

A Tendon-Driven Beaded Spine Robot for Shape-Adaptive Locomotion

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Abstract—Wheel-based mobile robots can move efficiently on flat ground, but their fixed body shape can limit sharp turning and obstacle traversal. This work presents a tendon-driven mobile robot that combines wheel-based locomotion with active body deformation using four motors. Two motors drive the wheels for forward and backward motion, while the other two motors actuate the lateral and vertical tendon pairs that bend the beaded spine. The spine consists of rigid beads woven into a flexible three-dimensional structure. Within each antagonistic pair, the motor direction determines which tendon is tensioned and thus the bending direction; releasing tension allows passive deformation during contact. We use open-loop command sequences to evaluate forward and backward locomotion, curvature-assisted turns in both directions, and traversal of a fixed step through qualitative experiments. These results suggest that a single beaded spine can serve as a shared mechanical resource for steering, lifting, and passive deformation. These results suggest that a single beaded spine can integrate active shape control and passive compliance can enable low-actuator-count mobile robot to adapt their bodies to cluttered and uneven environments.

I. INTRODUCTION

Mobility in unstructured environments depends not only on how a robot generates propulsion, but also on how its body interacts with the terrain [1]. Many wheeled mobile robots use rigid chassis designs because they are simple and efficient on flat ground. However, when the terrain includes tight spaces, uneven contacts, or obstacles comparable to the size of the robot, a fixed body shape can limit mobility. A rigid chassis cannot easily redistribute its weight to maintain contact, steer around constraints, or lift part of the body over an obstacle. In contrast, animals often use spinal flexibility to reshape the body during locomotion, improving maneuverability, and enabling coordinated interaction with complex terrain [2]. This motivates mobile robot designs that treat body shape as an adaptive mechanical structure rather than a fixed feature.

Prior work has explored both passive and active spines to improve robot locomotion. Passive compliant spines can absorb impacts and conform to terrain, but their behavior is limited by fixed material stiffness and geometry [3]. Active spines, while able to reshape the body for steering, turning, or obstacle traversal, often require additional joints, actuators, or control complexity [4]. In a bioinspired mouse robot, lateral flexion of a compliant spine improved walking speed and turning agility [2], showing the potential benefit of spine-mediated body motion. However, designing a spine that can support both controlled shape change and passive

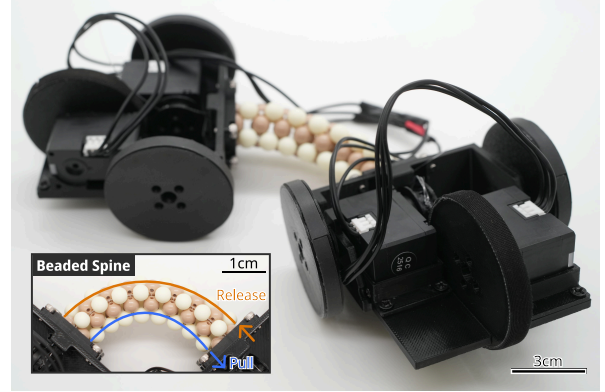


Fig. 1. Two-module, four-motor mobile robot with a tendon-driven beaded spine. Inset: tendon-driven bending of the spine.

environmental compliance remains challenging. A possible solution is seen with beaded metamaterials [5], which offer both shape changing and stiffness tuning properties.

In this paper, we investigate whether a bead-based spine can serve as an adaptive flexible body for a wheeled mobile robot (Fig. 1). The proposed spine is used as a shared mechanical structure for both active shape control through tendon actuation and passive deformation enabled by stiffness tuning during environmental contact. Our contributions are: (1) a compact wheeled robot with a tendon-driven bead-based spine for lateral and vertical body-shape adaptation; (2) spine-mediated locomotion behaviors, including curvature-assisted turning and step traversal; and (3) experimental demonstrations showing that active body-shape adaptation extends the mobility of a simple four-motor wheeled robot.

II. ROBOT DESIGN AND METHODS

The robot prototype is 250 mm long, 95 mm wide, and 50 mm in height, with a mass of 303 g. It consists of four DYNAMIXEL XL330-M288-T smart servo motors, and combines wheel-based locomotion with a tendon-driven spine that changes its body shape. The robot spine consists of discrete rigid beads woven into a flexible three-dimensional structure. The beads are arranged in layers and woven together using a nylon monofilament in an angle weave pattern. This pattern permits relative motion between rigid beads, allowing the beaded structure to behave as a compliant spine while the nylon thread maintains structural connectivity.

The beaded spine supports commanded lateral and vertical bending through tendon actuation and passive adaptation to improve ground contact when the tendons are relaxed. Fig. 2 shows the top and side view of the robot with motor locations, wheel arrangement, tendon routing, and

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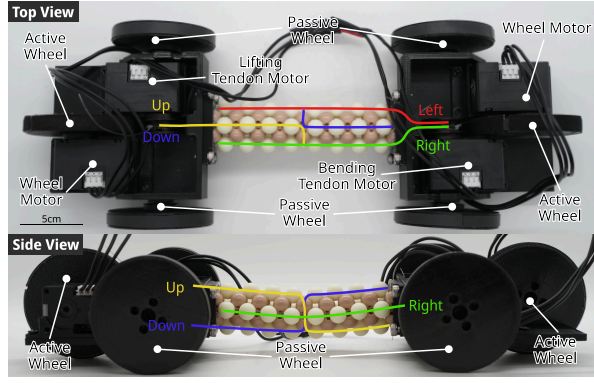


Fig. 2. Robot architecture showing the wheel and tendon motors, passive wheels, and tendon routing for lateral and vertical spine bending.

corresponding bending directions.

The spine contains four actuation tendons arranged as two antagonistic pairs; one tendon motor drives each pair. The routing is designed to bend the spine toward a tensioned tendon as the opposing tendon is released. The pairs are intended for lateral bending and for vertical lift that moves one module relative to the other.

The robot consists of two rigid wheeled modules connected by the beaded spine. Each module contains one active wheel powered by a wheel motor, two passive wheels for support, and one tendon motor to actuate the beaded-spine. The two wheel motors provide forward and backward propulsion, and two tendon motors actuate the lateral and vertical tendon pairs.

III. EXPERIMENTAL SETUP AND RESULTS

A. Experimental Setup:

To qualitatively evaluate the robot's ability for step traversal and turning, we used velocity control for the wheel motors and current-based position control for the tendon motors. Motions of the motors are hard-coded as open-loop sequences. During all experiments, the robot was connected by cables to an external power supply and control computer, and the cables were moved by hand to prevent tangling. For turning, the lateral tendon motor bends the spine, while the wheel motors drive the robot. Reversing the tendon motor changes the turning direction. For step climbing, the vertical tendon motor lifts the front module. The wheel motors then place it on the step, the tendons are released, and the robot continues forward. Fig. 3 shows selected frames for qualitative evaluation from one continuous trial for step traversal and curvature assisted turning.

B. Step Traversal:

In Fig. 3, the top row shows the robot climbing a 20 mm high step (40% of the robot's height) using a sequence of lifting, placing, releasing, and advancing. The vertical tendon motor first lifted the front module, and the wheel motors then placed it on the step. Releasing the tendons allowed the spine to deform passively as the robot continued forward. The complete step-climbing sequence, measured from the start to the end of the robot motion, lasted 19 s.

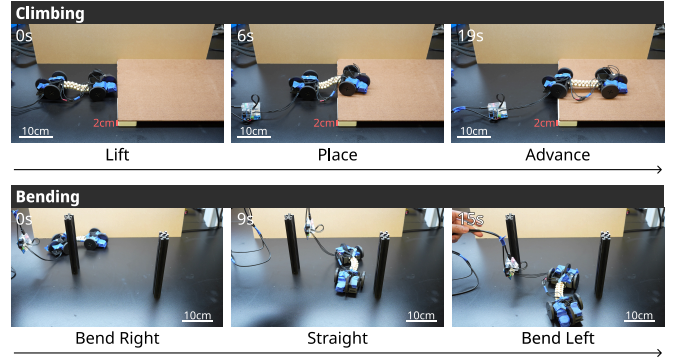


Fig. 3. Selected frames from continuous locomotion trials: climbing a 20 mm high step (top) and curvature-assisted right and left turns (bottom). For each row, $t = 0$ marks the start of the displayed segment, not the start of the complete motion sequence.

C. Curvature Assisted Turning:

The two-module robot moved forward and backward with the spine in its neutral configuration. Lateral spine bending changed the robot's heading in the commanded direction, and reversing the tendon motor produced a turn in the opposite direction as shown in the Fig. 3 bottom tile. The complete turning sequence lasted 15 s.

IV. CONCLUSION AND FUTURE WORK

This paper provides a qualitative proof of concept that one tendon-driven beaded spine can serve as a shared mechanical resource in a four-motor wheeled robot. Lateral bending changed the robot's heading, while vertical bending lifted the front module during step traversal. When the tendons were released, the spine remained flexible and deformed passively during contact. However, the current evaluation did not quantify repeatability or include a rigid-spine comparison.

Future work will compare the current robot to a version with a rigid spine. We will measure success rate for turning and step climbing tasks, turning radius, and maximum traversable step height for both robots. We will also study how the spine length affects lifting capacity and deformation range. Additionally, we will quantify the relationship between tendon commands and spine shape. These studies will help guide the design of beaded spines for mobile robots that use body shape changes to improve locomotion in cluttered environments.

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