Improving Grip Stability Using Passive Compliant Microspine Arrays for Soft Robots in Unstructured Terrain

Lauren Ervin, Harish Bezawada, and Vishesh Vikas[1]

Abstract— **Microspine grippers are small spines commonly found on insect legs that reinforce surface interaction by engaging with asperities to increase shear force and traction. An array of such microspines, when integrated into the limbs or undercarriage of a robot, can provide the ability to maneuver uneven terrains, traverse inclines, and even climb walls. Meanwhile, the conformability and adaptability of soft robots makes them ideal candidates for applications involving traversal of complex, unstructured terrains. However, there remains a real-life realization gap for soft locomotors pertaining to their transition from controlled lab environment to the field that can be bridged by improving grip stability through effective integration of microspines. In this research, a passive, compliant microspine stacked array design is proposed to enhance the locomotion capabilities of mobile soft robots. A microspine array integration method effectively addresses the stiffness mismatch between soft, compliant, and rigid components. Additionally, a reduction in complexity results from actuation of the surface-conformable soft limb using a single actuator. The two-row, stacked microspine array configuration offers improved gripping capabilities on steep and irregular surfaces. This design is incorporated into three different robot configurations - the baseline without microspines and two others with different combinations of microspine arrays. Field experiments are conducted on surfaces of varying surface roughness and non-uniformity - concrete, brick, compact sand, and tree roots. Experimental results demonstrate that the inclusion of microspine arrays increases planar displacement an average of 10 times. The improved grip stability, repeatability, and, terrain traversability is reflected by a decrease in the relative standard deviation of the locomotion gaits.**

I. INTRODUCTION

In nature, animals resist slipping and falling by increasing interaction with surfaces in a number of ways. Snakes maintain a large surface area in contact with the ground to increase the amount of propulsive force aiding in locomotion, and snake-inspired robots have been developed with textured skins for increased traction [1], [2]. In constrast, geckos utilize van der Waals interactions to provide an adhesive force against surfaces, and gecko inspired, synthetic adhesives attached to robots have been investigated on a range of surfaces [3], [4]. Insects such as caterpillars and cockroaches are able to climb vertical surfaces with small spines attached to their legs; these microspines increase shear force and traction by engaging with surface asperities. Many researchers have integrated synthetic microspine arrays into robots to enable maneuverability of uneven terrains, traversability of inclines, and climbing walls [5]–[12].

Integrating microspines into Soft Robots (SoRos) is an attractive option due to their adaptability and conformability to changing surface topologies.The continuum nature and impact resistance of soft materials passively allow SoRos additional flexibility and more effective interaction with complex and non-uniform surfaces. However, SoRos lack grip stability, contributing to them historically struggling with efficient locomotion as well as locomoting over unstructured terrain. Because of this, SoRo designs that can traverse outside and perform real tasks outside of a lab setting are under-researched. One of the main design challenges pertains to integrating a soft, low stiffness body with hard, high stiffness micropsines. A soft inchworm design attaches an array of microspines to either foot of the inchworm using adhesive bonding technology [13]. However, deeply irregular surfaces remain difficult to overcome due to the uniform distribution of the microspines and integration technique that restricts the usage to surfaces with regular, fine asperities. All this calls for need of compliance and independent movement per microspine to increase surface geometry traversability.

Contributions. The research addresses the real-world implementation gap by incorporating compliant microspines into the limbs of the Motor Tendon Actuated (MTA) SoRo, significantly enhancing grip stability and traversability across various terrains for mobile SoRos. The proposed single-material design with intelligent soft-compliant integration reduces complexity by using a single actuator to passively control an entire array fixed to the end of a soft limb. This research, (1) proposes a compliant mechanism, two-row stacked microspine array design that improves grip stability and increases traversable surface topologies of mobile SoRos; (2) identifies critical design parameters that improve locomotion capabilities while reducing complexity by controlling an entire microspine array with only a single actuator through intelligent soft-compliant integration; (3) investigates the grip stability and repeatability of a baseline SoRo compared against two different microspine array configurations on uniform concrete, partially uniform brick, granular compact sand, and non-uniform tree roots; and (4) experimentally concludes that the inclusion of compliant microspine arrays in SoRos increases planar displacement on all surfaces through enhanced surface engagement resulting in capabilities to traverse complex, unstructured environments.

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[1]Lauren Ervin, Harish Bezawada, and Vishesh Vikas are with the Agile Robotics Lab, University of Alabama, Tuscaloosa, AL 35487, USA {lefaris, hbezawada}@crimson.ua.edu, vvikas@ua.edu

II. MICROSPINE ARRAY DESIGN

The critical design parameters of the mechanism can be identified as (1) compliance of individual microspines and the angle of their interaction with a surface, (2) the array configuration of multiple microspines, and (3) effective rigid-soft integration with the robot body.

A. Compliant Mechanism Microspine Design

The single-material mechanism, shown in Fig. 1, allows compliance with an exposed joint while simplifying the fabrication process. It is fabricated out of TPU with 95A Shore hardness. Halfway through the additive manufacturing process, a microspine is inserted into a channel left in the middle of the mechanism, highlighted in Fig. 1c). Once finished, the angle of surface interaction, α, can be modified for different surface topologies if necessary.

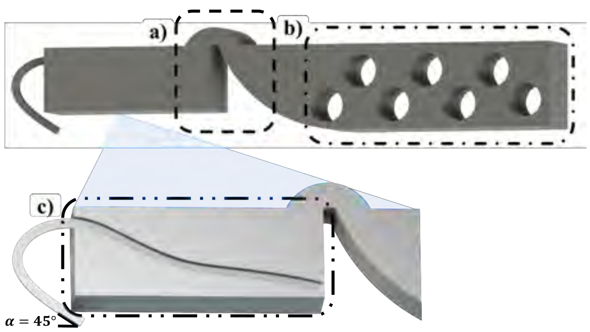

Fig. 1: Compliant microspine. a) A hinge joint enables passive compliance. b) Embedded holes facilitate mechanical integration into the soft limb. c) A rigid microspine is inserted in a center channel matching the spine topology set halfway into the mechanism with contact angle of $\alpha = 45°$.

B. Microspine Array Configuration

The array configuration ensures multiple microspines remain active on complex surfaces. The proposed design is a two-row, stacked array configuration consisting of ten microspines. It is observed that microspines on the bottom row are commonly active on more uniform terrain. The top row can become active on highly irregular surfaces without hindering the movement of the bottom row of microspines. Crucially, not all microspines need to interact with a surface for the microspine array to be effective, shown in Fig. 2. This is a byproduct of the passive nature and built-in redundancy.

C. Effective Soft-Compliant Integration Through Anchoring

The soft-compliant integration reduces design complexity by allowing each microspine to passively move independent of one another with a single actuator controlling the entire array configuration. To achieve this, a mold is created with channels for each mechanism at the tip of a limb. Half of the compliant mechanism contains holes that mechanically anchor it into the silicone limb, preventing it from being freely pulled out of the limb during microspine gripping. This anchoring method is essential for ensuring the microspine

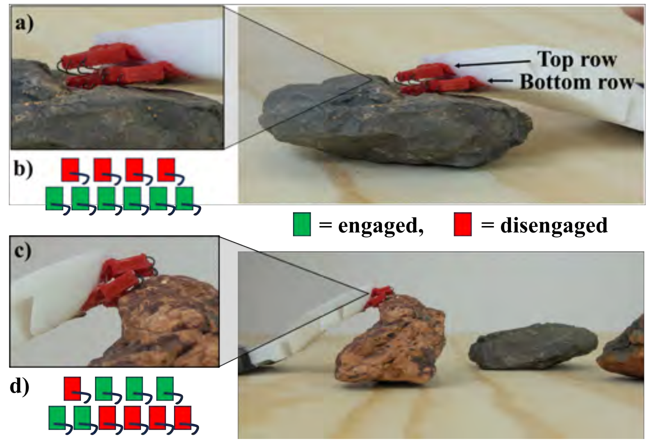

Fig. 2: Array configuration. a) Close-up of the microspines gripping onto a non-uniform rock. b) All six bottom row microspines are engaged (green) while the top row remains disengaged (red). c) Close-up of the microspines gripping onto a steeper rock. d) Two of the bottom row and three of the top row microspines are engaged with the surface.

does not come loose over time. The remaining, exposed half of the mechanism contains the microspine.

III. EXPERIMENTATION

A. Experimental Configurations

The baseline configuration with Zero Microspine Limbs, 0ML, is a three-limb MTA SoRo [14]. This is compared against 1) One Microspine Limb, 1ML, with the microspine array affixed to a single limb, and 2) Two Microspine Limb, 2ML, with a microspine array equipped on two limbs, shown in Fig. 3. The microspines are angled towards the surface opposite the expected direction of movement.

(a) 0ML (b) 1ML (c) 2ML

Fig. 3: Three robot configurations: a) baseline aqua SoRo; b) white SoRo with 10 microspines in an array on one limb; c) red SoRo with 20 microspines in two arrays on two limbs.

B. Experimental Setup and Field Experiments

The field experiments are performed on four surfaces of increasing roughness and unstructured nature - uniform concrete, partially uniform brick, granular compact sand with pebbles, and a non-uniform forest floor containing leaf litter and large tree roots. Three trials (60 push-pull gaits per trial) are performed for each configuration and surface, resulting in a total of 36 trials. A 36h11 family AprilTag from the AprilTag visual fiducial system [15] is attached to each limb to aid in tracking. The tracking algorithm code is available at github.com/AgileRoboticsLab/SoftRobotics-Microspines.

IV. RESULTS

The translation results of 0ML, 1ML, and 2ML are compared on four surfaces. Fig. 4 shows the average displacement and standard deviation of the three trials per SoRo.

The concrete surface is level with a uniform distribution of asperities. Here, both 1ML and 2ML outperform 0ML in terms of displacement. 1ML had an average displacement over 30× greater and 2ML over 10× greater than 0ML, respectively. 2ML was also the most consistent across trials.

The partially uniform brick contains gaps in between bricks that can catch microspines at random. Given the soft and deformable nature of the SoRo, the stuck microspines were always able to wiggle free, enabling continued movement. Both 1ML and 2ML had far greater average displacement than 0ML, roughly 25× and 18× more. This was the only surface where 0ML had the lowest standard deviation, which can be attributed to the other two robots randomly getting stuck when crossing the brick perimeters.

The granular, compact sand was not entirely level with various pebbles, holes, insects, and small sticks. The loose, granular top layer was easy to become partially submerged in with all three SoRos. Due to this, the average displacement is far lower on this surface. The two microspine limbs on 2ML seemed to dig itself deeper, resulting in average displacement of only 0.46cm and the lowest standard deviation. 1ML still outperformed 0ML with over 3× increased displacement.

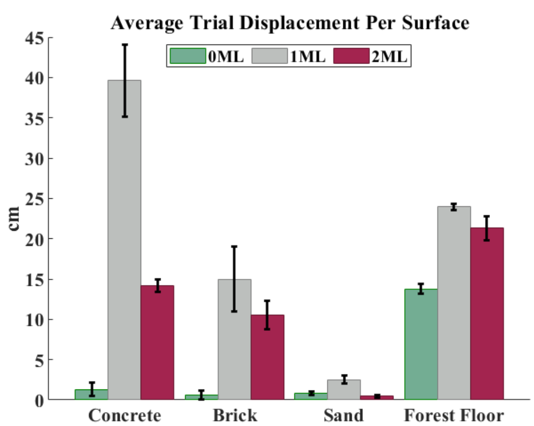

Fig. 4: The average displacement data per prototype and surface combination with standard deviation error bars.

On the unstructured forest floor, the SoRos first overcame a 4" tall tree root and then leaves and other tree debris. All SoRos successfully traversed over the tree root due to the conformable nature of the soft limbs.However, only 1ML and 2ML navigated through the thick tree debris afterwards; 0ML became stuck at the tree root base in each of its trials. This is exhibited in lower average displacement for 0ML than 1ML or 2ML. The forest floor was critical for testing as it was the most unstructured of the four experimental surfaces and showcases the benefits of the soft limbs paired with the added gripping stability of the microspine array.

The SoRos moved for 60 gaits for each of the trials, resulting in 720 gaits per robot. The consistency is analyzed by examining the 180 poses on a given surface per prototype, shown in Fig. 5a). The average displacement per gait $(\Delta X, \Delta Y)$ and standard deviation over all gaits per prototype/surface is visualized in Fig. 5b). Only the uniform/partially uniform surfaces were analyzed as the gait-to-gait movement is much less consistent otherwise. On concrete, the average gait displacement per gait of both 1ML (0.65cm,0.44cm) and 2ML (0.20cm,0.15cm) is greater than 0ML (0.07cm,0.06cm). On brick, both 1ML (0.22cm,0.19cm) and 2ML (0.13cm,0.15cm) outperform 0ML (0.02cm,0.01cm).

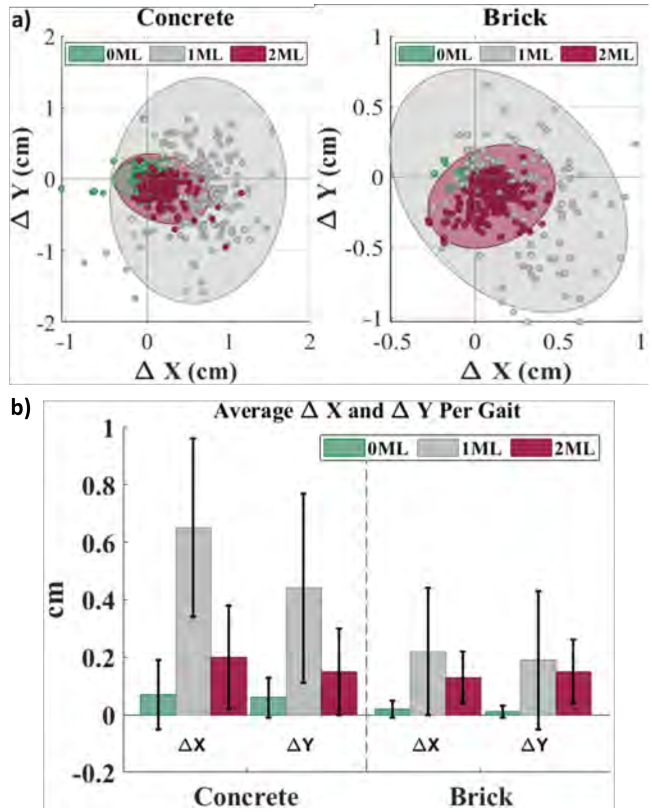

Fig. 5: Gait analysis. a) Every ΔX and ΔY position per gait on concrete and brick. b) The average absolute ΔX and ΔY displacement per gait on concrete and brick.

The relative standard deviation (RSD) on concrete is 135.96% for 0ML, 37.05% for 1ML, and 70.55% for 2ML. On the brick surface, the RSD is 159.94% for 0ML, 54.24% for 1ML, and 89.95% for 2ML. Both 1ML and 2ML have a significantly lower RSD than 0ML, indicating the microspine array provides both greater grip stability and repeatability.

Examples of a single trial of each prototype row on each surface column is visualized in Fig. 6.The starting and end points are green and blue dots, and the path of traversal is a red, gradient line. On all surfaces, 1ML interacts with the environment significantly more than the baseline 0ML, resulting in greater overall movement. On every surface except for compact sand, 2ML outperforms 0ML.

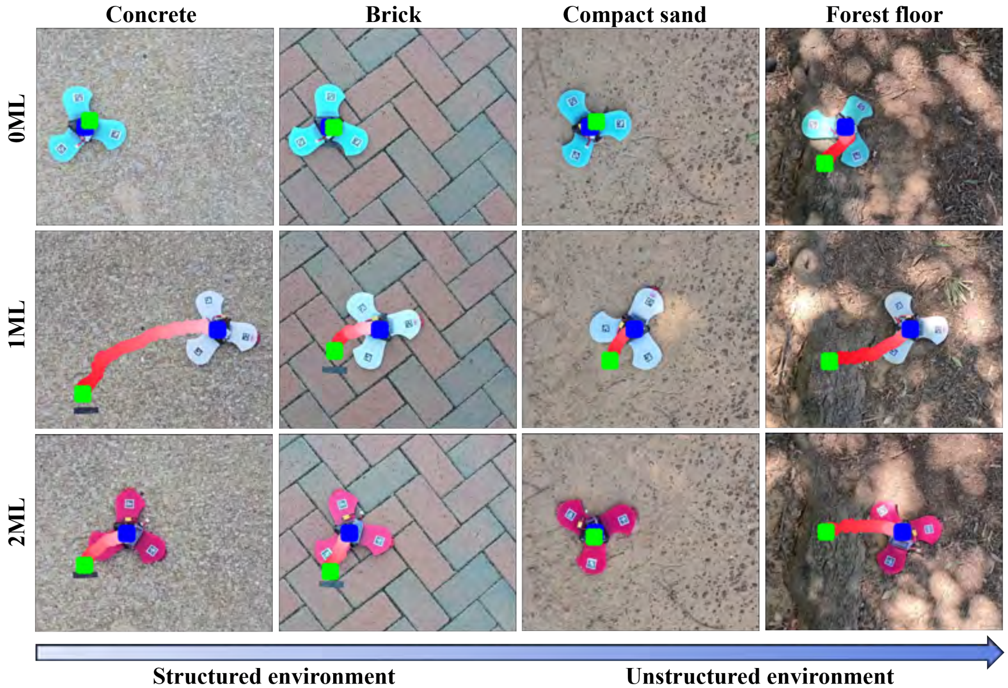

Fig. 6: Experimental results for 0ML, 1ML, and 2ML on concrete, brick, compact sand, and a forest floor. Rows represent the different surfaces increasing in unstructured nature with the three different prototypes distinguished by columns.

V. CONCLUSION AND FUTURE WORK

SoRos show immense potential with inherent conformability and adaptability, yet they lack adequate grip stability to overcome non-uniform surfaces. Improving environment interaction using compliant microspines is one of the missing pieces that will facilitate shrinking the real-life realization gap. The proposed compliant microspine resolves the stiffness mismatch through soft-compliant integration technique. The stacked array configuration enables the SoRo to maintain interaction when extreme surface discrepancies are present. The results from field experiments reflect the improved performance of two array configurations over a baseline SoRo on four different surfaces. Future work includes optimizing microspine array configurations for different surfaces, performing additional field experiments, and exploring the generalizability of the design to different prototypes.

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