Pinbot: A Walking Robot with Locking Pin Arrays for Passive Adaptability to Rough Terrains

Seonghoon Noh, *Student Member, IEEE* and Aaron M. Dollar, *Senior Member, IEEE*

Abstract— To date, many control strategies for legged robots have been proposed for stable locomotion over rough and unstructured terrains. However, these approaches require sensing information throughout locomotion, which may be noisy or unavailable at times. An alternative solution to rough terrain locomotion is a legged robot design that can passively adapt to the variations in the terrain without requiring knowledge of them. This paper presents one such solution in the design of a walking robot that employs pin array mechanisms to passively adapt to rough terrains. The pins are passively dropped over the terrain to conform to its variations and then locked to provide a statically stable stance. Locomotion is achieved with parallel four-bar linkages that swing forward the platforms in an alternating manner. Experimental evaluation of the robot demonstrates that the pin arrays enable legged locomotion over rough terrains under open-loop control.

I. INTRODUCTION

The mechanical design and control strategy for legged robots are often closely tied, giving rise to various maneuvering capabilities. Some recent legged robots such as the MIT Cheetah 3 [1] and ANYmal [2] feature the prominent universal-revolute leg topology. Thanks to the use of elaborate control methods necessitated by the high number of joints and actuators in these robots, they are able to achieve impressive dynamic maneuvers. In contrast, designs intended for more quasi-static locomotion have also enabled legged robot locomotion while allowing a simpler control approach, sometimes even open-loop. Notable examples of these include RHex [3], a hexapod robot with compliant, arched legs for rough terrain locomotion, and Sprawlita [4], a robot with pneumatically actuated prismatic legs and compliant hip joints.

One mechanism that has not yet been explored in legged robots is a pin array, but it has been briefly explored in a few other robotic applications. Perhaps the earliest robotic application of a pin array was a universal gripper concept named the 'Omnigripper' [5] in which two surfaces consisting of pin arrays are lowered onto an object to adapt to its top surface and then closed like a parallel gripper for grasping. A more recent adaption of pin arrays in a universal gripper was presented in [6]. In this universal gripper, pins with an elliptical cross section are arranged perpendicularly for jamming through relative rotation. The jammed pins then provide the necessary lateral force for grasping objects.

In mobile robots, a slightly different mechanism known as microspines, which are small, sharp tips with compliant
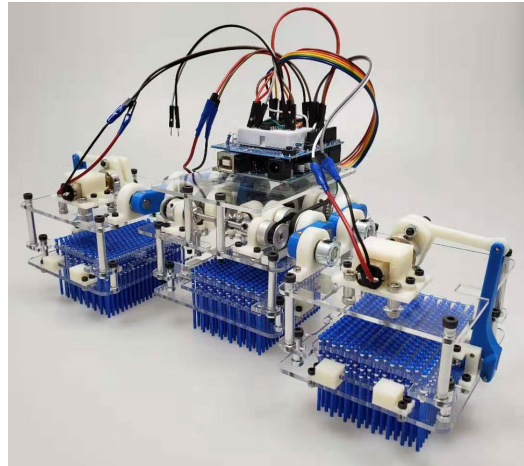
Figure 1. The walking robot standing with three pin arrays

flexures, have been used to assist in walking, climbing, and standing over rocky terrains in various situations. Kim et al. designed SpinybotII, a wall-climbing robot, with compliant microspines that engage the asperities on vertical, rough surfaces to cling without actuation and to climb while carrying a payload of its own weight [7]. Carpenter et al. have also utilized arrays of compliant microspines for locomotion over rough, vertical surfaces but in a rotary configuration as in a wheel [8]. Another variation known as a linearly-constrained spine mechanism also consists of sharp, needle-like tips but are constrained to prismatic motion and uses compression springs for compliance. Wang et al. used this mechanism to assist a human-scale robot in walking over rough terrains [9, 10]. Other unique applications of microspines include those designed by Parness et al. as anchors for the JPL LEMUR IIb robot for exploration and drilling in microgravity environments like asteroids [11] and microspines in a grapple created by Nguyen et al. for perching in aerial robots [12].

In this work, we present the design of a walking robot that uses pin arrays to passively adapt to rough terrains during locomotion. The pins are released to passively drop onto the terrain and are "locked" using a locking plate that applies a lateral force on them. The locked pins support a statically stable stance while other pins are moved forward via a parallel four-bar linkage in an alternating stance gait. We first discuss the pin array mechanism and its design parameters. We then present the locomotion mechanism and the corresponding locomotion strategy. Lastly, we demonstrate the pin arrays' ability to passively adapt to rough terrains.

II. PIN ARRAY MECHANISM

A pin array in this work is a set of densely populated prismatic joints whose stroke is unactuated and is specified by the pins' contact with the environment or lack thereof, i.e.,
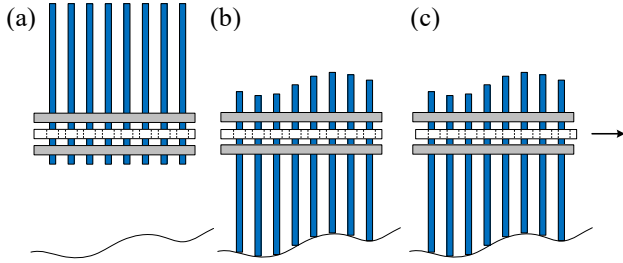
Figure 2. (a) A pin array in swing phase hovers over a rough terrain. (b) The pins are released to fall under their weight and passively adapt to the terrain. (c) The locking plate (white) is pulled horizontally to lock the pins.

resting on a surface or being suspended in air. Instead, the actuation in a pin array mechanism locks the pins such that their stroke remains fixed. By passively dropping onto and conforming to the terrain rather than being actuated by a motor or a spring, the pin arrays achieve passive adaptability and thus reduce the likelihood of postural disturbance due to ground reaction forces. Moreover, the pins' vertical, prismatic orientation suggests several favorable attributes for legged locomotion such as constrained vertical linear motion for obstacle clearance and minimal horizontal forces.

A. Pin array locking mechanism

The pin locking strategy in this work embodies a principle similar to that of other material jamming mechanisms seen in variable stiffness robots. One notable example is the universal gripper based on granular jamming by Brown et al. [13]. Follmer et al. and Stanley et al. have used particle jamming to modulate the stiffness of tactile user interfaces [14, 15]. Kim et al. used layer jamming to create a variable stiffness mechanism for applications in minimally invasive surgeries [16].

In contrast to these jamming mechanisms which constrain continuous or discrete, adjacent bodies, the pin array locking mechanism must constrain discrete, separated bodies. The mechanism must also be able to exert a sufficient force parallel to the pins to support the weight of the robot. Since the pins will have different strokes when standing on a rough terrain, the locking mechanism must not be dependent on the pins' length. Such mechanism would confine its motion to a plane perpendicular to the pins' motion.

A one degree-of-freedom locking mechanism may consist of numerous, coupled components that individually constrain the pins or a monolithic component that can affect the pins simultaneously. The former can quickly result in a complicated design since the pins are expected to be compactly placed. As for the latter, an appropriate, monolithic component already exists in a pin array assembly: the pin array support plates. Therefore, a pin array support plate can be added to jam the pins by applying a lateral force on the pins to lock them via friction.

The locking mechanism that translates this locking plate is a six-bar rocker-slider linkage, shown in Figure 3 and is driven by a small DC motor. The two additional links in comparison to a typical four-bar rocker-slider linkage allow the motor to be placed above the pin array. At one end of the rocker's motion range, the locking plate ideally is perfectly aligned with the other two pin array support plates that lie above and below the locking plate. At the other end, the locking plate is displaced with respect to the other two support plates and is jamming the pins.

While this is a function generation problem in linkage synthesis, it is sufficient to create a linkage that has the following characteristics because only the two ends of the motion range are of interest. The transmission angles across the linkage should seek to maximize the locking force when the slider link is approaching the locking configuration. The motion range of the slider link

Figure 3. The six-bar linkage for locking. A DC motor actuates the input link (orange) to translate the locking plate (green) and jam the pins.

should be great enough to contact as many pins as possible. Given these conditions, the lateral force on the locking plate is approximately multiplied by the mechanical advantage of the lever colored in cyan in Figure 3.
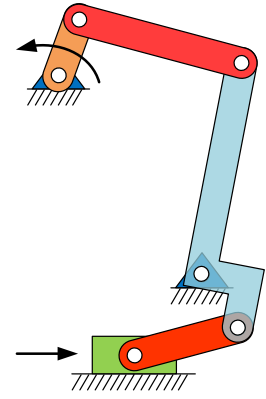
B. Pin array density

The density of the pin array primarily affects the pin arrays' ability to support the robot's weight and to passively adapt to terrains. As described previously, the pins are jammed by a locking plate that is actuated to move laterally against the pins, and the resulting frictional force locks the pins. This locking method induces a double shear stress on the pins. Assuming that the locking plate and the pins are perfectly perpendicular and that the shear stress is evenly divided between the two shear planes, the shear stress in a single shear plane for each pin is given by

$$\tau = \frac{F}{2N\pi r^2} \qquad (1)$$

where F is the lateral force applied by the locking plate, N is the number of pins in the array, and r is the radius of the pin.

Clearly, the minimum locking force to support the robot weight depends on the coefficient of friction between the locking plate and the pins. For a given coefficient of friction, the locking force should be sufficiently high to prevent the pins from slipping but not too high that the pins fail in shear. Calculating this range of allowable forces can be difficult since not all pins will experience the same force due to variations in their pose upon locking and/or variations in the locking plate. Also, simply using a stronger pin material can unnecessarily increase the total weight, which in turn increases the required locking force. Therefore, a high pin array density is required to use a light pin material and to distribute the shear stress among the pins supporting the robot's weight.

One consequence of a high pin density is the likelihood that some pins will not lock at all. Since the force exerted on each pin is approximately proportional to the amount of axial misalignment between the holes in the fixed support plates and the moving locking plate, not all pins will have enough friction to support their own weight. Thus, these unlocked pins will not share the shear force nor will they support the weight of the robot. The minimum force the locking plate must apply on the

pins to support the robot's total mass, m, is dependent on μ_s, the coefficient of static friction between the locking plate and the pins. Therefore, the average minimum shear stress in a shear plane of a locked pin is

$$\tau_a = \frac{mg}{2n\mu_s\pi r^2} \qquad (2)$$

where n is the number of actually locked pins.

III. LOCOMOTION

In this section, we develop the design and control strategy for a walking robot that can achieve locomotion under open-loop control by leveraging the passive adaptability of the pin array mechanism. The walking robot in this work adopts a statically stable gait to accommodate the locking speed of the pin array mechanism prototype and to evaluate its performance without requiring a complex control method. We discuss how multiple pin array mechanisms can be combined and coordinated to achieve rough terrain locomotion.

A. Pin array layout

The layout and the number of pin arrays must be such that the robot can maintain stability during locomotion, so we look to a stability metric for selecting the configuration. Several stability metrics for legged robots have been previously proposed, but two prominent metrics include the stability margin proposed by McGhee and Frank [17] and the energy stability margin proposed by Messuri and Klein [18]. Without a priori knowledge of the terrain and with countlessly different types of terrain, the design of the pin array layout can only be guided by the stability margin by assuming a flat terrain for now. However, the importance of the energy stability margin will become more apparent when the locking mechanism of the pin array is evaluated.

The stability margin is the perpendicular distance between the robot's center of gravity projected onto a horizontal plane and an edge of the support polygon, a convex polygon created by the robot's ground contacts. The energy stability margin extends the stability margin to uneven terrains and is the energy required for the robot's center of gravity to rotate over the corresponding edge of the support boundary, a 3D convex hull formed by the footholds. The energy stability margin is as follows

$$S_E = mg|R|(1 - cos\theta)cos\psi \qquad (3)$$

where R is the vector from the midpoint of AB, an edge formed by two adjacent footholds to the robot's center of gravity and θ and ψ are the angles by which R is rotated to lie in the vertical plane and to align with the vertical axis respectively.

Although legged robots with statically stable gaits typically have at least four legs, we desire to keep the pin array layout and the required locomotion mechanism as minimal as possible. Therefore, we select the pin array layout from three candidate configurations: two, three, and four pin arrays. By representing a pin array as a rectangular arrangement of pins, the support polygon of the robot can be found as a polygon consisting of the outermost corner pins in stance phase. Furthermore, with a predominantly symmetric pin array assembly, the center of gravity for each pin array can be approximated to be at its centroid, and the robot's total center of gravity can be easily determined.

First gait phase   Second gait phase

● robot center of gravity   ● pin array center of gravity
—— stance phase pin array   – – – swing phase pin array
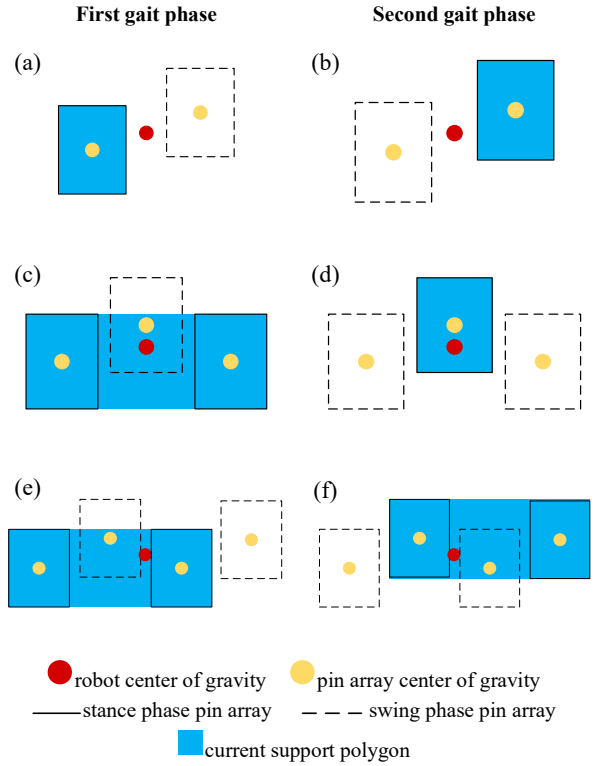■ current support polygon

Figure 4. Top views of three possible pin array layouts and their support polygon during the two gait phases. The two pin array layout (a, b) cannot maintain static stability whereas the three (c, d) or four (e, f) pin array layouts can always be statically stable.

Figure 4 contains diagrams of the robot support polygon before and after the stance switching for three different layouts that are joined by some abstract locomotion mechanism not illustrated. A suitable layout should use the minimum number of pin arrays while keeping the projected robot center of gravity within the support polygon. It is clear that the design with two pin arrays presents the classic control problem of a bipedal robot, for which additional bodies must be controlled to balance the robot. Therefore, this configuration is not a feasible design for a statically stable locomotion. The designs with three and four pin arrays can both maintain static stability at all times, but the former is chosen to keep the robot design minimal.

B. Locomotion mechanism

Unlike common leg mechanisms in legged robots, a pin array mechanism cannot accomplish locomotion alone since the pins can only move vertically. However, the pin array walker is by no means the first to require a separate locomotion mechanism. Ambler, a large six-legged robot, rotated its vertical, prismatic legs in the body plane for locomotion [19]. Another locomotion strategy is to horizontally translate one frame or platform forward while keeping another in stance in an alternating manner. This method was adopted by a planetary rover prototype dubbed the "walking beam" developed by the Martin-Marietta Corporation, which regrettably does not have a citable publication, and by another legged robot from our previous work [20].

However, unlike these aforementioned legged robots, the pin array walker does not have the ability to retract its legs, the

pins, once they are released, so it requires an upward motion during the gait cycle to allow the pins to clear any obstacles in front of them. Therefore, a parallel four-bar linkage is used to join each of the two side pin arrays to the center pin array. The linkage rotates half a revolution and then stops to allow the side and center pin arrays to switch their gait phase, as shown in Figure 4. The parallel four-bar linkage was chosen for its simple design and actuation that can provide the cyclical motion needed for an alternating gait.

The length of the two rotating links in the four-bar linkage determines the required input torque for locomotion, the stride length, and the maximum obstacle clearance height. It also affects the stability margin of the robot because the robot's center of gravity can approach or cross over the edges of the support polygon during locomotion. Without strict performance requirements, the design of the locomotion mechanism was guided by the motor's available torque and the stability margin of the robot at its designed scale.

C. Gait cycle

Because the prismatic motion of the pins is unactuated and the robot begins its locomotion with its pins pushed in, the pins must be allowed to fully release initially such that subsequent half revolutions of the linkage will continue to allow the pins to drop fully and utilize their full length. Therefore, the linkage first rotates from a horizontal configuration to an angle less than 180° to allow maximum extension of the pins. This angle can be quickly found based on the length of the pins at maximum extension, the kinematic parameters of the parallel four-bar linkage and the robot's design parameters. To minimize the impulse on the pin arrays during switching due to impact with the ground, the angle should allow the pins to fully contact the ground.

IV. Robot Prototype

The robot consists of three pin arrays that are joined by two parallel four-bar linkages that enable locomotion. The pin arrays are made from commercially available plastic pins and laser-cut acrylic sheets for a convenient manufacturing process. A small DC motor actuates each locking linkage. The side pin arrays have a small counterweight to balance the weight distribution due to an asymmetric design. Maximum retraction and extension of the pins are determined by the height of the top plate and the three lower plates of the pin
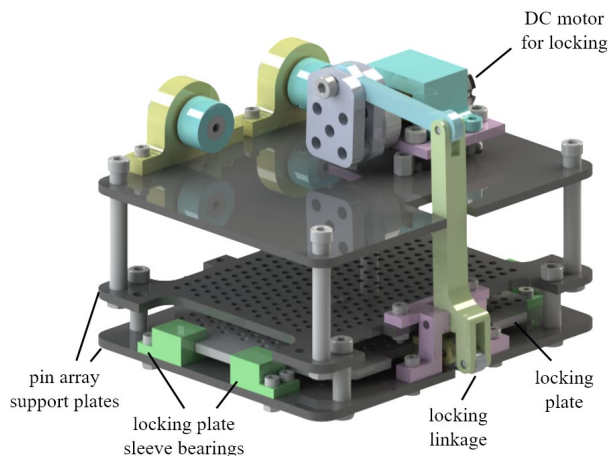

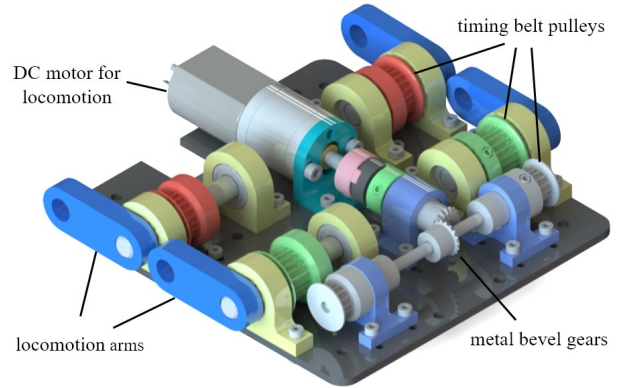Figure 5. A rendering of a pin aray assembly

Figure 6. A rendering of the locomotion mechanism

array assembly respectively. In this prototype, only about half of the pin's total length is usable for passively adapting to the terrain, which is about 0.96 inches. The mass of each side pin array and the center pin array is 149 grams and 521 grams respectively, totaling in 819 grams.

The actuation unit for the locomotion mechanism is located on the center pin array. Timing belts couple the rotation of the parallel links in the four-bar linkages to ensure continuous motion past the singularity, and a metal bevel gear train drives the two linkages. The length of the rotating links in the linkage gives a stride length of 23 mm. Each pair of adjacent pulleys has its own timing belt, and the timing belts are tensioned by sliding out the outer pulleys. Deflection of the acrylic base due to the belt tensioning is reduced by reinforcing it with aluminum bars.

L293D H-bridge chips on an Arduino prototype shield are used for the motor control. Position control of the DC motor for locomotion is implemented with a PID controller on an Arduino Uno. The PID control's command is limited to a maximum value to maintain a quasi-static locomotion. Due to the resulting low angular speed of the DC motor, the integral term is also limited to a maximum value to prevent integral windup. The small DC motors for the locking linkages are actuated to stall and then turned off to avoid damage. The robot is powered with an external, benchtop power supply.

V. Evaluation

A. Pin array mechanism

We first evaluate the pin array's locking mechanism and its implications on the stability of the robot. Because the diameter of the pinholes in the support and locking plates dictates whether the locking plate can contact every pin with a sufficient lateral force, numerous fabrication iterations (all using a laser cutter) were required to improve the uniformity of the locking force distribution while minimizing the friction on the pins during the release. Despite these iterations, only a portion of the pins could be locked.

Figure 7 shows an image of a locked pin array after it was oriented upside down to allow the ineffectively locked pins to slide out. For every locked pin array, there often were alternating rows of locked and unlocked pins, resulting in a higher average shear stress in the locked pins. This may be attributed to the arrangement pattern of the pins on the plates.
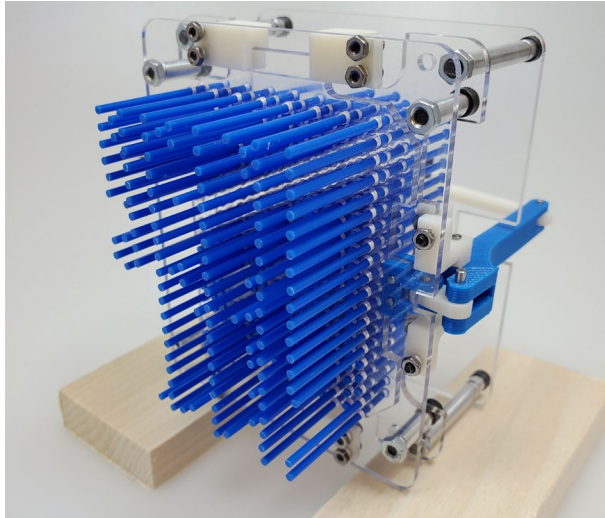
Figure 7. A bottom view of a locked pin array after being rotated upside down to check for unlocked pins. The pins extending out towards the viewer are the locked pins.

It can also be observed in Figure 7 that not all of the four corner pins, or even their adjacent pins, are locked. This shows that the support polygon of the robot is not constant and often smaller than the theoretical support polygon.

Several factors contribute to this observation in the pin array mechanism. The aforementioned tolerance in the pinhole diameter necessary for allowing all pins to release smoothly creates enough gap between the holes and the pins such that the pins can have random angular misalignments with respect to the vertical plane. Thus, the lateral locking force on each pin is not completely perpendicular to its side, which produces different frictional forces on the pins. The tolerance also creates differences in the axial misalignment of the pinholes, which affects the lateral force exerted on each pin.

The pin arrays' passive adaptability to arbitrary features can be observed in Figure 8, in which a pin array stands on rock-like objects and on human fingers. In both situations, the pin array was simply placed over the objects and locked. Because the motion of the pins induces a negligible amount of ground reaction force, postural stability is maintained regardless of the terrain features. Applications for the pin array's passive adaptability can range from standing on numerous, small asperities to maintaining a stable foothold on a non-flat surface. Of course, this does not consider the frictional forces necessary to maintain a fixed ground contact, which will be discussed in the next section.
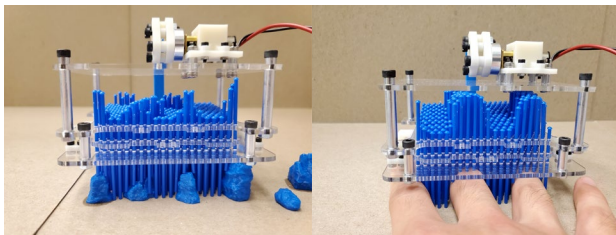

Figure 8. Side views of a pin array passively adapting to rough, rock-like features (left) and a human hand (right).

TABLE I. MAXIMUM LOAD SUPPORTED BY A PIN ARRAY

Left pin array	Center pin array	Right pin array
1450 g	1050 g	1350 g

Quantitative evaluation of the pin array mechanism involved measuring the maximum load supported by different areas of the pin arrays: the four corner and center areas, each of which consists of about thirty pins. The pin arrays were locked at maximum extension and placed upside down. Calibration weights were placed directly on the pins in increments of 10 grams and then 50 grams over the corresponding region to determine the maximum load. For measuring the maximum load for an entire pin array, a thin, acrylic plate was placed over all pins to distribute the weight.

Table I reports the maximum load supported by each of the three pin arrays. The two side pin arrays supported a similar amount, but the center pin array supported much less. This may be attributed to the moment induced on the locking plate by the offset between the midplane and the plane of the locking linkage in the center pin array. This moment may have exacerbated the misalignment in the center pin array, reducing its effectiveness.

Figure 9 presents the measurements from the maximum load test as a visual representation of the locking force distribution discretized across the regions of the pin arrays. While the center regions could support loads comparable to the maximum measured in each pin array, some of the corner regions could only support a fraction of the maximum values or even none at all. This diagram reveals that an actual support polygon constructed from the convex hull of the pins is not representative of the robot's stability during locomotion even over a flat terrain.

Extending this comparison to the energy stability margin, one may recall that it quantifies the energy required to rotate and topple a rigid body over a given edge formed by two adjacent footholds. Whereas the energy stability margin captures the stability of a fixed robot configuration, i.e., rigid legs, the stability metric represented by Figure 9 is more conservative and accurate in that it shows the maximum force under which a region of the support boundary will be compromised. Thus, it may be useful to obtain an updated stability metric that also considers the reconfigurability of leg mechanisms such as a pin array.
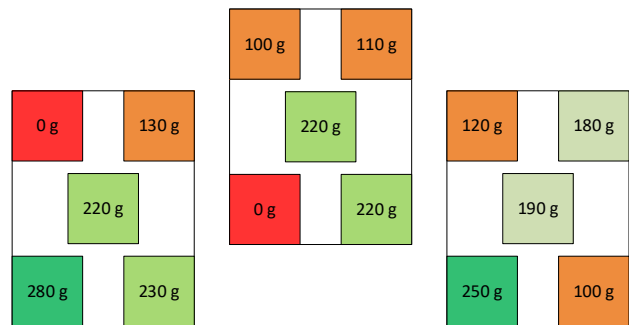

Figure 9. Maximum load supported by each region of the three pin arrays. The red regions consistently did not have enough locked pins to place a calibration weight over the area.
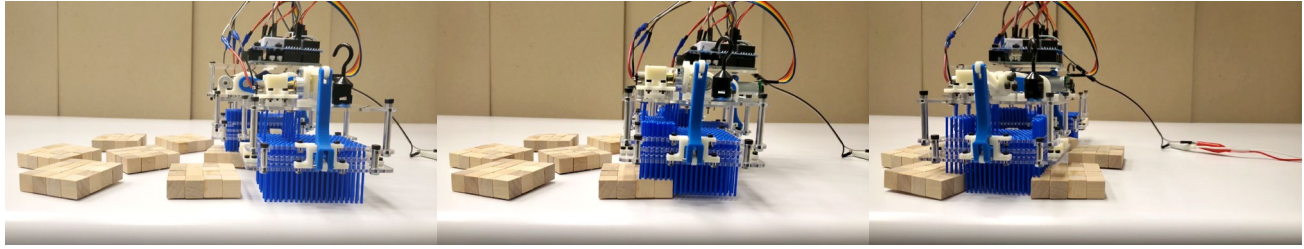
Figure 10. Views of the robot walking over wooden blocks. In the left image, the center pin array partially lands over a wooden block and adapts to the height difference between the its front and rear pins. In the center image, the side pin arrays are seen adapting to the wooden block in a similar manner. In the right image, the side pin arrays are standing between two wooden blocks.

B. Locomotion

The robot's ability to walk was tested over two terrains: a smooth, level terrain and a terrain with obstacles. In both situations, the robot used the same, fixed gait parameters and did not utilize any sensing or planning. By doing so, the tests highlighted the benefits of passive adaptability of the pin arrays in rough terrain locomotion.

The robot walked over the smooth terrain effortlessly and exhibited minimal changes in its posture. When walking over the terrain with obstacles, the robot benefited from the passive adaptability of the pin arrays to support its stance without any footstep planning. This can be observed in Figure 10 that depicts the robot's locomotion over wooden blocks with a nominal thickness of 0.5". In the left image, the center pin array has partially landed over a wooden block when it enters the stance phase. Despite the height difference between the front and rear parts of the pin array, the pins extend to different lengths according to the terrain. The center image provides a clear view of this behavior in the side pin arrays. The right image shows the side pin arrays standing in between wooden blocks to their front and rear.

During these tests, the pin array walker demonstrated the need for better traction and a method for adapting to changing slopes. The robot was occasionally observed undergoing undesired yaw rotation upon collision with the terrain. Depending on the type of asperities on the terrain, pins with sharper tips or tips with a friction material may be required. Also, the rotating motion of the locomotion mechanism imparted some horizontal velocity to the pins, sometimes causing them to deflect or jam with the terrain features. This either resulted in some postural disturbance or a yaw rotation.

VI. CONCLUSION AND FUTURE WORK

In this work, we presented the design of a walking robot that can passively adapt to rough terrains using pin arrays. The robot successfully maneuvered over obstacles and demonstrated high adaptability to various terrain features under open-loop control. Evaluation of the robot indicated that while the pin array walker can support several times its own weight, the uneven distribution of the locking force limits its stability and thus its locomotion performance.

The current proof-of-concept prototype is limited in its stride length, gait speed and payload carrying capability by the locking mechanism. The mechanism's effectiveness may be improved by adding a friction material such as silicone to the pinholes to increase the frictional force and by preventing unwanted jamming or slipping of the pins during locomotion.

A more effective pin array mechanism can provide a consistent support boundary like that of a fully-actuated robot, while maintaining passive adaptability, a useful trait in rough terrain locomotion. The results presented here also identified a need for a legged robot stability metric that can quantify the reconfigurability in robot legs, which could be a fruitful topic for future research.

The current design assumes there is no drastic change in the terrain's overall slope. To consider the problem of locomotion over changing slopes while adapting to smaller asperities, a more appropriate locomotion mechanism will need to be implemented. The design also lacks to ability to steer or control its yaw rotation, which is a necessary function for mobile robots. Optimization of the pin array size and density may be useful after material properties and other design parameters are finalized.

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