HexaFlex: Design and Testing of a Hexapod with a Flexible Origami-Inspired Spine

Daniel V. Moyer†, Gabrielle G. Conard†,*, Robin Hall, Dongquan Ji, Yanbo Hua, ZeHai Li, Jiaming Du, Chenhan Guan, and Cagdas D. Onal*

WPI Soft Robotics Lab, Worcester Polytechnic Institute, Worcester, MA, USA
*Corresponding Authors' Emails: ggconard@wpi.edu, cdonal@wpi.edu
†These authors contributed equally to this work.

Abstract. While legged robots have taken great strides in navigating complex terrain, the traditional rigid bodies used often limit their ability to adapt to highly uneven terrain and narrow passageways. Incorporating a flexible spine can address these issues by enhancing the robot's adaptability to its environment. This paper introduces HexaFlex, a hexapod robot with a flexible origami-inspired spine. We detail the mechanical design, control architecture, and gait generation methods. To quantify the benefits of the flexible spine, the robot was tested in confined spaces and over obstacles. HexaFlex achieved a maximum speed of 0.92 BL/s (0.25 m/s) with a cost of transport (COT) of 5.2 on flat terrain, and the flexible spine enabled the robot to navigate turns with a minimum radius of 0.34 BL (0.09 m). It also operated in an outdoor environment to test its robustness in a real-world scenario. The flexible spine improves locomotion efficiency and maneuverability, improving on traditional rigid robots.

Keywords: soft robotics, mobile robots, locomotion, flexible spine

1 Introduction

Legged robots have shown considerable success traversing unstructured terrains, accessing areas like rocky fields, forest floors, or debris-strewn environments into which simpler wheeled robots cannot tread [1]. Among these platforms, hexapod robots are favored for their inherent stability and redundancy [2]. However, most hexapods employ rigid bodies that constrain the robot's ability to negotiate severe terrain variations or pass through narrow openings. A body capable of bending or twisting can drastically improve a robot's adaptability.

Many spine designs have been explored for quadruped robots, ranging from a single joint to continuum structures [3–10]. Most of these works focused on enhancing the speed and efficiency of a given robot's gaits (such as walking, bounding, galloping, or jumping), but did not address the question of improving a legged robot's ability to navigate obstacles and passageways using flexible spines. Since hexapod robots are advantageous for their inherent stability, they are less capable of dynamic motion, meaning that previous investigations on dynamic quadruped gaits are less applicable to work on hexapod robots. A couple of exceptions include NeRmo [3, 11] and SQuRo [4], two rodent-inspired robots that demonstrate improved agility through mazes when equipped with articulated spines. However, since the spines in these robots are designed primarily for lateral bending, neither explores the use of vertical bending for obstacle climbing (though SQuRo is capable of climbing over an obstacle due to its leg design).

Considerably less investigation on this topic has been done for hexapod platforms. Robots like HECTOR [12], SpaceClimber [13], ModPod [14], and the passive-spine hexapod robot presented in [15] use articulated spines consisting of one to two joints connecting two to three body segments. Attempting to achieve bending in more than one plane with an articulated spine can greatly increase the design complexity, and as a result, most of these designs were optimized for bending in one plane. Although the spine of ModPod is capable of 2 degree-of-freedom (DoF) bending along the lateral and vertical planes, improving its ability to turn and climb over obstacles, the spines of HECTOR and the passive-spine hexapod robot are limited to lateral bending, and that of SpaceClimber is limited to vertical bending. In addition, the impacts of the articulated spines on the behavior of HECTOR and SpaceClimber are not discussed, and experiments with the passive-spine hexapod robot focused on the forward walking gait, making it difficult to assess how these spines impacted the robots' agility.

To avoid some of the limitations of articulated spines, the hexapod platform presented in [16] takes inspiration from soft robotics and employs two pneumatically-actuated spines. However, the paper only investigates in-place rotation and straight-line walking. The robot employs the spine for forward locomotion since it has unactuated legs, making it difficult to compare to robots with actuated legs. In addition, making a robot that is dependent on pneumatic actuation untethered remains a challenge. Cable-actuated continuum structures, such as origami-inspired structures, are promising alternatives due to their electrical actuation principle (which can be made portable). Such structures have proved successful in our previous work on wheeled and whegged robots [17, 18]. Incorporating legs would allow a robot to access terrains that wheels or even whegs would not be capable of handling.

Thus, in this paper, we build on this previous work and introduce **HexaFlex**, a hexapod robot that incorporates a flexible, origami-inspired spine. This design takes advantage of traditional servo-driven legs for high force and precise control, while simultaneously exploiting the compliance of a cable-actuated origami mechanism in the body. The flexible 3-DoF spine of the robot is capable of lateral and vertical bending and axial compression, offering advantages in turning, obstacle negotiation, and adjusting to uneven terrain.

2 Technical Approach

2.1 Robot Design

HexaFlex, shown in Figure 1, measures 0.27 m in body length (BL) and weighs 1.03 kg. The robot consists of three rigid body sections connected by two flexible

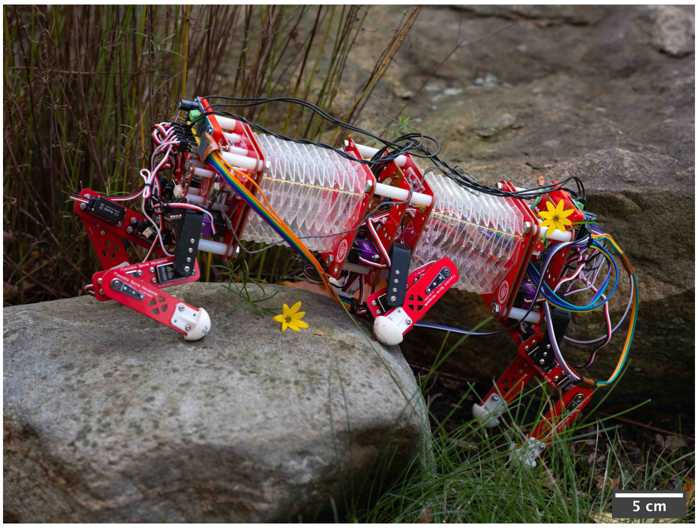

Fig. 1: HexaFlex: A hexapod robot with a flexible origami-inspired spine. The robot uses its flexible spine to improve maneuverability and terrain adaptability. It has a body length of 0.27 m and a total weight of 1.03 kg.

origami-inspired spine modules. Each rigid section is supported by two legs. The rigid sections and legs are constructed from FR-4 material, a lightweight and strong material commonly used in printed circuit boards. Each leg is actuated by three miniature servo motors (A20BHM), one each for the hip bracket, femur link, and tibia link.

The flexible origami-inspired spine modules are constructed from laser-cut and creased polyethylene terephthalate (PET) films hand-folded following the Yoshimura origami pattern, as we described in [19]. This fold pattern allows for axial and bending deformation while resisting torsional forces. PET film was chosen for its low cost and high strength-to-weight ratio. In previous work, we demonstrated the reliability of these modules by measuring insignificant performance degradation over the course of 1000 axial length change cycles [19]. Each spine module is actuated using three Kevlar cables threaded through the origami structure and attached to three DC motors with spools. By controlling the length of these cables via the motors, the module can bend or change length, allowing the robot to change its posture in response to user input. The stiffness of the origami structure provides the restoration force needed to return the module to its neutral straight length when the cables are extended.

The control system is based on a Jetson Nano single-board computer, which runs the control algorithms and interfaces with an Xbox controller for user input during testing. The robot is connected to the Jetson Nano via a cable bundle for communication and power supply. The Jetson Nano is primarily offboard to make it easier to interface with using a monitor, but it can be embedded for tetherless applications. The Jetson Nano sends commands to a PCA9685 servo motor controller, which controls the 18 A20BHM servo motors. It also sends commands to the two spine module motor drivers, which are custom PCBAs designed to drive three DC motors and monitor Hall sensor quadrature encoder feedback. Though the robot is tethered to the Jeston Nano for control, it is powered independently using a 7.4V battery onboard the robot. However, to make it easier to measure current consumption during experiments to determine the speed and cost of transport, we powered the system using a regulated power supply instead of the battery.

2.2 Gait Generation and Spine Control

Three hexapod gait patterns are employed by HexaFlex: the tripod gait, where three legs step together while the other three support the robot; the tetrapod gait, where two legs step together while the other four support the robot; and an alternating forward-propagating wave gait, where each leg lifts sequentially in a traveling wave from back to front. The footfall pattern for each gait is illustrated in Figure 2. Each gait requires dividing the motion of the feet into stance and swing phases. To achieve smooth foot paths, the swing trajectory over one cycle T is parameterized via a quintic polynomial in time t for the horizontal component of the foot's motion, $x(t)$, while a sinusoidal or polynomial function is used for the vertical component of the foot's motion, $z(t)$, to lift and place the foot: $x(t) = x_0 + \mathit{\Delta} x \left(10\,t^3 - 15\,t^4 + 6\,t^5\right)$, $z(t) = z_0 + h\,\sin(\pi t)$, where $0 \leq t \leq 1$ is the normalized swing time, x_0 and z_0 are the initial horizontal and vertical positions, $\mathit{\Delta} x$ is the horizontal travel distance in one step, and h is step height. During stance, z is constant to maintain ground contact, and x moves backward relative to the body to generate thrust.

A human operator can use the Xbox controller to modify the hexapod's stance height, foot trajectory, and locomotion trajectory. Additionally, the operator also manually controls the position of the flexible spine to enhance HexaFlex's performance in challenging environments. For instance, while the front legs are in swing, bending the spine upward helps lift the front body segment, facilitating climbing. Likewise, for tight turns, bending the spine laterally shortens the turning radius. While integrating spine control into an autonomous gait planner will improve the robot's performance and the user experience, this was beyond the scope of this work, which focused on the physical capabilities of the HexaFlex platform.

3 Experiments and Results

Speed, cost of transport (COT), turning radius, and maneuverability were analyzed to assess the robot's performance indoors on flat surfaces, while HexaFlex's ability to navigate uneven terrain was tested outdoors. An Xbox controller was used to provide input commands for movement and posture adjustments.

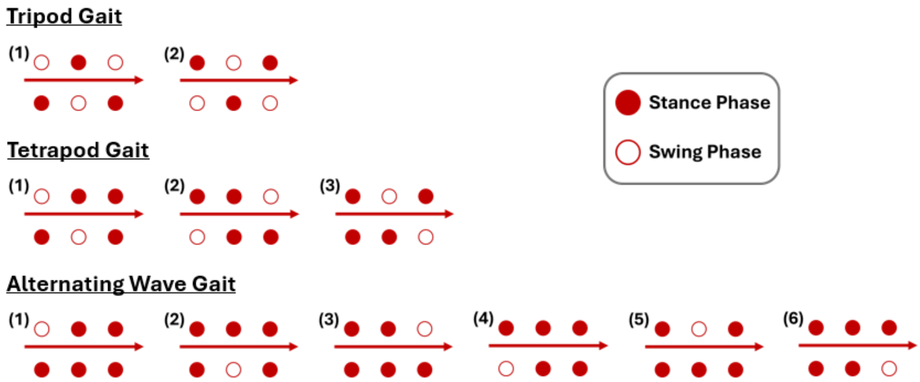

Fig. 2: Footfall Patterns - An overhead perspective of the footfall patterns of the three hexapod gaits over a full cycle is illustrated above. A shaded circle represents when a foot is in the stance phase and in contact with the ground, while an unshaded circle represents when a foot is in the swing phase.

3.1 Turning Radius and Maze Navigation

In an open space, we ran a forward walking gait and measured the turning radius achieved by bending the flexible spine. We measured the minimum turning radius to be 0.09 m (3.5 in) while bending the spine using Physlet Tracker [20] (Fig. 3.1). To quantify the effect of the flexible spine on the turning radius, the same test was repeated with a fixed spine configuration. The fixed full-length configuration achieved a turning radius of 0.23 m (9 in), while the fixed minimum compressed-length configuration (in which the body length is reduced by 32% to 0.18 m) had a turning radius of 0.17 m (6.75 in). The flexible spine significantly reduces the turning radius, especially as the robot length increases. The smaller turning radius greatly enhances the maneuverability of the robot.

Additionally, the robot navigated a maze with 90-degree turns of widths down to 0.16 m (roughly 0.6 BL). Figure 3.2 shows three modes: (A) fixed full-length configuration, (B) fixed compressed-length configuration, and (C) flexible spine configuration. Only the flexible mode successfully performed the tightest turns without collisions.

3.2 Speed and Cost of Transport

In a straight-line test on flat indoor flooring, HexaFlex reached a maximum speed of 0.25 m/s, or approximately 0.92 BL/s, using the tripod gait. We measured the average power consumption to be $P \approx 13.0\,\mathrm{W}$ under nominal conditions (7.13 V at 1.82 A). The average cost of transport (COT) was about 5.2, given by $\mathrm{COT} = P/(m\,g\,\bar{v})$, where $m = 1.03\,\mathrm{kg}$, $g = 9.81\,\mathrm{m/s^2}$, and $\bar{v} = 0.25\,\mathrm{m/s}$. In future work, measuring a range of speeds under different terrain loads could yield a fuller efficiency profile, as changing the speed or payload would alter the robot's power consumption.

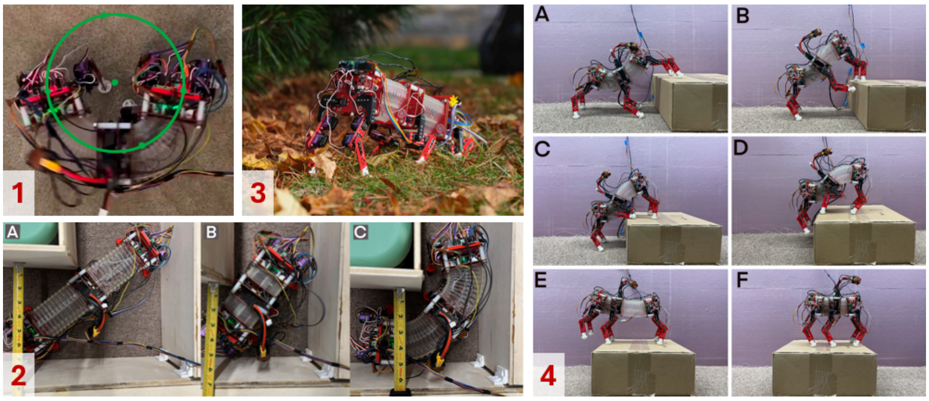

Fig. 3: Experiments and Demonstrations: 1) Top view of HexaFlex making a tight circular turn with spine bending, achieving a turning radius of 0.09 m (3.5 in). It completes one full circle in 27 s; 2) HexaFlex demonstrating its turning capability in a confined space with three different modes: (A) fixed full-length, (B) fixed compressed-length, and (C) flexible spine. By bending its flexible spine, HexaFlex can make tighter turns compared to the rigid configurations; 3) HexaFlex navigating an uneven outdoor environment. The robot can operate over complex terrain and through debris; 4) HexaFlex climbing over an 0.14 m (1.07 leg lengths) tall obstacle. The sequence A - F shows stages from approach to overcoming the obstacle.

3.3 Posture Adaptation and Obstacle Climbing

HexaFlex is capable of walking while in different posture modes, with stance heights ranging from 0.136 to 0.223 m. This is advantageous for passing under obstacles or maintaining a low center of gravity on steep slopes.

Additionally, this platform is also capable of climbing obstacles as high as 0.14 m (1.07 leg lengths). As shown in Figure 3.4, the spine bends upward to lift the front segment and allow the front legs to mount the ledge. Next, the spine partially relaxes while the middle legs push the body upward. This coordinated motion between the spine and leg gait is repeated until HexaFlex is entirely on the box. In climbing tests, we observed that partial spine bending effectively prevents the robot's center of mass from tipping backward and thus helps maintain stable contact.

3.4 Outdoor Field Testing

To evaluate real-world performance, we tested HexaFlex on grass, gravel, and uneven soil. On short grass, the robot walked at about 0.5 BL/s; on gravel, about 0.6 to 0.7 BL/s. These speeds are reduced from 0.92 BL/s on smooth flooring. However, HexaFlex maintained stability thanks to the six-leg design and body compliance, which mitigates sudden changes in terrain height. Figure 3.3 shows

Table 1: Comparison of HexaFlex with Similar Robots

Robot	Body Length (m)	Speed (m/s, BL/s)	Turning Radius (m, BL)	Step Height (m, LL)	COT
NeRmo [3, 11]	0.405	0.3, 0.74*	0.14, 0.35*	-	-
SQuRo [4]	0.188**	0.196, 1.04*	0.066, 0.35*	0.03, 0.86*	-
HexaFlex (This work)	**0.27**	**0.25, 0.921**	**0.09, 0.33**	**0.14, 1.07**	**5.2**

*Calculated from provided data in paper.

**For comparison, 1 BL was defined as the entire robot's length.

an example of the robot on a campus walkway with debris. Future improvements may include real-time spine control based on inertial/force feedback to further enhance stability in rough terrain.

4 Discussion

The experimental results above demonstrate that the continuum origami spine improves the robot's performance, which is consistent with the findings demonstrated with the quadruped platforms NeRmo and SQuRo in [3] and [4]. Table 1 compares the performance of HexaFlex with those platforms, accounting for both physical values and body-normalized values, where body length is BL and leg length is LL. (Note that [4] reports its normalized values using a body length of 136 mm, which excludes SQuRo's head and tail. However, since [3] provides only the overall length of NeRmo, we recomputed the normalized length values using the overall body length of 188 mm for SQuRO.) HECTOR [12] is not included due to not providing relevant metrics, and SpaceClimber [13] is excluded since nearly all the reported results are from experiments on inclines, which makes them incomparable to those from experiments performed with HexaFlex. ModPod does not report the maximum step height over which the robot can climb, but instead states that its maximum vertical reach is 34 cm [14]. Assuming the legs are approximately 12 cm long, this would work out to be 2.83 LL, which is very large compared to other legged robots. However, the high vertical reach is due not to its leg length or design (as it would be with rigid-spined robots), but its body length (95 cm) and its ability to bend its spine vertically. Thus, its vertical reach is roughly equivalent to lifting the first of its three rigid segments straight up, assuming each segment is about one-third of the body length. Since vertical reach is not indicative of its stair-climbing abilities, ModPod's performance is difficult to compare to that of HexaFlex.

Relative to its length, HexaFlex achieves a slightly smaller turning radius than both NeRmo and SQuRo. In addition, HexaFlex is able to climb taller obstacles relative to its leg length than SQuRo, likely due to the fact that the spine of SQuRo cannot bend vertically. (Neither the ability of NeRmo's spine to bend vertically nor its obstacle climbing capabilities are explicitly explored.) This demonstrates the advantages of continuum spines, which can achieve large bending angles in multiple directions. While HexaFlex achieves higher speeds than NeRmo relative to its length, it is slightly slower than SQuRo. Though NeRmo is the slowest of the three, experiments performed with this platform demonstrated that the speed of a robot can be increased by incorporating spine bending into a given gait, as seen in real animals [3]. This observation is similar to quadrupeds that employed vertically-bending spines to gallop faster [5, 6] or jump farther [8]. Bending the spine swings a given foot further forward, effectively increasing the stride length of that foot. Developing gaits that merge both spine and leg motion is part of the future work on HexaFlex.

5 Conclusion and Future Work

We have presented HexaFlex, a hexapod robot with a flexible origami-inspired spine. The robot's design combines rigidity and flexibility, enabling enhanced maneuverability and adaptability. Experimental results demonstrate the effectiveness of the design, showcasing improved turning capabilities, posture adjustments, and efficient electrical performance. The flexible spine allowed for smoother turns and reduced the mechanical strain on individual leg joints. The robot was able to climb obstacles, navigate a confined maze, and even operate on uneven terrain outdoors, demonstrating its potential for applications in complex environments.

Manually controlling the flexible spine introduced challenges in maintaining synchronization between the spine actuation and leg movements. Developing gait plans that synchronize spine and leg motion is needed to ensure whole-body coordination and improve the robot's speed and efficiency. Additionally, adding sensors to detect uneven terrain may improve adaptability and enable the robot to operate more autonomously. Finally, implementing wireless communication with the Jetson Nano or another platform would allow the robot to operate completely untethered. In the meantime, this work lays the foundation for further research into flexible-bodied robots capable of operating in various settings, with potential applications across multiple fields.

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