SnakeTrack, A Bio-inspired, Single Track Mobile Robot with Compliant Vertebral Column for Surveillance and Inspection

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Abstract. This paper presents the conceptual and embodiment design of a bio-inspired single track ground mobile robot, named SnakeTrack, designed for surveillance and inspection tasks in unstructured environments with narrow spaces. Its main components are the vertebral column, characterized by two end modules and a variable number of vertebrae connected by compliant joints, and the peripherical track. The robot is actuated by four motors, two for the track motion and two to command the lateral flexion of the vertebral column for steering, while limited passive torsion and retroflexion of the vertebral column are allowed by the compliant joints to adapt to terrain unevenness, improving traction. Vision is provided by two cameras placed on the end modules, behind the tracks, which are characterized by dedicated openings. The pitch of vertebrae and tracks is equal, then the robot is modular, and its length can be changed on the basis of the environment features and the required onboard equipment.

Keywords: Ground mobile robot · Tracked locomotion · Single track robot · Snake robot · Worm robot

1 Introduction

In the present technological scenario, service robotics is one of the fastest expanding research areas. In particular, ground mobile robots can substitute human beings in a wide variety of hazardous and unsafe applications, as well as surveillance, inspection of sites with chemical or radioactive contamination, intervention in extreme environments, rescue operations, homeland security.

There are many different kinds of calamities which originate from natural and man-made causes, such as earthquakes, floods, hurricanes, fires. It is crucial to reach the victims and casualties within the first 48 h after the disaster. To this aim, technological studies are concentrated on the development of search and rescue robots. The biggest contribution of these robots will be keeping the search and rescue personnel out of the disaster region and gathering and processing more information from the sites via several sensors and accordingly, preventing further casualties and losses of lives.

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Independently of the payload, which depends on the specific task, a ground mobile robot is primarily characterized by its locomotion system. Ground mobile robots are often required to move in unstructured environments, and the selection of the locomotion architecture is based on the expected operative conditions.

Locomotion systems can be classified into three main categories: wheeled robots (W) [1, 2], tracked robots (T) [3, 4], legged robots (L) [5, 6]; moreover, hybrid robots exploit the four possible combinations of these systems: Legged-Wheeled (LW) [7–9], Legged-Tracked (LT) [10, 11], Wheeled-Tracked (WT) [12, 13], Legged-Wheeled-Tracked (LWT) [14]. A comparison of the operative features of these locomotion principles is outlined in [15].

In particular, tracked robots are characterized by excellent motion capabilities on yielding and uneven terrains, due to their large contact surface between tracks and ground. Despite such advantages, they are slower and less efficient than wheeled robots. For inspection of narrow spaces, some researchers have proposed snake-like tracked robots, with tracked modules in series [16]. A similar approach to design robots for inspection of narrow spaces is to adopt a single peripheral track. In [17] a flexible mobile mono-track named FMT is proposed and compared to classical differential steering tracked robots. In [18], another similar robot with peripherical single track is proposed, named Reconfigurable Continuous Track Robot (RCTR).

In the following a novel snake-like, single track robot with steering capability is proposed, named SnakeTrack, designed for surveillance and inspection of narrow spaces.

2 Functional Design of SnakeTrack

Figure 1 represents the external view of the proposed SnakeTrack robot. Its overall dimensions are 640 mm (length) $\times$ 150 mm (width) $\times$ 120 mm (height). Its main structural components are the vertebral column and the track.

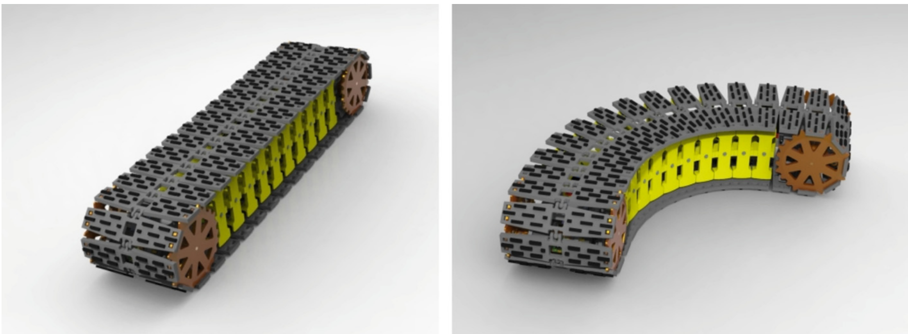

Fig. 1. External view of SnakeTrack, in straight position (left) and in steering position with minimum turning radius (right).

The vertebral column of SnakeTrack is composed of a variable number of vertebrae (ten in Fig. 2, V) and two end modules (Fig. 2, E). The length of the robot can be changed by varying the number of the vertebrae; they are connected by compliant joints, with low stiffness for the yaw rotation, to allow lateral flexion for steering (Fig. 1, right) with low energy consumption.

The robot is symmetric both in front-rear and up-down planes, so the end modules are equal, and each one hosts two actuators, one for the track motion (Fig. 2, TA) and one to command lateral flexion (Fig. 2, SA). Each SA actuator contains a gearmotor connected to a winch (Fig. 2, W). The winch can pull a rope (Fig. 2, R) which passes through lateral holes in the vertebrae. One end of the rope is fixed to the winch, and the other end is fixed to the opposite end module. Therefore, lateral steering is obtained by pulling the rope on the side of the center of rotation of the desired turn. Consequently, the motions of the two TA actuators are not independent, as well as the motions of the two SA actuators. As a matter of fact, the two TA actuators, connected to the track sprockets, must rotate at the same speed, and when one SA actuator pulls a rope, the other SA actuator must loosen the opposite rope.

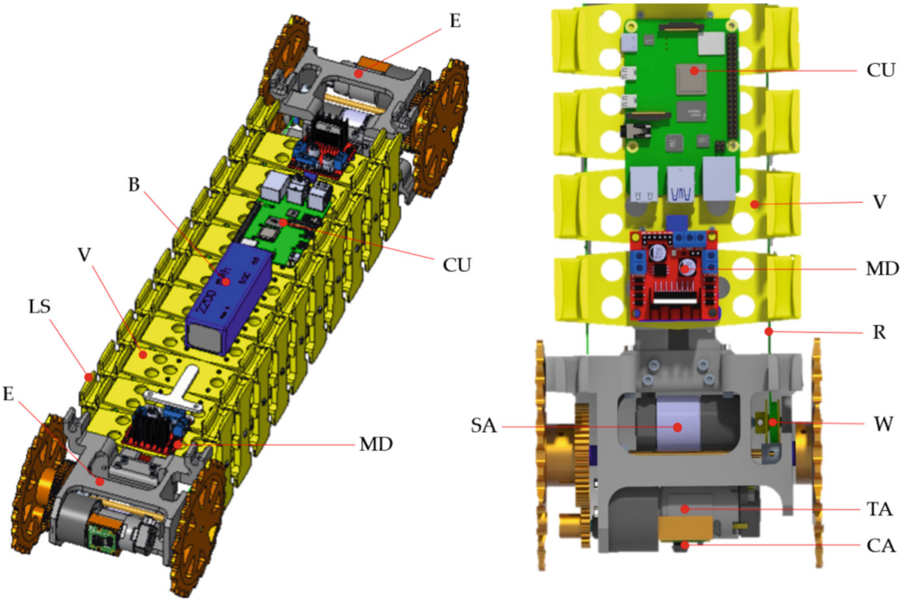

Fig. 2. Vertebral column of SnakeTrack.

A detail of the track modules is shown in Fig. 3. They are characterized by central openings (Fig. 3, O) that allow, during the track motion, an intermittent view by means of the two cameras mounted on the end modules (Fig. 3, CA). The track modules are guided by lateral supports (Fig. 3, LS), attached to each vertebra, in which the track guiding pegs (Fig. 3, GP) pass during the track motion.

Camera vision is active during the track motion only in the phases in which the camera faces the track opening. Considering a robot speed of 0.1 m/s, with a track pitch of 40 mm, the camera view can be updated 2.5 times per second; even if the vision is not continuous, this rate is sufficient to guide the robot at this speed. However, when

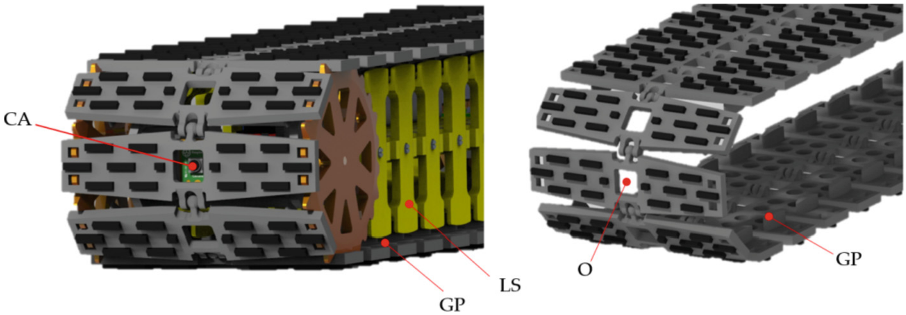

Fig. 3. Detail of the track modules with central opening for camera vision.

continuous camera vision is required for monitoring, the robot can stop with the track opening aligned with the camera.

Control unit (Fig. 2, CU), batteries (Fig. 2, B), motor drivers (Fig. 2, MD), and sensors can be hosted by the vertebrae, in the space between the lateral supports. Besides the two cameras, the robot can be equipped with additional environmental sensors for specific tasks. The robot is completely modular, and the number of vertebrae can be changed, varying the available space for the payload.

3 Constructive Design of the Vertebral Joints

For the realization of the vertebral joints, several alternatives have been considered, starting from the functional requirements of limited stiffness in the yaw direction (for actuated lateral flexion with low energy consumption) and higher stiffness in the pitch direction (for passive retroflexion) and in the roll direction (for passive torsion). Passive retroflexion and torsion of the vertebral column are needed to obtain a flexible structure which adapts to terrain unevenness, improving traction.

The most widespread approach for realizing compliant joints in robotics is to realize lumped elastic elements in which compliance is concentrated. For universal joints, several possible designs are considered in [19]. In Fig. 4, two possible solutions are represented: the two-axis flexure joint (Fig. 4a) and the compliant cardan U joint (Fig. 4b). Such compliant realizations of universal joints also allow a compliance along x (roll torsion), therefore they can be used as vertebral joints for SnakeTrack.

The two-axis flexure joint is the extension to two axes of the revolute flexure hinge, and has the same main drawback: the stress is highly concentrated in the central section, and this lowers its mechanical resistance. Different stiffness along y and z can be obtained by adopting a rectangular central section (Fig. 4a). The compliant cardan U-joint of Fig. 4b reduces the stress concentration issue, since strains and stresses are evenly distributed along the flexure plates fy and fz, that usually have constant thicknesses. Different stiffnesses along y and z can be obtained by adopting different thicknesses and lengths for the fy and fx flexure plates. The mechanical resistance of this joint can be further improved by replacing the flexure plates with inserts in superelastic materials (Fig. 4c), as proposed in [20, 21], but this greatly increases the joint size and weight

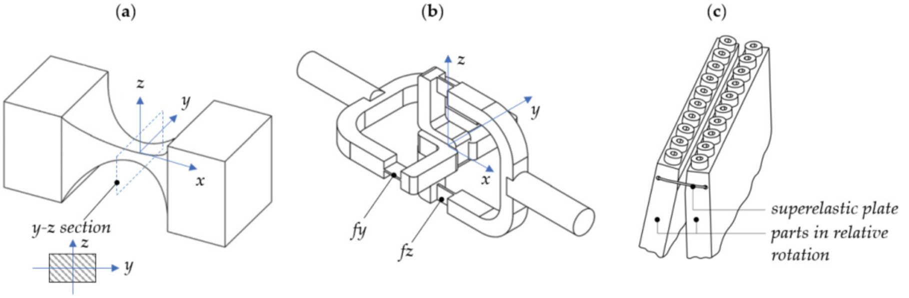

Fig. 4. Possible realizations of compliant universal joints: two-axis flexure joint (**a**) and compliant cardan U joint (**b**); revolute joint with superelastic insert (**c**).

because it can't be realized in a single part. On the other hand, the practical realization of a flexible cardan U joint is rather complex even with additive manufacturing techniques. An alternative approach to design a 3-DoF compliant joint is represented by beam-based compliant mechanisms [22], but they not being very compact, are not suited for the present application.

An alternative solution, which greatly simplifies the design of the vertebral joints, is to use the soft robotic paradigm, adopting a compliant joint without shrinkages, exploiting the hyperelasticity of materials such as thermoplastic polyurethane (TPU).

Figure 5 represents the design of the proposed compliant joints. Each vertebra is composed of a central core (C) and two external plates (P), fixed by bolts. A central TPU elastic element (EE) connects two adjacent vertebrae; the two external plates P lock the elastic element EE. Moreover, the contact of the profiles of the plates P of two adjacent vertebrae, with limited gap when EE is undeformed (0.13 mm), limits the relative pitch and roll motion and consequently the passive retroflexion and torsion, while lateral flexion and is almost not affected by the plates P.

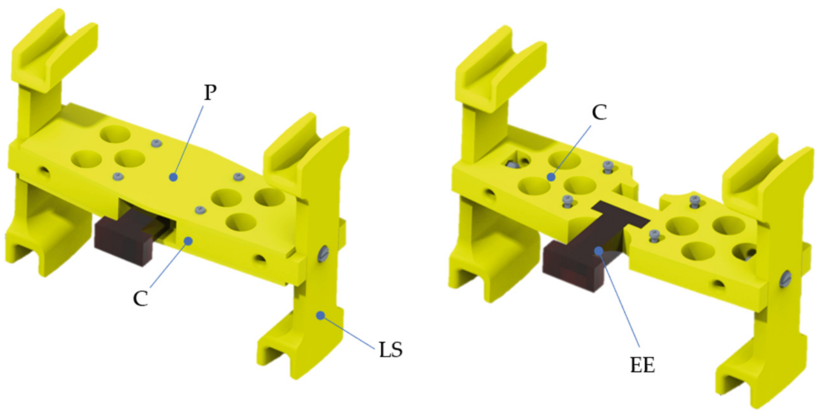

Fig. 5. Design of the compliant vertebral joints: core (C), external plates (P), lateral supports (LS) TPU elastic element (EE).

This design has the following advantages: low cost, resilience to shocks much higher than conventional compliant joints, possibility of easily tuning the range of retroflexion by changing the shape of the plates P and consequently the gap between the plates of two adjacent vertebrae.

4 Prototyping and Preliminary Experimental Tests

The first prototype of the SnakeTrack has been realized and the first experimental tests are in progress, at present with the robot radio controlled by an operator. These tests have confirmed the overall functionality of the proposed mechanical design, and in particular the capability to steer using the lateral flexion (Fig. 6, left) and to move adapting to terrain unevenness by means of the passive retroflexion and torsion of the vertebral joints (Fig. 6, right).

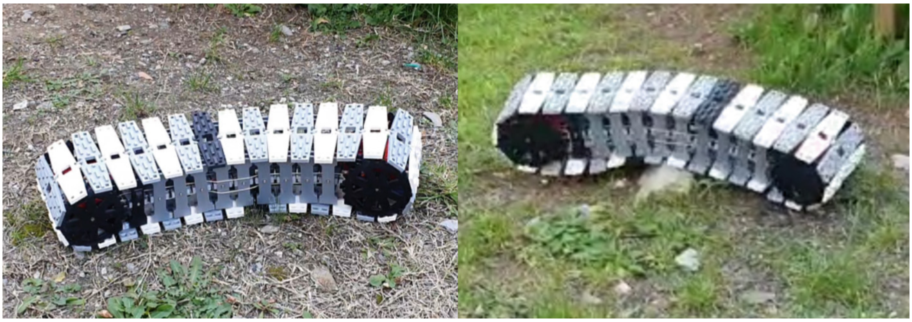

Fig. 6. Preliminary experimental tests on the SnakeTrack prototype: steering (left) and locomotion on uneven grounds (right).

These tests are fundamental to refine the shape of the components which are in relative motion during the track rotation. In particular, the shape of these elements must be carefully revised to increase the reliability of the track functionality even in steered position and/or in presence of terrain unevenness: the pegs of the track sprocket, the holes of the track modules which host the sprocket pegs, the ends of the track lateral supports (Fig. 5, LS).

5 Conclusions and Future Developments

The overall design of a small size tracked robot for surveillance and inspection of unstructured and narrow spaces has been presented. It is characterized by a modular structure composed of a vertebral column and a single peripherical track revolving around it. The vertebral column can perform actuated lateral flexion for steering, while passive retroflexion and torsion are allowed by the compliant vertebral joints to adapt to terrain unevenness. Thanks to the modular architecture, the length of the robot can be adapted to the payload necessary for the specific task.

The robot is fully symmetric and can continue operating after a capsize; moreover, if it falls on its flank, it can restore the correct position by combining lateral flexion, to lift on the track ends, and track motion. The conceptual design of the robot has been presented and the embodiment design of the vertebral joints has been discussed. The preliminary tests on the first prototype are in progress. The first experimental results have confirmed the robot capability to walk and steer while adapting to uneven grounds and suggested possible refinements in the detailed design of the tracks and of the steering system. In the next steps of the research, these modifications will be implemented to obtain improved prototypes.

Author Contributions. S.N. conceived the robot architecture and the locomotion system; S.N. and L.B. developed the detailed embodiment design, performed the experimental characterization of the compliant vertebral joints and prepared the manuscript; P.F. supervised the scientific methodology.

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