A systematic approach to creating terrain-capable hybrid soft/hard myriapod robots

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***Abstract*— Multi-legged animals (myriapods) such as centipedes move effectively in diverse terrain; flexible bodies and limbs allow them to morphologically adapt to the environment. To examine how the variation in body/limb forms of myriapods affect the mechanics and performance of terrestrial locomotion, we built a low-cost multi-legged hybrid (containing soft and hard components) robot which has 8 segments, each with two limbs driven out of phase. The back elements and limb pairs are driven by servo motors. Building on new theoretical results from geometric mechanics applied to myriapods, we systematically tested gait patterns with different leg contacts and body undulations on various laboratory and natural environments including flat and uneven rigid ground, stairs, and unstructured natural terrain (leaf litter, grass). On flat ground, the robot with rigid components moved in the same way as the theoretically predicted gaits. As the complexity of the environment increased, the robot's performance suffered (and theoretical predictions became unavailable) due to deleterious interactions like jamming of limbs. However, adding flexibility into the robot's body parts (legs, body joints etc.) improved the open-loop locomotion performance (often to levels of that on flat ground) by either reducing the effects of environmental disturbances or increasing stability. Our findings show that in order to produce an agile, robust locomotive device, we need to understand the importance of body morphology and complex, dynamic interactions between an organism and its environment through systematic experiments in both the laboratory and natural environment.**

I. Introduction

Limbs play an important role in the locomotion of animals, offering effective body support [1], enabling rapid maneuverability [2], [3] and facilitating obstacle crossing [4], [5] and climbing [6], [7]. Legged animals robustly adapt to and negotiate rough terrain with agility and stability that outmatches any human-built machine in natural environments [8]. This outstanding mobility has attracted the attention of robotics researchers [9]. However, there are many challenges that even the most advanced rugged terrain robot, BigDog, struggles with due to the complexity of discrete dynamic interactions between the feet and the environment [10]. Subtle variations in leg and body morphology and kinematics can lead to substantial differences in performance [11]. Furthermore, interactions between unpredictable obstacles sometimes lead to deteriorating locomotor performance and eventual total locomotor failure. For many situations, selection of a suitable gait requires an appreciable modeling and control effort for

This paper has supplementary downloadable material available at http://ieeexplore.ieee.org, provided by the authors. This includes a multimedia AVI format movie clip, which show demonstrations of our device.

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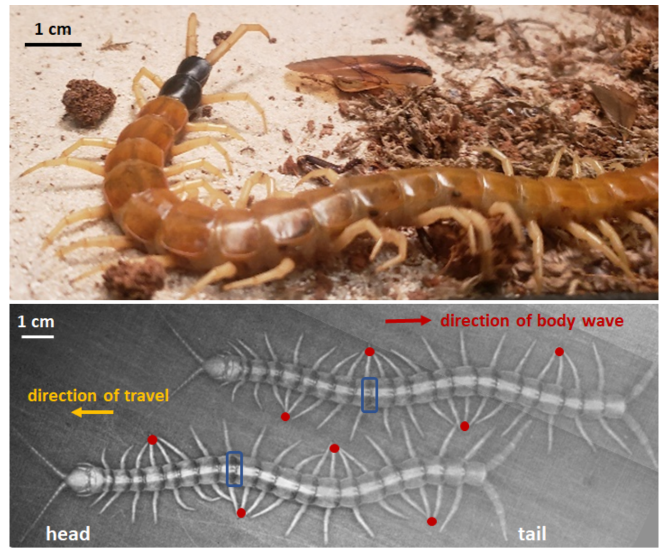

Fig. 1. **Centipede locomotion on rough and flat terrain.** (top) Black-headed centipede (*Scolopendra heros* (∼20 cm) moving on a cluttered environment (courtesy of J. R. Mendelson III), (bottom) Snapshots from the experiment that show body undulation and leg contacts. The North American centipede (*Scolopendra polymorpha*) is locomoting on a flat terrain with a retrograde body wave (propagating in the opposite direction of movement). Red dots show the points of contact with the ground. The blue rectangle on the body shows the same point on the body for the two images. (by the courtesy of A. Carruthers)

improvement of mobility with legs in unstructured environments [12]–[15].

To overcome challenges associated with locomotion over unstructured terrestrial environments, researchers have begun to use soft, often elastic components in robotic systems [16], [17]. Robots made from soft, elastic materials offer unique opportunities in areas in which conventional rigid robots are not viable. They are adaptable to the environment; however, they are hard to model and control, floppy, slow, and the locomotion is limited to specific environments [18].

Hybrid systems that combine the advantages of soft and hard components are expected to be more natural in their movements and generally more adaptable and robust in cluttered environments [19]. RHex is the first autonomous hexapod robot that has remarkable terrain capabilities with passive compliant legs [20]. The Sprawl family robots consisting of passive compliant joints and pneumatic actuators can navigate over unstructured terrain with a simple open-loop controller without sensory feedback [21]. The gecko-like robot, StickyBot, climbs smooth surfaces using compliant toes with a directional adhesion [22] that can

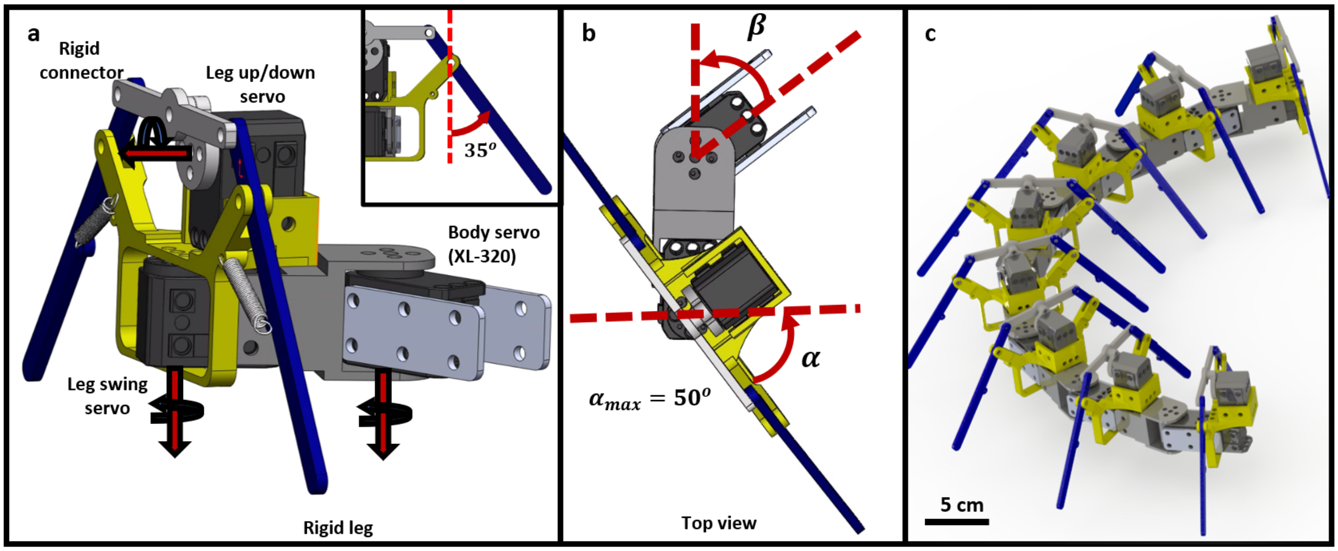

Fig. 2. **Robophysical model of a centipede.** (a) CAD diagram of the segment of the robot. The legs (blue) are out-of-phase and their up/down and for/aft positions are controlled by two different servos (XL-320). Body servo controls the lateral undulation of the body. Body angle and legs are coupled to each other. Inset shows the neutral angle (35^o) of the leg. (b) Top view of the segment that shows body angle, β, and leg for/aft angle, α. (c) CAD diagram of a segmented 3D-printed multi-legged robot developed to model the locomotion of centipede.

adapt to curved surfaces. A few recent robophysical studies have shown promising results in which biologically-inspired passive mechanical design features improved individual maneuverability and robustness in arthropods [23]–[27]. For example, inspired by the flexibility and adaptability of cockroaches Jayaram [23] designed a SCM manufactured palm-sized robot [28] that can splay its legs outward when squashed and covered it with a low friction plastic shield similar to the wings covering the back of a cockroach. The compliant exoskeletal flexures of the robot can compress and absorb impacts and collisions on the body and provide flexibility in confined environments, which is critical for real-world applications such as search-and-rescue in rubble. Minimalist robotic models have provided powerful platforms for testing biological hypotheses about mechanical design and movement control strategies [30], [31]. To investigate how passive compliance of the body parts (legs, spine etc.) could improve the motion agility in a variety of environments (including rough terrain, hard ground, obstacle climbing etc.) we take a robophysics approach [30], [31] and designed a robophysical model with morphology representing the simple version of a multi-legged locomotor. Our biological model, a centipede, is a terrestrial soft-bodied multi-legged animal that moves using synchronized movements of the body wave and legs [8], [32] (Fig. 1a-b). By the mechanical limitations and facilitation provided by the skeleton and muscles, centipedes produce a wide range of agile locomotory behavior including undulatory motion in diverse environments [8], [32]. The robophysical model allows us to systematically explore performance over a range of movements, including those not used by our biological model. We implemented flexible elements to the robot to best match the morphological characteristics of a centipede. These mechanical changes improved agility on challenging surfaces without adding sensors or changing the control system. We tested the performance of the robot with gaits obtained by a mathematical model which relies on the framework of geometric mechanics [33]–[37]. Our modeling approach allows us to understand the underlying mechanisms in the locomotion of biological systems and certain aspects of performance related to the coordination of legs and body. Our findings suggest that proper leg-body coordination can enhance the locomotion performance and that increasing the spatial wave number (leg phase shift) of the leg wave can improve the centipedes' capability crossing rough terrain.

II. Materials and Methods

A. Robophysical Model

A better understanding of degrees of freedom (DOFs) in centipede kinematics can aid in designing a simple robot with fewer joints that are capable of mimicking its biological counterparts. Centipedes have a segmented, flexible body with paired appendages on each segment (see Fig. 1). The legs substantially elevate the body and play an important role in maintaining the body's balance while moving in a variety of environments. Coordinated with the retraction/protraction times of the limbs the body segments actively undulate in a transverse horizontal plane [8], [32], [38].

We designed the robophysical model of a centipede by considering three main DoFs: forward/backward and upward/downward motions of the legs and lateral undulation of the body. To simplify the mechanical system and reduce the number of actuators, which can be costly in terms of energy and fabrication time, we coupled the horizontal and vertical motion of two legs on a segment with rigid connectors. The leg to body connector (yellow part in Fig. 2a) has angled pivot joints for the legs and connects the leg up/down servo to the leg swing servo. The mechanism that controls the vertical

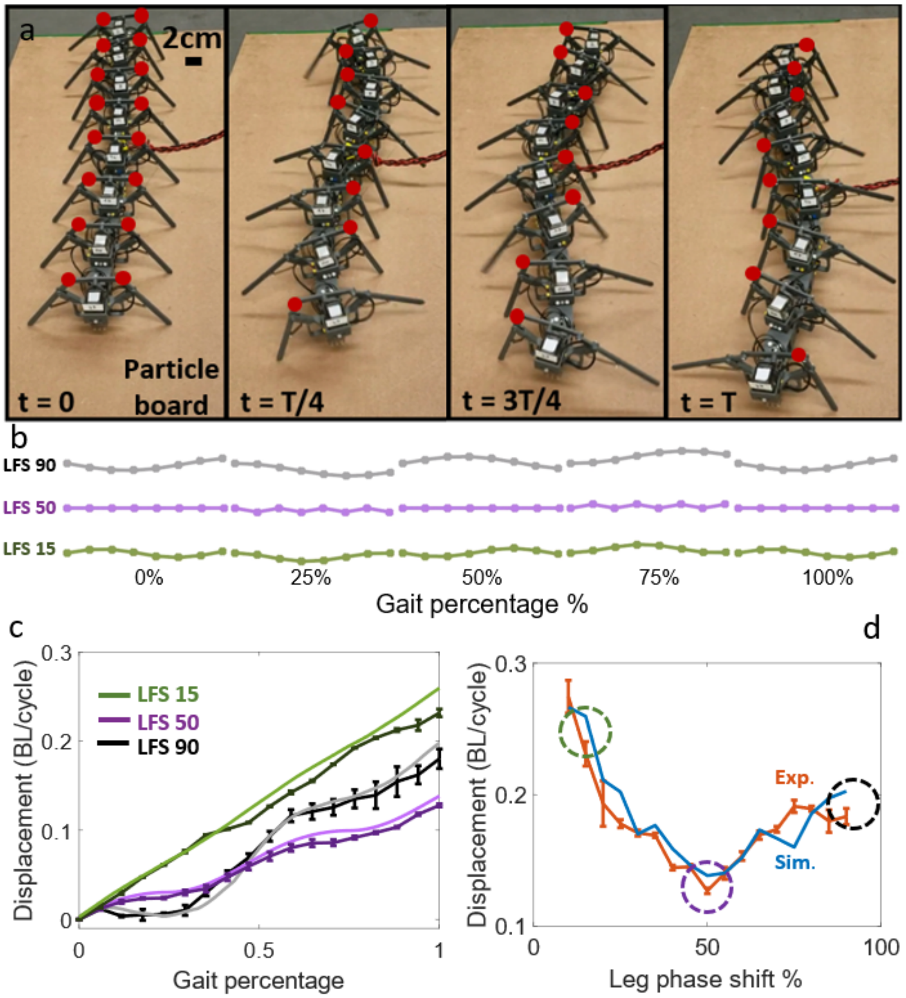

Fig. 3. **Experimental and simulated results on flat hard ground (particle board).** Description of gait patterns. (a) Extension of Hildebrand quadruped gait definition [29] to multi-legged locomotion. The gait is defined by two variables: leg phase shift (LFS) and duty factor. Snapshots from the experiment (LFS 15 % and duty factor 50% of a period T) on a particle board. Red dots show the legs on the ground. (b) Body curvature of the robot as a function of gait percentage for LFS 90 (green), 50 (purple) and 15 % (gray). (c) Example simulated (light) and experimental (dark) CoM trajectories of the robot for LFS 90 (green), 50 (purple) and 15 % (black). (d) Simulated (blue) and experimental (red, averaged over 5 runs/3 cycles) displacement (BL/cycle) of the CoM with fixed duty factor (50%) for LFS from 10 to 90 % on a flat particle board.

motion of the legs is similar to the four-bar mechanism, the hip joints are hinged to each other using a rigid 1DoF revolute joint which is connected to the leg up/down servo whose rotation axis is parallel to the anteroposterior line. The legs can lift up to 35^o from their neutral position which corresponded to maximum lift, about 4cm above the ground. The vertical distance of the pivot joints from the ground is chosen so that the leg with a vertical hip height, h_{leg} = 8.5 cm, can provide enough leverage from the ground. The neutral angle of the leg (see inset of the Fig. 2a) can be modified according to desired body posture by changing the length of the rigid connector between legs. The lateral body angle, β, is actively controlled by a servo. The final design of a segment (length = 9 cm) with three servos is given in Fig. 2a. This modular design allows us to change the number of the segments (and legs) of the robot easily, which has important implications for the understanding of the locomotor mechanics and evolutionary morphology of multi-legged systems.

B. Gait Design

There are many possible footfall patterns that legged animals could use during locomotion. Gaits are generally considered to be discrete patterns of footfalls and are divided into two categories, symmetrical and asymmetrical, according to relative contact duration of a pair of legs (fore or hind) [29], [39]. Hildebrand showed that the symmetrical gait patterns of many-four legged animals are characterized by leg phase (% of gait cycle that fore footfall follows hind on same side) and duty factor (% of gait cycle that each foot is on the ground) [29], [39]. The gait cycle was divided into a retraction period and a protraction period. In the retraction period, the foot is in contact with the ground and exerts a forward propulsive thrust to the body. In the protraction period it is in air and moves forward.

Hildebrand used footfall patterns to characterize the quadrupedal gaits; however, the gait formula does not include the body undulation. In our previous studies [40], [41], we elucidated the benefits of using lateral body undulation in conjunction with footfall patterns described by Hildebrand's formula. In this paper, we extended Hildebrand gait formula to multi-legged systems and decomposed the centipede locomotion into lateral body undulations and leg movements [29], [39]. The contact patterns of the legs are:

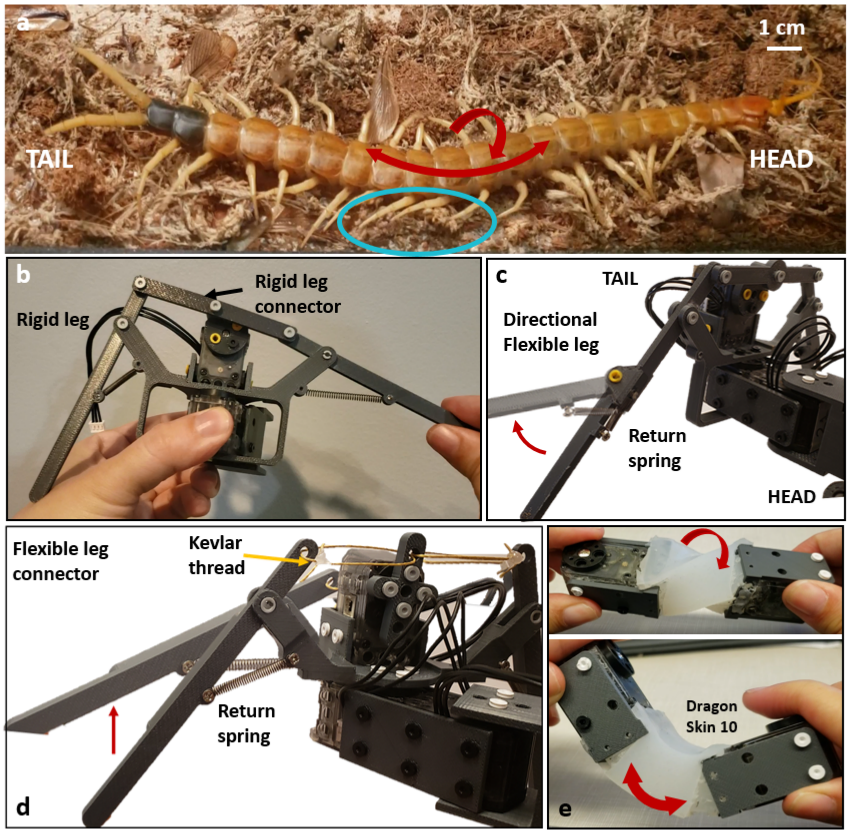

Fig. 4. **Bioinspired soft joints and leg design.** (a) A centipede (*Scolopendra heros*) with a segmented flexible torso locomoting on rough terrain. Red arrows show the dorsoventral and lateral flexion of the body and blue circle shows how the legs bend when they are blocked with obstacles. (b) A segment with rigid parts. 1-DoF rigid legs are coupled with a rigid connector. (c) Directional flexible leg with a return spring. Red arrow shows the direction of the bending (head to tail). (d) Rigid legs connected to the same motor with a flexible non-extensible Kevlar thread. (e) Passive flexible body joints casted with a liquid silicone (Dragon Skin 10) using a 3D printed mold.

$$c_i^l(t) = \sigma(t + 2\pi i LFS) \quad c_i^r(t) = \sigma(t + 2\pi i LFS + \pi) \quad (1)$$

$$\sigma(t) = \begin{cases} 1 \text{ (contact)}, & \text{if } (t \bmod 2\pi) < \pi \\ 0 \text{ (lifted)}, & \text{otherwise} \end{cases} \quad (2)$$

where c_i^l and c_i^r are the contact state of i-th left and right legs respectively; LFS is the relative phase shift between adjacent legs. We prescribed the lateral body undulation as a traveling wave, such that j-th joint is prescribed as $\alpha_j(t) = A_\alpha \sin(t + 2\pi Lj + \phi_0)$, where A_α is the amplitude of leg movements and ϕ_0 is the relative phase offset between body undulation and leg movements. ϕ_0 is optimized by using geometric mechanics gait design framework ([40]–[42]).

C. Hard Ground Experiments

To systematically evaluate the performance impact of variation in body-leg coordination, we constructed a robophysical model of the centipede (Fig. 2c) from the eight segments given in Fig. 2a (total length = 72cm). All parts of the segments were 3D printed by ABS plastic. Fig. 3a shows snapshots from one of the experiments (LFS 15%, duty factor 50%) for a cycle (T). The red dots show the legs on the ground. At the beginning of each experiment, all the legs are positioned to their neutral position and the body angle is set to zero. The robot moved on a level, smooth hardboard (60×120 cm) for five trials of three steps each per condition. We explored all the gaits with a duty factor 50% (means all the legs are on the ground during half of the cycle) and LFS from 10 to 90% with an increment of 5%. The x and y coordinates of the IR markers on each segment were captured at 120 Hz by a motion capture system that consists of six Flex 13 cameras (Natural Point).

The robot was controlled using a Robotis Usb2Dynamixel board via Matlab R2018a and powered by U2D2 Power Hub Board using an external power supply (12V, 10A). The actuator positions were determined by the equations given in Sec.II-B. An open-loop control signal was sent to the robot such that the gait parameters were not changed during the locomotion, and the control signals would continue to be sent as a function of time regardless of external forces. The frequency of the gait cycle is fixed to 0.5 Hz. We tracked the CoM of the eight markers on the body, the average of which was then used to determine displacement of the robot. Because of the toe shape and mechanical properties of the robot (inherent flexibility of the plastic legs, joints etc.), the robot experiences anisotropic coulomb friction (friction force or traction depends on the direction of sliding). We empirically measured the anisotropic friction ratio (f= 0.7) by pulling the robot along its longitudinal and transverse axes when all the legs were on the ground.

The robot performed 17 different gaits with a lateral body undulation. The amplitude of each body servos is the same for all the gaits and were actively controlled during the gait cycle. Fig. 3b shows the shape of the body as a function of gait percentage. The amplitude of body wave increases as the leg phase shift increases or decreases from 50 %. The body wave is 180^o out-of-phase for the gaits LFS$N\%$

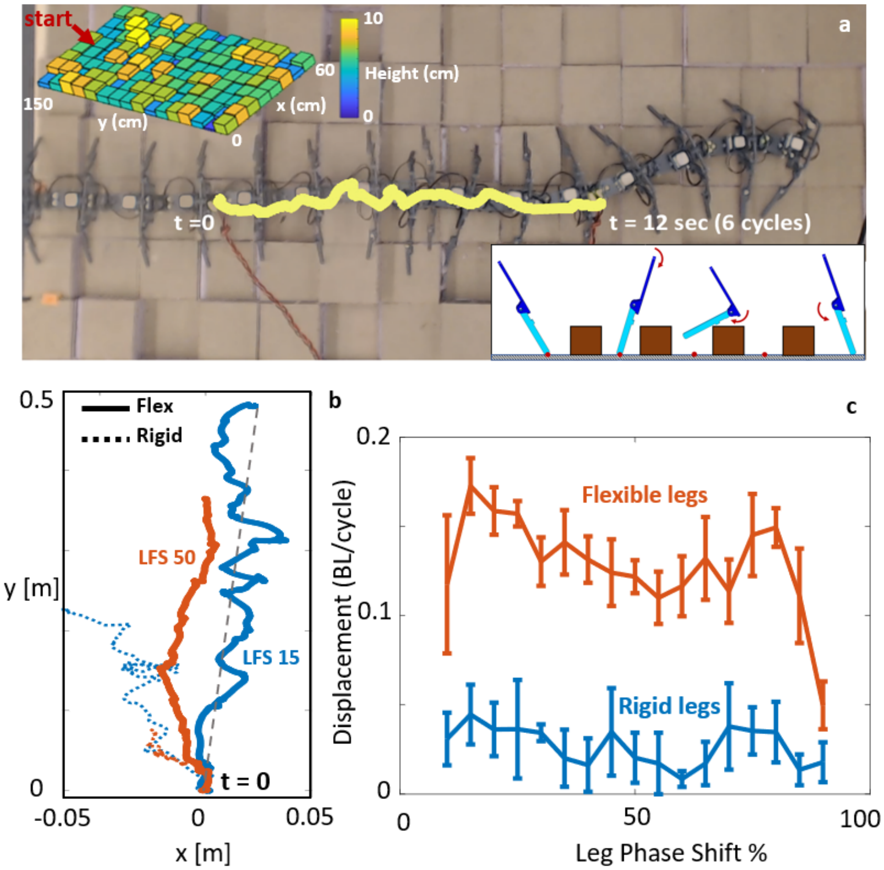

Fig. 5. **Locomotion on rough terrain with and without flexible legs** (a) The robot with flexible legs were run over a rough terrain (60 cm×80 cm) with a Gaussian distribution of blocks (10 cm×10 cm) up to 1.25 times the hip height of the robot from the starting point shown in a top inset. The robot experienced repeated random perturbations while locomoting over the terrain. The CoM trajectory (yellow) is plotted for LFS 15% and duty factor 50% over six cycles. The bottom figures show the bending states the leg experienced with an obstacle. (b) Example CoM trajectory of the robot with (solid) and without (dotted) flexible legs for LFS 15% (blue) and LFS 50% (red). For all the experiments duty factor is fixed to 50%. The gray dashed line shows the total distance traveled. (c) Displacement/cycle with (red) and without (blue) flexible legs for LFS 10 to 90% (with an increment of 5%) and duty factor 50%. All the data points are averaged over 6 runs/6 cycles.

and LFS$(100 - N)\%$, $10 \leq N \leq 90$. The robot employs retrograde body wave (head to tail) for LFS<50% and direct wave (tail to head) for LFS>50%. There is a good match between theory and experiments in the gaits with retrograde waves; meanwhile, the gaits with direct waves show less agreement Fig. 3c-d. From the experiments, we observed that the robot slips more and the locomotive performance of the robot can be significantly decreased when the gait has direct wave.

The properly coordinated body undulation and leg movements improves the forward displacement of the robot for all sequences of leg movement. When the gait has retrograde wave, the body undulation is beneficial regardless of friction anisotropy. Conversely, the contribution of the body undulation on locomotion performance is sensitive to friction anisotropy and it is most beneficial when the anisotropic ratio is greater than one.

D. Directional Flexible Leg and Soft Joint Design

The robophysical model of a centipede given in previous sections can yield a simpler mechanism with fewer kinematic parameters and its locomotion performance can be well-estimated theoretically on a flat terrain. However, in real-world applications, the robots need to be capable of locomoting effectively and robustly over varied unstructured terrestrial substrates, which requires an appreciable modeling and control effort. Inspired by highly adaptive locomotion of biological organisms, several studies propose that the control of locomotion on challenging terrain can be simplified using passive elements in the mechanisms [20]–[24].

Centipedes have a multi-segmented flexible body and multi-joint legs that can adapt their shapes to the environment. As seen in Fig. 4a, the centipede curves its body dorsoventrally and smoothly bends its legs to overcome the obstacles (see supplementary movie). Here we have improved rough terrain locomotion capabilities of our robot by adding flexible and soft elements to the legs and the body by mimicking the centipede morphology and their passive interaction with the environment.

Variable	Definition	Value	Unit
k_{joint}	Spring constant of the soft joints	0.011	N/m
t_{motor}	Stall torque of XL-320 servo	0.39	$N.m$
k_{spring}	Spring constant of the leg return spring	0.2	kg/cm

As we described earlier, to reduce the number of actuators used in the system the legs on each side of the segment are coupled rigidly (see Fig. 4b). We removed the coupling of the leg movement on the horizontal axis by adding a directional flexible joint to the leg. The directional flexible leg shown in Fig. 4c has two rigid segments (lower and upper) whose total length is equal to the rigid legs used in Sec.II-C. The leg is stiff when the torque on the joint is positive (counterclockwise) and bends back when the

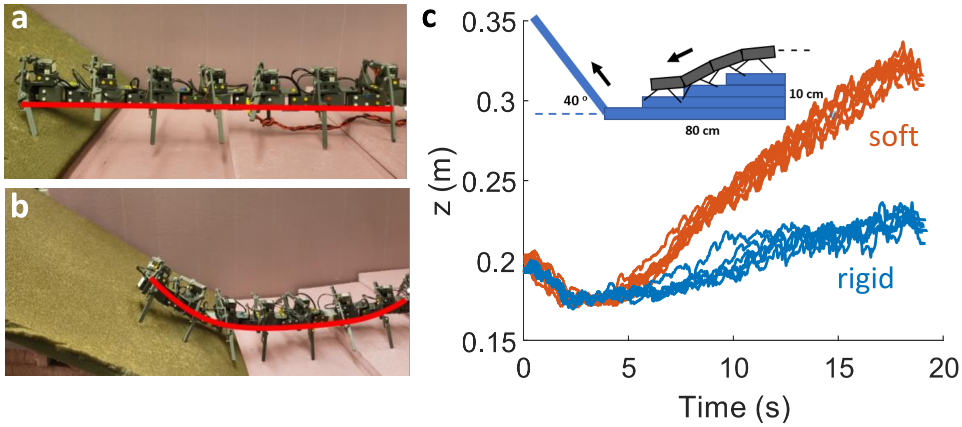

Fig. 6. **Locomotion on rough terrain with and without soft body joints** The robot with (a) rigid and (b) two soft body joints were run over a rough terrain (stairs and inclined surface). The red solid lines show the shape of the body when it climbs the 40^o incline. The surface of the incline is covered with foam to reduce the slip. (c) The CoM_z trajectories (with soft (red) and rigid (blue) joints) are plotted for LFS 35% and duty factor 50% over 6 runs/15 cycles. The inset shows the dimension of the obstacle course.

torque is negative (clockwise). The rigidity in one direction provides enough thrust during the retraction period. The directional flexibility creates a more effectively distributed contact area and provides robust obstacle crossing ability without disturbing the gait. Bending usually occurs when the leg is in air (during protraction period) and is blocked with an obstacle. After the contact with the obstacle ended, the initial configuration was restored by a helical extension spring attached to the knee joint which rotated the lower part of the leg.

The coupling of the leg movement on the vertical axis is broken by replacing the rigid connector with a non-extensible Kevlar thread (size 207) of the same size. The leg can freely rotate from the hip joint and returns to its neutral position by a helical extension spring attached between the leg and the rigid swing connector (the yellow part in Fig. 2a). The flexible connection between legs provides extra flexibility on the vertical plane and removes pairwise effects of external disturbances on the legs. Both the flexible leg and the flexible leg connector improves the robustness of the robot to uncertainty in the environment.

From animal experiments, we observed that the portion of the body that is unsupported by the legs has a tendency to curve downwards passively under gravity (see Fig. 4a). This compliance distributes the forces on the body, reduces loss of foot contact, and provides shape adaptability to the environment. In our robophysical model, we actively control the lateral undulation; however, we do not have any active joints that control the dorsoventral undulation. To add an extra degree-of-freedom to the robot body without complicating the design and control architecture, we incorporated passive compliant joints that were cast with a liquid silicone (Dragon Skin 10) using a 3D printed mold. During our experiments, we used two soft joints ($l = 1.5$ cm) between 2^{nd} and 3^{rd}, and 6^{th} and 7^{th} joints. We tested the performance of the robot over the laboratory created obstacle-course (stairs 20x2.5 cm and 40^o incline) given in Fig.6. All the experiments were started from the same initial position. The robot started to climb an incline after walking 20 cm down the stairs. The robot with rigid body segments was stuck at the beginning of the incline (Fig. 6a) while the one with soft segments climbed easily by adapting its shape to the ground (Fig. 6b). The height of the CoM for 6 runs are given in Fig. 6. This passive compliance enhanced the performance of the robot on unstructured environments such as natural terrain cluttered with obstacles, stairs, big rocks etc. (see the supplementary movie). There are some design (length and hardness of the joints) and implementation parameters (number and position of the soft joints) we need to further investigate.

E. Rough Terrain Experiments

We propose that the control of locomotion on challenging terrain can be simplified by effectively coupling motion of the legs with the environment. A robophysical model of a centipede with 16 legs allows us to systematically test how locomotor performance in rough terrain under repeated perturbations was affected by variations in gait and foot flexibility. This model can provide useful insight into biological systems and lead to a design principle for artifacts. Natural substrates such as leaf litter, pebbles, shrubbery, rocks, and soil are too complex to allow discovery of how the robot scrambles over rough terrain. To understand the robot running over natural cluttered environments, we constructed an artificial rough terrain with a Gaussian distribution of surface heights. The rough terrain surface was constructed using 10 cm $\times$ 10 cm variable height blocks of foam formed into a track 150·cm long by 60·cm wide (see top inset of Fig. 5a). The height of each block was randomly assigned to a value selected from a Gaussian distribution with mean and variance approximately leg-hip height and one-quarter leg-hip height respectively.

At the beginning of each experiment, we started the robot from the mid point of the obstacle course shown in Fig. 5a. The maximum height of the legs were set to $\sim$1.5 cm. We tested all the gaits used in hard ground experiments (Sec.II-C) with and without flexible legs. Bottom inset of Fig. 5a shows the states of the flexible leg when it locomotes over an obstacle. With current flexible leg design the maximum height of an obstacle that the robot can pass is $\sim$5 cm. For each gait parameter, we performed 6 runs with 6 gait cycles. We tracked the markers on the body using the setup described in Sec.II-C and calculate displacement (BL/cycle) of the CoM and averaged the 36 cycles. Fig. 5b shows all the results

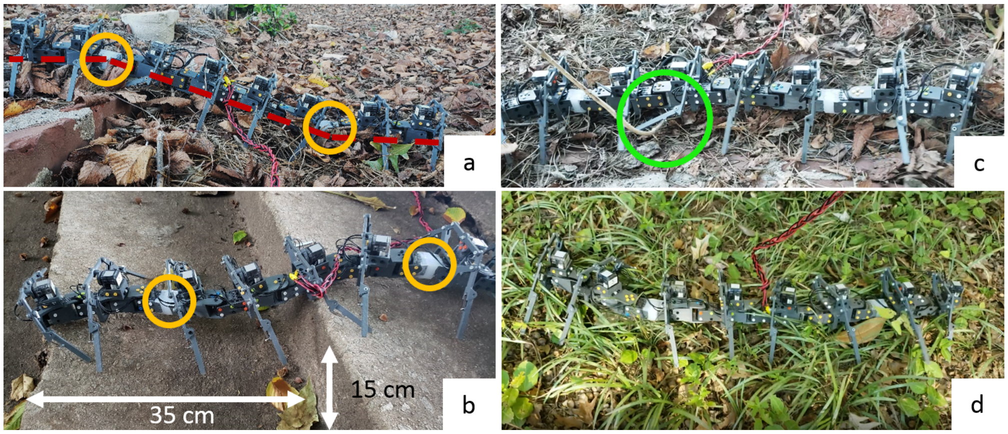

Fig. 7. **Demonstration of the robot locomotion with passive flexible joints and directional flexible legs coupled with rigid connectors on the natural environment.** (a) The robot with two passive soft joints (yellow circles show the position of the joints on the body) moving on a cluttered environment by adapting its shape to the terrain. (b) The robot is going down the stairs (h = 15cm, w = 35cm). (c) Passing an obstacle in a cluttered environment with directional flexible legs (green circle). (d) Locomotion on a terrain with grass, leafs, rocks etc. (see the supplementary movie)

with rigid (blue) and flexible (red) legs and Fig. 5c shows the example trajectories of CoM of the robot for LFS 15% (blue) and 50% (red) with rigid (dashed) and flexible (solid) legs. For all the gait patterns $15 \leq LFS \leq 80$, the flexible-legged robot outperformed approximately 3 times better than the rigid-legged robot. We observed that when the amplitude of the body curvature is high (LFS = 10,85,90%) the probability of failure due to leg jamming increases. Also the performance of the robot was less sensitive to gait parameter (leg phase shift) compared to hard ground experiments.

F. Outdoor Experiments

We have not tested the effects of the flexibility in vertical leg motion and dorsoventral body motion systematically in laboratory experiments, and leave this idea for future work. However, we performed outdoor experiments with directional flexible legs and soft body joints to show that the robot is capable of traveling in an unstructured, cluttered environment successfully (see supplementary movies).

The outdoor experimental areas consisted of stairs, long grass, stones, autumnal oak leaves and acorns, broken wooden pieces and some parking areas covered with gravel or tiles (Fig. 7). We tested a few of the gaits that were used in the laboratory experiments. All the terrain types contained many different features that were too difficult for a small robot to handle. However, the robot passed over the obstacles using its flexible legs and locomoted over the bumpy terrains by adapting its shape to the environment successfully. The failures happened when more than half of the legs lost contact with the ground and could not produce thrust. The servos we used in the robot have inherent overtorque protection. In some of the experiments, we observed how some of the servos became disabled when they were overloaded; however, the robot continued to walk. As stated in a previous study [43], multi-legged systems are robust to leg failures. We will investigate in more detail the possibility of failure modes as we add several compliant elements to the robot.

III. Conclusion and Future Works

We explored the capability of the robophysical model of a centipede to exploit the advantages of limb-body coordination and passive structures that allow effective interaction with diverse terradynamic surfaces and offer inherent robustness to uncertainty. We proposed that the control of locomotion on challenging terrain can be simplified by effectively coupling the motion of the legs or morphing the shape of the body to the environments using passive compliant elements. Despite the lack of diverse, accurate, and robust sensors, the mechanical modifications allow us to use same open-loop control strategies in diverse terrain. We systematically tested the locomotor performance of the robot with the directional flexible and rigid legs using the theoretically calculated gaits that are optimized according to forward speed on a flat and an artificial uneven terrain. Furthermore, we demonstrated that the robot can negotiate unstructured natural environments without large decrements in performance and recover from perturbations. However, there are different gait optimization criteria according to the environment such as stability, energy efficiency and success rate that should be considered. Using a closed-loop controller, we will improve the locomotion capabilities of the robot by either changing the gait or actively controlling the stiffness of the joints according to environment.

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