 1.8 kg, while able to extend its limb up to 1.2 m away. With versatile movement options, EEWOC has the potential to fully traverse large metal structures such as ships or buildings for use in inspection tasks. This paper presents a detailed view of the overall system and mechanism design, and successful climbing demonstrations are shown on steel structures. The paper concludes by detailing EEWOC's future capabilities and additional tests and theories needed to refine its maneuvers and control.

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

FIGURE 1: EEWOC'S ABILITY TO EXTEND AND BEND TO PLACE ITS MAGNETIC GRIPPERS ON COMPLEX FEATURES GRANTS IT A WIDE VARIETY OF MOBILITY OPTIONS ON STEEL STRUCTURES.

1. INTRODUCTION

Climbing robots present a growing area of interest for tasks that involve safety risks to humans in environments high off the ground. This commonly includes inspection or surveillance tasks, where vertical mobility is useful for accessing locations that are difficult or dangerous to reach for humans. For example, urban and industrial environments such as buildings and factories require routine structural inspection in hard-to-reach locations like roofs and cooling towers. While these environments seem to be ideal use cases for a climbing robot, these structures can actually be highly challenging to navigate while climbing, with a wide variety of external features such as pillars, pipes, and platforms that protrude from the surface.

While there are currently many different types of climbing robots in development, they are commonly confined to climbing a single specific surface, such as a pane of glass or a featureless wall [1] [2] [3]. This limits their usefulness in real world applications, where urban and industrial terrain can be fairly unstructured and full of features that pose as obstacles while climbing. While legged climbing robots attempt to solve this with greater adaptability to surface variations, this comes at the cost of weight and

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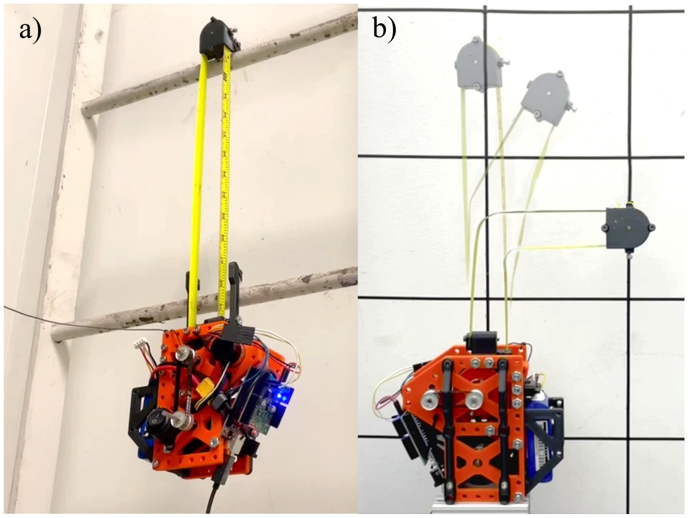

FIGURE 2: A) PREVIOUS EEMMMA-1 PROTOTYPE EXTENDING ITS LIMB TO CLIMB A LADDER USING PASSIVE HOOKS. B) SNAPSHOTS OF EEMMMA-1 BENDING THE LIMB.

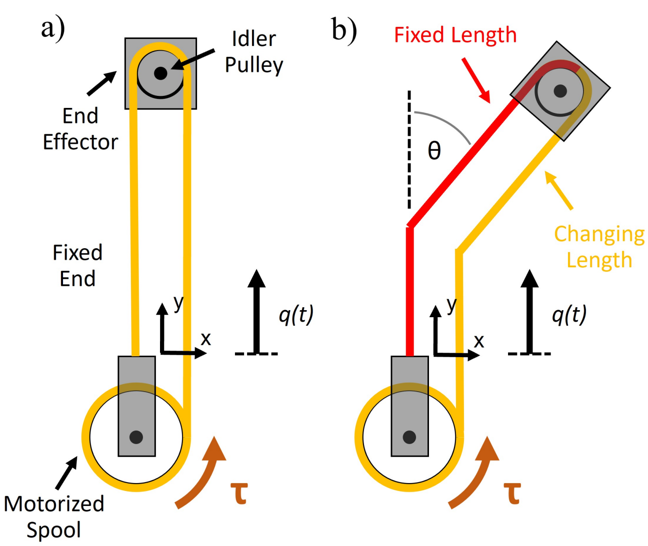

FIGURE 3: A) EEMMMA-1 INTERNAL LAYOUT, SHOWING THE U-SHAPED CONTINUOUS TAPE STRUCTURE. B) EEMMMA-1 BENDING MODE. A SMALL BRAKE STOPS THE IDLER PULLEY FROM ROTATING. ACTUATING THE TAPE SPOOL WITH TORQUE $-\tau$ NOW CONTROLS ONLY THE RIGHT SIDE OF THE TAPE, AND THE RESULTING DIFFERENCE IN SEGMENT LENGTHS CAUSES THE LIMB TO ROTATE UNTIL A FOLD IS GENERATED.

complexity. Additionally, the mobility of legged climbers is limited by the length of their limbs, which confines their reachable workspace to a relatively small area. This prevents their effective use in environments where anchor points are sparse.

The EEMMMa (Elastic Extending Mechanism for Mobility and Manipulation) concept presented in our previous work addresses these climbing challenges with an unconventional movement scheme [4]. A highly extendable tape spring limb is used to grapple and suspend itself to move quickly and safely between distant anchor points. Additionally, the limb can induce a controlled bend to place anchors around obstacles. This system was originally envisioned for use in a small mobile platform to navigate highly rough terrain such as cave systems and forest canopies, using its highly extendable limb to grasp suitable anchor points that may be far from each other.

The EEMMMa-1 prototype detailed in our previous work demonstrated the great potential of an extending and bending robotic limb for lightweight mobile platforms. While this proof-of-concept prototype consisted of only the 1-DOF tape spring limb, its successful demonstrations showed the powerful versatility of such a system, shown in Fig. 2. EEMMMa-1 was shown climbing ladders and shelves at up to 1.5 bodylengths per second, matching the speed of the fastest wall climbing robots [2]. EEMMMa-1 utilized passively deforming hooks on the end effector and main body that allowed it to quickly extend, attach, ascend, and detach from consecutive levels.

The limb's unique closed-loop U-shaped tape spring structure shown in Fig. 3a grants several advantageous properties. The most notable advantage of this layout is the ability to induce a controlled bend as seen in Fig. 3b. EEMMMa uses a form of mechanical multiplexing to control its bending mode with a single main actuator. This conveniently reduces the system's size and weight, although it cannot control both extending and bending simultaneously. EEMMMa-1 demonstrated extending its limb above a flight of stairs, then bending to place its end effector on the top surface of a step, although it could not climb the stairs due to its single degree of freedom. Additionally, the U-shaped tape spring causes the segments to be oriented back-to-back, which allows the limb to handle significant loads in compression [5] [6]. EEMMMa-1 also showed the ability to "stand" with the main body suspended above the limb.

Despite these successes, EEMMMa-1 was limited due to its simple nature as a single degree of freedom system. Unable to aim, EEMMMa-1 was limited to climbing in straight lines, greatly reducing the advantage of the large workspace granted by the highly extendable limb. To reduce weight, the end effector utilized an entirely passive gripper with no actuation, and the bending mode had to be manually activated by turning a small screw at the end effector. These attributes further limited its ability to be deployed in a real environment.

EEWOC is a new multimodal wheeled and limbed robot that is designed to overcome these limitations, depicted in Fig. 1. It fully utilizes the advantages of the EEMMMa concept to freely move between distant points in 3-D space. EEWOC has additional actuated degrees of freedom to help aim its limb towards target surfaces. It also has wheels to assist with climbing over features, as well as drive efficiently on horizontal surfaces when climbing is not necessary. Importantly, EEWOC's new degrees of freedom allow it to not just climb single walls, but also bend around corners and potentially transition to adjacent walls by swinging. It can also bend to place its gripper onto roofs or ledges and climb onto them with assistance from the wheels.

EEWOC's gripper is equipped with an actuated magnetic mechanism that allows it to attach and detach from metal surfaces such as steel. This grants it full access to industrial metal environments, making it useful for inspection or surveillance tasks on steel structures such as buildings, power transmission

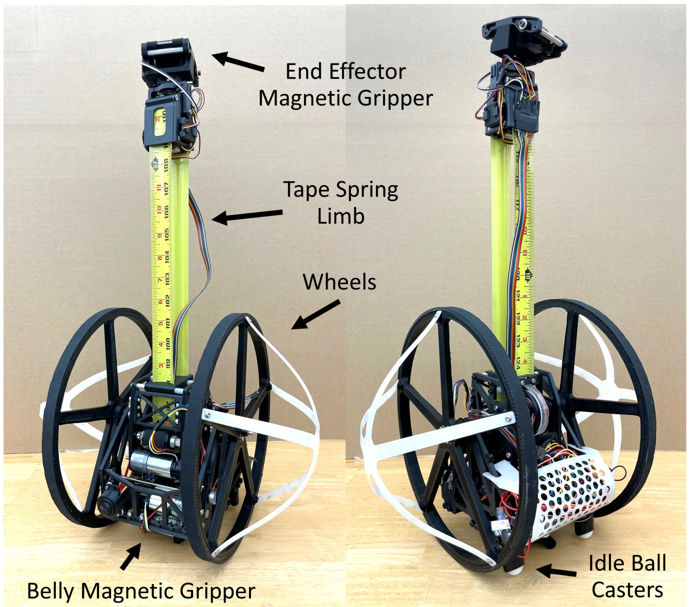

FIGURE 4: FRONT AND BACK VIEW OF EEWOC PROTOTYPE, WITH LABELED MAJOR COMPONENTS.

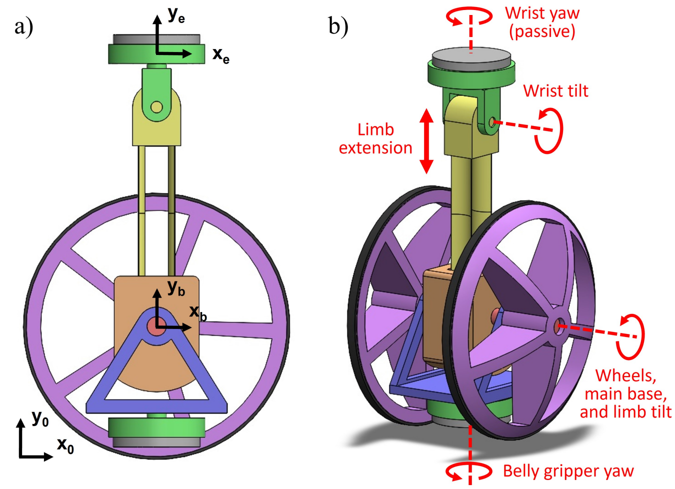

FIGURE 5: A) SIMPLIFIED MODEL OF EEWOC'S MAJOR COMPONENTS IN ITS DEFAULT CONFIGURATION. THIS INCLUDES THE EEMMMA LIMB MODULE (ORANGE), TAPE AND END EFFECTOR (YELLOW), TWO GRIPPERS (GREEN), MAIN BASE (BLUE), AND WHEELS (PURPLE). THE LIMB MODULE, MAIN BASE, AND WHEELS ROTATE AROUND A SINGLE PRIMARY SHAFT (RED). THE GLOBAL COORDINATE SYSTEM IS DEFINED BY x_0-y_0, MAIN BODY'S AXES ARE DEFINED BY x_b-y_b, AND THE END EFFECTOR'S AXES ARE DEFINED BY x_e-y_e. B) ANGLED VIEW SHOWING EEWOC'S PRIMARY DEGREES OF FREEDOM.

lines, ships, and factories. EEWOC's ability to bend allows it to navigate around corners in addition to other common structural obstacles, such as pillars, ridges, portholes, pipes, windowsills, and platforms.

The combination of wheels and extendable limb grants EEWOC versatile multimodal movement that can be useful in other unstructured environments as well. For example, EEWOC can be equipped with a microspine gripper and deployed in a cave system for a geologic study. Here, it can use its limb to hoist itself into a small hard-to-reach tunnel, then switch to wheeled movement to move more efficiently inside the tunnel. With a greatly enhanced reach, EEWOC's unique mobility scheme can allow it to traverse a variety of environments with ease.

2. DESIGN

EEWOC's design will be broken down into five main parts: 1) background information, 2) an overview of operations, 3) the upgraded EEMMMa limb module and end effector, 4) the magnetic gripper, and 5) the main base structure which houses the electronics, wheels, and belly gripper. A front and back view is shown in Fig. 4. The entire system is 25x30x30 cm and weighs 1.8 kg. A simplified model of the assembly with major highlighted parts and axes can be seen in Fig. 5.

2.1 Background Information

Existing climbing robots use many different approaches to attach onto surfaces, with some common types including magnetic attraction [7], [8], [9], pneumatic suction [10] [11] [3], or mechanical attachment using hooks or microspines [12] [13] [2] [14]. These small climbing robots are commonly designed with inspection, surveillance, or search-and-rescue tasks in mind, and are preferably lightweight since they must support their own mass while ascending. Since EEWOC is designed to operate on large-scale ferromagnetic structures, we will look primarily at existing climbing robots that use a magnetic method of attachment. In this case, using permanent magnets is preferable over electromagnets, since they do not require a constant power supply to operate and are thus more efficient for small mobile systems. This allows the robot to "perch" on vertical surfaces for extended periods of time, as it does not need to expend power to remain at its current location. The permanent magnets also help avoid a total system failure from falling in the event of sudden power loss.

To achieve vertical mobility, climbing robots use a wide variety of movement schemes. These generally fall into three categories:

- Multi-degree of freedom arm robots
- Multi-legged robots
- Wheeled or tracked robots

Multi-degree of freedom arms generally take the form of a segmented arm or snake-like structure that grant them better maneuverability over 3D obstacles [7] [1]. However, these also tend to be bulky, complex, and heavy due to the number of actuators required. They are also slow due to their step-by-step locomotion scheme, resulting in crawling or inchworm-like sequential movements. Multi-legged climbing robots [8] [15] [16] can offer even greater mobility options and have redundant limbs for safety, but possess many of the same shortcomings and are even larger and bulkier than the single-arm type robots. A key observation for these arm and leg type robots is that their speed and maneuverability is limited by the length of their limbs. A limited reach both negatively affects the distance traversed with each step, and also limits the range of graspable anchor points which can prevent

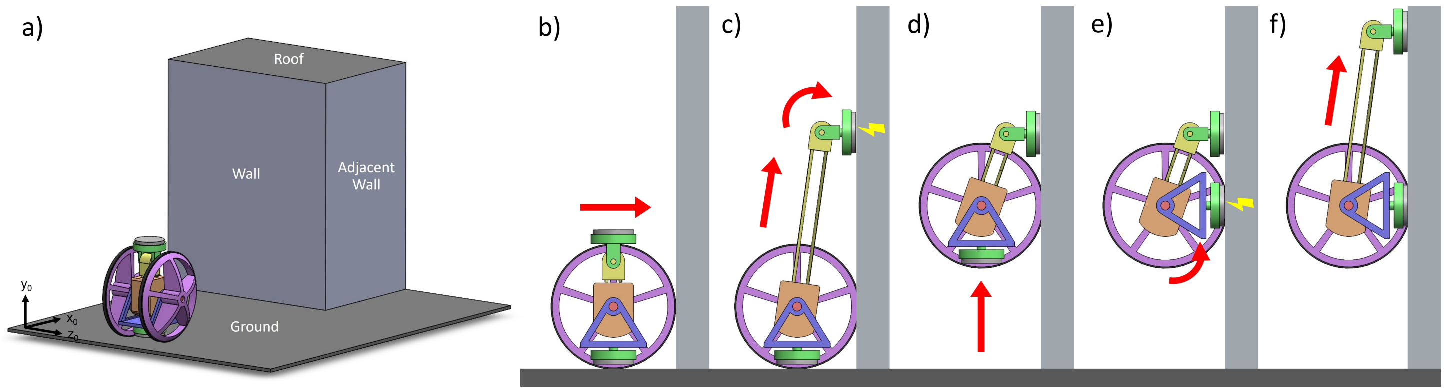

FIGURE 6: OVERVIEW OF EEWOC'S BASIC OPERATIONS. A) ISOMETRIC VIEW OF THE INITIAL SETUP. B) EEWOC DRIVES INTO THE WALL. C) THE LIMB EXTENDS UPWARD AND ROTATES WRIST TO PUT GRIPPER IN CONTACT WITH THE WALL, THEN MAGNETIZES TO ANCHOR. D) THE LIMB TAPE RETRACTS, PULLING THE BODY UPWARDS. E) WHEN FULLY ASCENDED, THE BELLY GRIPPER IS ACTIVATED TO ANCHOR THE BODY TO ITS CURRENT POSITION. F) THE LIMB IS AIMED AGAIN AND THE SEQUENCE CAN BE REPEATED TO SCALE THE WHOLE STRUCTURE.

them from being deployed in environments where suitable anchor points are sparse.

Wheeled climbing robots have greater climbing speed than the other two types due to their continuous locomotion rather than slow step-by-step movement [9] [17] [18] [19]. However, they are often limited to climbing very specific types of surfaces since they are unable to avoid obstacles, cannot maneuver around curved or uneven surfaces, and cannot perform wall transitions since they must maintain continuous contact with the wall.

There are also a number of hybrid systems that attempt to combine mobility schemes to overcome these limitations. Some notable examples utilize a hybrid wheel and single arm magnetic system to achieve more complex maneuvers such as transitioning around corners and external features [20] [21] [22]. Another example uses continuously rotating permanent magnetic wheels with a quadrupedal system to climb over surface variations [8]. However, the limbs used in these examples are still limited by their length, allowing them to only transition over small-scale obstacles and nearby adjacent corners. Additionally, the use of conventional rigid link manipulator arms adds significantly to the overall weight and bulk of these systems, which is not ideal for climbing. Furthermore, magnetic wheels add unnecessary weight since the wheel's outer circumference must contain heavy magnetic elements.

EEWOC addresses these issues by leveraging the unique properties of its tape spring limb for rapid step-by-step movement, detailed in our previous work [4]. Tape springs are thin curved strips that exhibit natural directional stiffness that allows them to serve as structural members. When folded, their axis of curvature changes and they exhibit different properties at the fold [6] [23] [24]. This allows them to be spooled, greatly increasing their compactness.

EEWOC's tape spring limb offers a greatly enhanced reach with minimal weight compared to conventional bulky multi-DOF arms. The limb can also exhibit controlled bending, using mechanical multiplexing with only a single primary motor to achieve a functionally 2-DOF system. EEWOC's long reach and simplified design greatly increase the speed and simplicity of the stepping process, and allow it to move between 3D structures and traverse large scale obstacles much more easily than the previous examples. By using the main body itself as another anchor point, EEWOC eliminates the need for additional limbs. EEWOC's weight is further minimized by reducing the amount of magnets to only a single location where it is needed, eliminating the need for a large rotary magnet array on the wheels. The wheels grant the system much higher speed and efficiency on horizontal surfaces, and assist with certain climbing maneuvers such as transitioning onto ledges or roofs by rolling over geometries and obstacles.

2.2 Overview of Operations

EEWOC's movement scheme is highly versatile, since it can essentially move between any two points on an external metal surface or structure. For a simplified scenario, the basic case detailed here will involve EEWOC first approaching the wall of a metal building, then ascending the wall, and finally maneuvering onto a roof or around a corner. An overview of this process can be seen in Fig. 6.

EEWOC starts as a simple wheeled vehicle on the floor. In its standard configuration, depicted in Fig. 5, the limb and end effector gripper are pointing upwards vertically, with the main base and belly gripper pointing downwards towards the floor. A single primary shaft supports the limb module, main base structure, and wheels, and all three components can rotate concentrically with respect to each other.

EEWOC begins by driving forward until both wheels are in contact with the wall, seen in Fig. 6b. EEWOC then extends its limb vertically. When a desired height is reached, it rotates its wrist to place the end gripper in contact with the wall and activates the magnets, depicted in Fig. 6c. This firmly anchors the end effector to the wall. If more stability is needed at this ground stage, like if driving on a sloped surface, the belly gripper can be used to affix the main body to the ground to prevent the system from tilting backwards when extending the limb.

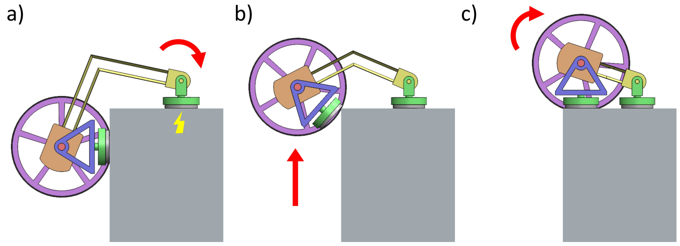

FIGURE 7: OVERVIEW OF EEWOC LEDGE CLIMBING SEQUENCE. A) THE LIMB IS EXTENDED AND BENDS TO PLACE THE GRIPPER ON THE TOP OF THE LEDGE, AND MAGNETIZES TO ANCHOR. B) THE LIMB IS RETRACTED, PULLING THE MAIN BODY ONTO THE LEDGE, ASSISTED BY THE WHEELS. C) LEDGE TRANSITION IS COMPLETE.

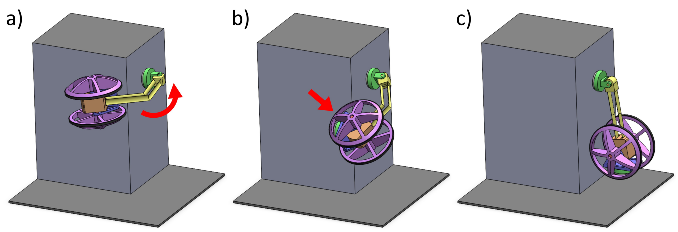

FIGURE 8: OVERVIEW OF EEWOC CORNER TRAVERSING. A) THE LIMB IS ANGLED AND EXTENDED BEYOND THE CORNER, THEN BENDS TO ANCHOR ONTO THE ADJACENT WALL. B) THE BELLY GRIPPER IS RELEASED, ALLOWING THE MAIN BODY TO "SWING" ONTO THE NEXT WALL. C) CORNER TRANSITION IS COMPLETE.

Next, the tape spring limb is retracted, pulling the main body upwards, seen in Fig. 6d. As it ascends, the wheels also rotate simultaneously to prevent unwanted skidding or grinding against the surface. Once it has fully ascended, it angles the main base upward to point the belly gripper towards the wall. It then magnetizes to anchor the main base to its current position, depicted in Fig. 6e. With its main body firmly attached, the end effector magnets are disengaged, and the limb is ready to be extended again. These steps can be repeated consecutively to scale large vertical distances.

To transition onto a roof or ledge, EEWOC first extends its limb, then bends it to place its gripper in contact with the top surface as depicted in Fig. 7. The limb can then be retracted to pull the main body up and over the edge of the roof, with the wheels providing additional assistance.

To transition around a corner, EEWOC rotates the belly gripper while attached to the wall. The limb then extends past the corner, as depicted in Fig. 8. The limb then bends to place its gripper on the next wall, and the magnets are engaged. Now, by releasing the belly gripper, the main body "swings" onto the next wall. An additional passive degree of freedom on the wrist yaw allows the main body to realign itself vertically with the wall from any arbitrary angle.

2.3 Upgraded EEMMMa Tape Spring Limb

EEWOC utilizes the latest version of the EEMMMa extending and bending robotic limb. This limb greatly extends the range

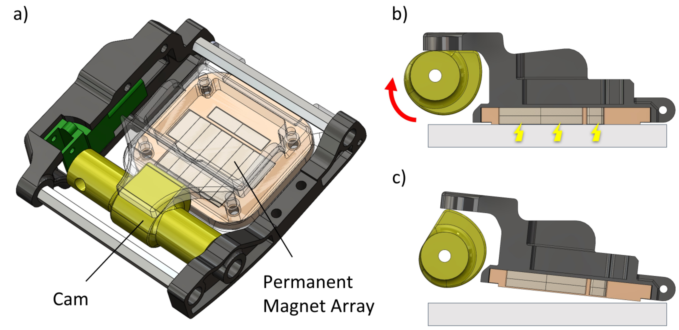

FIGURE 9: A) CLOSE UP VIEW OF EEWOC'S MAGNETIC GRIPPER. B) THE GRIPPER IN ITS ACTIVE STATE. C) THE GRIPPER IN ITS INACTIVE STATE, WHERE THE CAM HAS ROTATED TO PEEL THE MAGNETIC LEVER FROM THE SURFACE.

of available anchor points for EEWOC to grapple and move between. The tape is now a 1" (2.54 cm) wide STANLEY PowerLock tape, offering enhanced rigidity, and can now extend to up to 1.2 m (4 ft). The limb's better rigidity allows it to remain in a straightened configuration without folding at further extensions, and allows there to be additional mass at the end effector.

The original EEMMMa end effector has been significantly upgraded with additional features. It is now equipped with a small servo motor to actuate the braking function. The idler pulley has a ratchet feature that can lock its rotation when the servo-actuated pawl is engaged. This allows the spool motor to induce bending in the limb rather than extending it.

A second servo motor controls the wrist pitch, which allows it to orient the gripper towards a desired surface while bending around obstacles. The wrist also has a passive degree of freedom in yaw, but it does not include any passive degrees of freedom in pitch or roll to assist with aligning the gripper to the target surface. This is because the tape itself provides sufficient compliance to allow the magnetic gripper to easily align itself, which is further assisted by the magnetic attraction force.

Finally, the end effector now features a 6-DOF IMU that can be used to collect data on the end effector's rotation and acceleration. This data can be used to predict the end effector's position and orientation when it is extended away from the main body. This information is especially valuable when verifying whether an anchoring attempt was successful. Before transitioning between points, EEWOC can retract the tape spool gently to tug on the end effector. From this, the IMU data can show whether the magnetic anchor has firmly attached, or if it has slipped or otherwise failed.

Inside the tape spool module, the tension management system has been upgraded, with reduced size and weight. An additional wire spool feeds power and communications to the servos and IMU at the end effector.

2.4 Magnetic Gripper

EEWOC possesses two magnetic grippers: one on the end effector, and one on the underside of the main base structure. By attaching and detaching these consecutively to move between points, EEWOC can quickly climb metal structures. A detailed view of the gripper's mechanics is depicted in Fig. 9.

The magnetic gripper at the end effector allows EEWOC to utilize its long reach to grasp distant points. The other magnetic gripper (or "belly" gripper) is mounted on the underside of the main base. This gripper faces away from the center of the robot, pointing downwards towards the floor or outwards towards target surfaces. The belly gripper allows the main body to affix itself to its current location. Each gripper weighs 106 g, with a minimal mass design focus to reduce the amount of weight at the end effector.

EEWOC's magnetic grippers utilize an array of small neodymium permanent magnets that produce a large magnetic force. Each magnet is 2x4x10 mm and 32 magnets are placed inside a hinged lever arm that rests against a small cam. When the gripper needs to disengage, the cam rotates, causing the magnet-filled lever to peel away from the wall until the cam reaches its maximum radius. The magnets are inset at the far end of the lever arm, away from the fulcrum to maximize their distance from the surface while disengaged.

A small N20 DC motor with a worm gear drive allows the assembly to self-lock so that EEWOC can continuously remain in the desired active or inactive state. The cam also allows the magnetic force to be modulated by adjusting the clearance between the ground and the magnetic pad.

One of the gripper's major advantages is that the magnetic force assists with anchoring, since the gripper will automatically align itself to the surface. This eliminates the need for additional passive degrees of freedom at the wrist to orient the gripper. When the gripper approaches a target surface, the tape spring limb's natural compliance causes it to simply deform until the magnetic gripper makes contact.

Finally, the magnet array's outer edge is equipped with small strips of rubber to increase friction between the gripper and the target surface, which improves its ability to handle shear forces and prevent sliding.

2.5 Main Base Structure and Wheels

The main base structure contains all the electronics for power and communications. It also supports the primary shaft that the wheels and limb module rotate around. EEWOC has redundant degrees of freedom at this shaft that allow it to aim its major components relative to one another. By actuating both the arm pitch motor and the wheel motor at the same time, the main base can rotate to position the belly gripper towards a wall. By rotating the main base towards the wall, the system's center of mass moves closer to the surface, which is advantageous while climbing. This minimizes the pitch-back moment that could cause the robot to fall.

The EEMMMa limb module is connected to a brushed DC motor that allows its pitch to be controlled, aiming the limb up or down. It has a range of motion of 200°, which grants it enough range to be aimed towards surfaces that the wheels are in contact with. The belly gripper is connected to another brushed DC motor that allows the entire body to control its yaw angle when it is latched onto a surface. This combined with the pitch angle allows it to aim its limb towards any point in 3-D space.

The wheels are connected to another DC motor that allows them to drive either forward or backward. Only a single motor drives both wheels due to space and weight limitations. This means they cannot be used to steer the system, although the belly gripper's yaw motor can still be used to change direction on the ground. EEWOC's main design focus is to study the capabilities of the tape spring limb and climbing, with driving as a secondary feature. It should be noted that true steering capabilities can easily be added in the future with a small redesign.

FIGURE 10: SCREENSHOTS FROM EEWOC VERTICAL CLIMBING DEMONSTRATIONS.

To allow the main base to rotate itself freely, the wheels have a diameter of 260 mm. This is large enough to fully conceal the belly gripper when stowed, preventing the gripper assembly from skidding or grinding with the external surfaces. The wheel is wrapped with a 3 mm thick rubber strip to increase friction for driving and climbing. This also assists with impact mitigation when attempting to swing around corners. To further protect the system during impacts, the outer face of the wheel is equipped with a curved piece of delrin acetal plastic that acts like a spring to absorb side impacts.

A set of passive ball casters are mounted slightly behind the wheels to provide the system with static stability and eliminate the need for two-wheel balancing control. While climbing, the ball casters provide additional support against the wall to reduce the unwanted pitch-back moment that can cause the system to fall by peeling away from the wall.

3. TESTS AND RESULTS

In the following demonstrations, EEWOC shows its versatility as a mobile robot. With the ability to drive, climb, and bend around obstacles, EEWOC possesses a wide variety of 3D movement options in complex real-world environments. Tests were conducted on a variety of steel structures commonly found on commercial buildings and industrial spaces including walls, rails, ducting, pipes, and equipment. All demonstrations were

FIGURE 11: EEWOC STRAIGHT SIDEWAYS DEPLOYMENT DEMONSTRATION. THIS CAN BE USEFUL FOR TRAVERSING GAPS OR MOVING BETWEEN DISTANT FEATURES.

performed with simple open-loop control and manual input.

3.1 Climbing

To test its ability to scale vertical structures, EEWOC was subjected to a series of climbing trials on a flat steel wall. The first demonstration tested basic linear movement by sequentially extending and anchoring between points, as seen in Fig. 10. For each step, a safety test was performed before releasing the belly gripper. Successful anchoring was determined by gently retracting the tape and verifying that the IMU data showed no change. During trials, the gripper's magnets naturally pulled the end effector towards the wall, assisting the wrist pitch servo and eliminating the need to rotate the limb towards the wall for engagement. After this initial test, controlled descending was demonstrated by performing the climbing sequence in reverse to gently lower the main body to ground level.

As a final test, the belly gripper was rotated to deploy the limb sideways. This maneuver could be useful for passing windows or crossing gaps between buildings. In this orientation, the tape maintains its rigidity quite well while extended, thanks to its thickest dimension being in the direction of gravity. The gap distance that could be traversed using this method was limited however, since swinging too far a distance could cause the gripper to peel off from the wall. This is due to the main body's wheels no longer being in contact with the wall during the swing phase, and its weight results in a torque that peels the gripper away from the wall.

3.2 Bending to Climb Onto Ledge

To test basic maneuvers that involve bending, a ledge climbing test was conducted on the roof of a building. In this scenario, bending occurs in a single plane, with X_r, Y_r, X_e, and Y_e all lying in the same plane (refer to Fig. 5 for axes). Gravity provides a force in the Y_0-direction that draws the gripper closer to the surface, making engagement easier.

The limb was extended beyond the top edge of the roof, and bending was initiated to place the gripper on the top surface. With the magnetic gripper engaged, the limb was commanded to retract to let the main body ascend, with the wheels providing assistance. With the limb bent, its much lower rigidity and heavy load from the main body caused it to press against the corner of the ledge during the transition, which caused undesirable stress in the tape at that point. We are currently investigating a method to remedy this by partially activating the belly gripper to provide some attractive force between the wheels and the wall. This may create enough additional friction force to reduce the load carried by the tape during this maneuver.

FIGURE 12: EEWOC BENDING ITS LIMB TO PLACE THE MAGNETIC GRIPPER ON A TOP SURFACE, ALLOWING IT TO TRANSITION FROM WALL TO ROOF.

FIGURE 13: SCREENSHOTS FROM EEWOC CORNER TRANSITIONING ATTEMPT.

3.3 Bending to Transition to Adjacent Walls

While the previous demonstration only involved bending in a single plane, bending around corners is much more complex due to the development of a 3D fold. While folded, the tape spring limb possesses different stiffness properties that makes it more susceptible to out-of-plane displacement. While reaching around a corner, the gravitational force in Y_0 is no longer coplanar with the other frames, causing the end effector to displace slightly in Y_0. The resulting 3D fold is difficult to control and account for, but will explored more in-depth in future work.

Similar to the ledge climbing scenario, the limb was first extended sideways beyond the edge of the corner. Then limb was then bent to place the gripper on the adjacent wall and the end effector gripper was activated. The belly gripper was released, resulting in the robot "swinging" towards the new wall as the main body falls.

While EEWOC could successfully bend and place the gripper on an adjacent wall, it was unable to perform a successsful transition. The swinging maneuver requires significant air time, during which the main body is supported only by the end effector gripper. Without the wheels contacting any surface, the main body's weight applies a torque on the gripper that causes it to peel back away from the wall and the system to fall. In ongoing work, we are developing improved maneuvers to transition around corners with continuous wheel contact. This can potentially be done with the previously mentioned partially activated magnetic gripper method. A gripper housing redesign may also help distribute loads enough to counteract the pitch-back torque and allow the gripper to maintain hold.

4. CONCLUSION AND FUTURE WORK

In this paper, we detailed the design and preliminary capabilities of EEWOC, a novel compact and lightweight mobile robot that can travel freely along ferromagnetic 3D surfaces. The extending and bending capabilities offered by the unique tape spring limb combined with wheels grant EEWOC a versatile set of movement options in highly unstructured environments. EEWOC was shown to be capable of climbing up vertical metal structures, hoisting itself onto roofs, and reaching across gaps and obstacles. These abilities make it very well suited for use in environments with complex metal features such as buildings, ships, factories, and power transmission towers.

EEWOC's capabilities can be further explored in future work to improve its maneuverability. First, the IMU data will be used in future experiments to study the end effector's behavior during maneuvers. An additional IMU can potentially be added on the main base structure to track relative movement between the end effector and main body. This will allow us to study EEWOC's swinging behavior during transitions.

We are currently re-examining the roof transition maneuver, and are hoping to utilize the belly gripper to support some of the body weight to reduce the load on the tape as it lifts. The gripper's cam design allows the magnetic force to be modulated by rotating the cam to a different radius. This could allow us to grant the wheels enough friction force to offset the vertical load on the tape. We are hoping to use a similar method to allow corner transitioning between adjacent walls, using the partially activated belly gripper to maintain continuous contact with the walls during transition. Additionally, the end effector is currently being redesigned to reduce its thickness even further. This will reduce the moment arm from the weight of the main body and reduce the pitch-back torque that causes the gripper to peel away from the wall during swinging maneuvers. We are also currently testing simulated sample retrieval tasks to see how the limb responds to an external payload. A small ferromagnetic payload will be retrieved by the gripper either directly or after bending around an obstacle.

EEWOC also has several hardware upgrades currently in development. Since EEWOC was a proof of concept prototype, future versions will have a modified drive train for the wheels to allow the system to steer for better horizontal mobility. For other hardware upgrades, a lightweight microspine gripper is currently being developed to allow EEWOC to climb rough vertical surfaces such as cliffs and trees, and not be limited to just ferromagnetic structures. Future versions will also be equipped with a camera at the center of the gripper to see around corners and detect potential anchor points.

For controls improvements, the next step will be forming a closed-loop control structure for anchoring to new points and safely transitioning. If the camera is added to the end effector, EEWOC can use this new visual data with the IMU data to sense its current state and plan its next step. Closed-loop control will require a more detailed analysis of the tape spring bending behavior to form a better model of the limb's kinematics. As described in our previous paper, we are currently working on numerically or analytically characterizing the tape's large deflection and folded bending stiffness and rotation behavior.

The ultimate goal for this project will be to add multiple limbs to the system to move freely in 3D space. By deploying multiple limbs and anchoring to multiple points, the system could suspend itself in midair and not be limited to clinging to surface, able to move freely in 3D space.

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