CObRaSO: Compliant Omni-Direction Bendable Hybrid Rigid and Soft OmniCrawler Module

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Abstract—This paper presents a novel design of an Omnidirectional bendable Omnicrawler module. Compared to conventional crawlers, OmniCrawler module possesses an extra degree of freedom for sideways rolling motion, and the circular cross-section of the module enables holonomic motion of the robot. These advantages are further enhanced by the introduction of Omnidirectional joint with-in the module, which is the key contribution of this paper. This achieves high maneuverability and adaptability of the OmniCrawler module on an uneven surface. The Omni-directional bending is realized by means of two mechanisms: a Telescopic screw drive mechanism, and an arrangement of two independent 1-DOF joints aligned at 90° with respect to each other. The hybrid soft-rigid structure of the module provides compliant pathways for the lug-chain assembly which allows crawling motion even in the bent configuration of the module. We show that the unique modular design unveils its versatility by achieving compliance on an uneven surface, demonstrating its applications in different robotic platforms (an in-pipeline robot, Quadruped and snake robot) and exhibiting hybrid locomotive traits in various configurations of the robots. The mechanism and motion properties of the proposed module have been verified with the help of simulations and experiments on real robot prototype.

I. INTRODUCTION

Mobile robots capable of traversing unstructured environment are highly useful for inspection, exploration of the unknown and risky areas as well as for Urban search and rescue(U SAR) operations. High level of adaptability on uneven rough terrain and efficient maneuvering in confined spaces are the desired key functionalities of these robots. As discussed in [1], trafficability, maneuverability, and terrainability determine the performance of a robot locomotion and pose important challenges in the design of search and rescue robots.

The impressive capabilities of wheeled, legged and tracked based mobile robots on the rugged surface are well documented in literature [17]. Land-based robots are generally based on wheeled locomotion, due to their fast rolling and energy efficient motion on hard-flat surface/terrain [2]. Legged robots offer many advantages when navigating in uneven natural terrains as they possess good adaptability by varying the effective length and orientation of the legs [2]. Track robots are favorable due to their added advantages of crawling over holes and ability to smooth out the path, putting low pressure on terrain and providing large ground contact surface and traction [3]. These potential advantages of each locomotive trait have led to the development of a number of reconfigurable robots [4], [5], [6] as well as hybrid locomotion based robots [2], [7] and[8].

Fig. 1: (a) Prototype of the Proposed Module. (b) A Quadruped robot realized using 4 modules (c) An in-pipe climbing robot realized using Kinematic chain of 3 modules. (d) Snake robot realized using Kinematic chain of 3 modules.

This paper proposes a novel design of an Omni-directional bendable OmniCrawler module derived on the basis of combining the locomotion advantages of legged,tacked and wheeled robots along with few added features of compactness and holonomy. The design of the OmniCrawler module has been inspired by [9], and the key contribution of this paper is the incorporation of omnidirectional joints.
within the OmniCrawler module to make it comply in a desired orientation. The omnidirectional bending property is characterized by the design of a 2-DOF passive compliant roller chain and a hybrid structure of soft-rigid materials. In our previous work [10], OmniCrawler modules were designed with 1-DOF active compliant joints and the motion capabilities of the mechanism were demonstrated with its application in an in-pipe climbing robot (COCRiP), which consists of a kinematic chain of 3 such modules. The objective of this work is to extend the capabilities and scope of applications of the OmniCrawler module in several mobile robots. The unique modular design provides potential advantages of attaining varying configurations and achieving hybrid locomotion modes in a dynamically changing environment. Therefore, a combination of modularity, active compliance and omnidirectional motion enables it to navigate a wide range of surfaces and makes it capable as a reconfigurable search and rescue robot.

The key contributions of this paper are summarized as below:

1. A seminal concept of Omni-directional bending in an OmniCrawler module is introduced. This is realized using a hybrid combination of soft and rigid materials and a unique design of a 2-DOF roller chain.
2. The versatility of the modular design facilitates its integration with various categories of robots, such as in-pipe climbing robot, Quadruped, snake robot, robotic manipulator and legged robots.
3. Additionally, the omnidirectional compliance enhances its capabilities to exhibit various locomotive traits in different configurations. For instance, with the hybrid locomotion modes, the Quadruped can navigate through tight spaces by reconfiguring itself and switch between legged and crawling locomotion modes.

The modularity of the proposed design is characterized by its mechanical design, which is discussed in Section II. Different locomotion modes that can be achieved various configurations of these robots are discussed in Section III. Furthermore, Section IV shows the simulations and experimental results to demonstrate the exclusive applicability and versatility of this module in different robots.

II. MODULAR DESIGN

| Quantity       | Symbol | Values  |
|----------------|--------|---------|
| mass of module | $M_m$  | 0.320kg |
| length of module | $L_m$  | 0.24m   |
| Diameter of module | $d$    | 0.060m  |
| Driving motors saturation torque | $\tau_{\text{max}}$ | 1.5Nm   |
| Joint limit of omnidirectional joint | $\theta_{\text{max}}$ | 35°     |

A. OmniDirectional bendable OmniCrawler Module

The OmniCrawler module consists of a couple of chain-sprocket power transmission pairs on both sides of the chassis, driven by a micro motor which provides driving motion in the forward and backward direction. The exploded CAD view of the module demonstrating the arrangement of chains, lugs, motor mounts, bearings, gears, screw driven linear actuators and chassis in the module, is shown in Fig. 2. The power transmission from driving motors to chain-sprocket assembly takes place through spur gear trains. The backbone of the module consists of 3 circular rotating plates, interconnected by 2 omni-directional bending joints, which provides the guiding channel for the lug-chain assembly. The discontinuity in the pathway introduced as a result of gap between circular plates, is removed by embedding soft silicone rubber between them. Therefore, in the proposed design the shape of the robot is controlled by rigid actuators and the soft silicone rubber body passively deforms according to the design constraints of the rigid body. The cascaded arrangement of silicone rubber and rotating plates provides a continuous pathway for lug-chain assembly in straight as well as bent configuration, as shown in Fig. 3a and 3b. This
single cascaded arrangement of 2 circular plates with silicone rubber in between them is considered as a sub-module of the whole module in the subsequent discussions in paper. The circular cross-section of the module is characterized by the design and arrangement of two identical series of lugs resting on chain links through attachments via fastener and the module attains hemispherical shape at both its ends, as shown in Fig.3b. The unique design of a 2-DOF roller chain is discussed in the subsequent section. The design parameters of the module is listed in Table I.

![Fig. 4:](image) (a),(b) Bending along Y-axis. (c),(d) Bending along Z-axis.

1) Mechanisms to achieve Omni-directional bending: The omni-directional bending within the module is realized with 2 mechanisms as discussed below.

(i) Telescopic differential screw mechanism

The omni-directional bending is realized with 3 'Telescopic screw mechanism' based linear actuators, aligned at 120° apart from each other on a circular rotating plate. Previously, the Double-Screw-Drive(DSD) mechanism has been proposed by Ishii, Chiharu, et al [11], where the Omni-directional bending is achieved with 2 rotating linkages with left & right-handed screws and universal joints. The desired bending angle proportionally increases the length of the screw, thereby increasing the size of the coupler. In order to achieve sharp bending while keeping the size of coupler within constrained space, a 'Telescopic screw drive mechanism' is introduced. It interconnects multiple screws, similar to rods in a telescopic antenna. It consists of a master screw connected directly to the actuator’s rotor and the outer threads of successive screw is fastened to inner threads of the preceding screw. When the master screw reaches its extreme end during actuation, the stopper at its end transfers the rotational motion to the successive screws in a sequential manner. The arrangement of the screws, universal joints and the circular rotational links in one sub-module is shown in Fig 5. The robot consists of a cascade of such sub-modules and the power imposed on each of the telescopic screw assembly of a sub-module is transferred to the corresponding assembly of the cascaded sub-modules. Therefore, the number of sub-modules that can be cascaded is limited by the maximum power rating of the actuators. The differential rotations of the 3 telescopic screws result in the omni-directional bending of the module. This arrangement requires lesser number of motors but the bending directions of all the submodules are identical and interdepende

![Fig. 5:](image) (a) 3 telescopic screws aligned 120° between 2 circular rotational plates, (b) The differential linear actuation of the screws results in an omni-directional bending motion.

(ii) A mechanism of two independent 1-DOF joints aligned at 90°

Another mechanism to achieve omni-directional bending is realized by the collaborative control of 2 independent 1-DOF joints connected to the rotational joints. Both joints are aligned along the axes inclined at an angle of 90 degree with respect to each other. 2 rotational circular plates are actuated by each of the 2 joints and the offset distance between the joints achieves significant angular rotation within constraint space. 3 rigid body circular/cylindrical rotating links are interconnected by 2 omni-directional bending compliant joint. The arrangement of these joints in between the rotating plates, is shown in Fig. 6a, 6b. Primary basic experiments were performed using both of the above mentioned mechanisms, and it was observed that in applications like manipulation and legged locomotions which requires higher torque and quick controls, the second method is easier to integrate and use, while in applications like pipe climbing robot traversing smooth bends where uniform module bending is desirable with decent torque, the first method (telescopic screw bending) is easier to integrate as it requires fewer actuators and the bending is equal in all the cascaded modules.

2) 2-DOF Chain design: To comply with the bent chassis of the robot, a 2-DOF chain has been designed which possesses degree of freedom about yaw and pitch axes. Each link of the roller chain is designed with narrow grooves on its both sides. The relative rotation between two consecutive chain
links along these grooves adds an extra degree of freedom about yaw axis. The designed chain passively conforms with the bent structure of the module. The lugs rest on the chain links via fastener and chain-lug assembly adapts their shape with the varying surface. This is illustrated in Fig. 7b.

3) Tensioner to maintain optimal tension in chains in the bent configuration of the modules: To keep the chain intact with the bent chassis of the module and maintain optimal tension in both the chains while crawling in bent position, a mechanism to adjust the tension has been realized using linear screw actuators. The actuator adjusts the position of the respective sprocket corresponding to a chain, with the support of a slider. As the linear screw actuator is powered, the sprocket slides back or forth along the slider and the tension of the corresponding chain is adjusted. The arrangement of linear, screw actuator, sprocket and the slider are shown in Fig. 8.

III. Locomotion modes

The active compliance of the proposed design achieves adaptability on varying surfaces and versatility of the module enhances the capabilities of different robots to exhibit multiple locomotion modes in different attainable configurations. Different locomotion modes possible in different configurations of the robots are discussed below.

A. OmniCrawler in Non-compliant mode

1) Omni-directional Crawling on Flat Surface: The basic performance of the OmniCrawler module is its ability to crawl in arbitrary direction by the collaborative control of its two degrees of freedom along lateral and longitudinal direction, as shown in Fig. The circular cross-sectional design and arrangement of lugs enables it to crawl in any orientation of the module, except when the surface is in contact along the singularity line that does not allow longitudinal motion of the robot [15].

B. OmniCrawler in Compliant mode

1) Steering and Obstacle Aided Motion: With the omnidirectional bending compliance within the module, the robot conforms according to the shape and alignment of the obstacle and can overcome it either by steering around it or climbing over it. As the module crawls, the lug-chain assembly rotates around the curvature of the module and the motion is transferred to the obstacle or external object in contact with the actuated module. This hybrid surface and internal actuation property of the Crawler module facilitates obstacle-aided motion where the robot utilizes external obstacles and other terrain irregularities in a cluttered environment for propulsion. This property is highly useful for snake robot motion in confined and cluttered spaces [16]. This is illustrated in Fig. 10a and 10b.

2) Omni-direction Crawling on Uneven surface: The terrain adaptability and mobility of crawler modules have been improved with the development of articulated multi-tracked robots by linking several passive or active tracked modules [12]. Furthermore, a compliant robot ‘OUROBOT’ is build up of closed, deformable servo segments that changes its form to achieve high adaptability on rugged terrain [13],[14]. However, the inability to conform in 3 dimensions limits their applications where the robots can comply with the surface during forward and backward propulsion only. In the proposed design, omni-directional compliance of the module augments the holonomic property of the crawler module and adapts with uneven surface while crawling forward/backward as well as rolling sideways. This ensures that the module complies with the surface unevenness during omnidirectional crawling. This is unique and one of the key functionalities of the proposed Crawler module. The ability of module to conform with the surface in order to climb it, and perform
sideways rolling motion along the surface, are illustrated in Fig. 9a and 9b.

3) **Legged locomotion in unstructured environment:** The omni-directional compliant module has the potential benefits of enabling legged locomotion, in addition to crawling motion. Typically, all state of the art tracked robots have separate robotic arm/leg platform on top of crawler modules. The proposed modular design interchangeably exhibits manipulation and locomotion capabilities by switching modes of operation between crawling locomotion and legged locomotion. The module may further be used for manipulation tasks.

IV. APPLICATIONS AND EXPERIMENTS

A. **Quadruped**

The compliant modular design of the proposed modules are configured as 4 legs Quadruped robot design. The modules incorporated in the robot enables hybrid locomotion modes in different configurations of the robot. The different configurations for a Quadruped with the proposed modular design include crawler, wheel and legged robot modes, as shown in Fig. 11. When the module crawls with its one of the hemi-spherical end in contact with the surface, it possesses the characteristics of omni-wheeled locomotion, as discussed in [9]. The simulation results demonstrating the motion of each of these modes on uneven surface, are shown in Fig. 12a, 12b and 12c. All the simulations were carried out in ADAMS, a multi-body dynamics simulator, with the lumped model of each crawler module. The lumped model of each crawler mode is approximated as a cascade of omni-wheels. Multiple locomotion modes enable the capabilities of these robot to adapt to dynamically varying uneven terrain. One such instance is demonstrated in Fig. 12 where Quadruped robot switches its locomotion modes to navigate tight spaces.

B. **In-Pipeline Robot**

An in-Pipeline robot is realized with a kinematic chain of 3 compliant OmniCrawler modules interconnected by 2 torsion spring joints. In straight pipes, all 3 modules are aligned in-line with the pipe and are driven synchronously to propagate in forward/backward direction. The preloaded torsion spring joints provide the necessary clamping force to overcome robots own body weight and facilitate slip free driving motion. The modular configuration of the robot handles pipe diameter variations and holonomic motion enables alignment of robot along the direction of bend. The compliance further facilitates locomotion in sharp bends in small diameter pipes by complying with the curvature of the bend. In our previous work, each OmniCrawler module was realized with 1-DOF active compliant joints. This limits its traversability in bends aligned in the direction of 1-DOF planar joint and may find it difficult to negotiate non-planar bends. The experimental results to demonstrate the negotiation of sharp 45° in vertical pipe using our previous robot [10], is shown in Fig.13b. Rest of the experiments with 1-DOF compliant modular in-Pipeline climbing robot, COCrIP [10], can be viewed in this link (https://youtu.be/Esd47RzzpOU).

With the proposed design of the Omnidirectional bendable OmniCrawler module, the robot is able to negotiate non-planar bends, as illustrated in Fig. 13b.

C. **Snake Robot**

The snake robot can be realized with a kinematic chain of the proposed crawler modules. The potential advantage of the snake robot using the proposed module lies in the easy modes of locomotion. For instance, the straight and sideways rolling motion of can be performed by the omnidirectional motion capability of each of the crawler module, assuming the links connecting the adjacent modules are heavy enough to rotate modules about the links using an external rolling motor. This eases the locomotion of snake robots which would otherwise need joint actuations to perform slithering or side winding gaits to move forward or sideways, respectively. Fig. 14 shows the simulation results illustrating the advantage of compliance in crawler module helps snake robot traverse uneven field longitudinally.

V. CONCLUSION AND FUTURE WORK

In this paper, we discuss the design of a novel compliant omni-directional bendable OmniCrawler module. The versatility of the modular design and the ability to behave both as a manipulator and a crawler was tested which demonstrates its applications in different robotic platforms, like in-pipe climbing robot, Quadruped, snake robot, robotic manipulator and legged robots. It was concluded that this module design is not only able to integrate in different kinds of robots but also enhances their locomotion capabilities. In future, the integration of proximity sensors within the module may enable us to build dynamically conforming gaits when module traverses uneven terrain. In addition using this module to build other legged robots like Humanoid and biped can be an interesting scope.

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Fig. 9: Experiments demonstrating the robot complies with the surface curvature as it undergoes (a) Crawling while traversing in forward direction., (b) sideways rolling motion on the surface (along Z-axis).

Fig. 10: Experiments demonstrating the robot complies with the curvature of the obstacle and executes obstacle aided motion.

Fig. 11: Quadruped in (a) crawler robot configuration, (b) legged robot configuration, (c) wheeled robot configuration.

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Fig. 12: In Quadruped configuration, (a) robot crawls forward while complying dynamically with the unevenness of surface and climbing at a height 9cm. (b) robot rolls sideways on uneven surface, (c) omni-wheel locomotion mode on uneven terrain. (d) To navigate under confined spaces, the robot switches from legged to crawler model of locomotion.

Fig. 13: (a) Experiment demonstrating locomotion of robot in sharp 45° bend. (b) Simulation results demonstrating traversal in demonstrating locomotion of robot in sharp 45° bend.
Fig. 14: Kinematic chain of modules in snake configuration traversing uneven terrain.