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Preliminary design of a novel helical locomotion-based soft crawling robot for in-pipe inspection / Toccaceli, Lorenzo; Botta, Andrea; Tagliavini, Luigi; Baglieri, Lorenzo; Colucci, Giovanni; Duretto, Simone; Amodio, Francesco; Quaglia, Giuseppe. - ELETTRONICO. - 1:(2025), pp. 56-62. (The 8th Jc-IFToMM International Symposium Nagano (JPN) 21-22 June 2025) [10.57272/jciftomm.8.0_56].

Publisher:
Japanese Council of IFToMM

Published
DOI:10.57272/jciftomm.8.0_56

Proceedings of the 8th Jc-IFToMM International Symposium (2025)
The 31st Jc-IFToMM Symposium on Theory of Machines and Mechanisms
21-22 June 2025

Preliminary design of a novel helical locomotion-based soft crawling robot for in-pipe inspection

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Abstract

This paper presents a novel helical locomotion-based soft crawling robot for in-pipe inspection. In robotics, helical locomotion is a mechanism that enables a crawling robot to move forward. This is particularly evident for wave-like robots that exploit the actuation of one or more helical shafts to generate a propulsive wave. This mechanism may potentially be suitable for pipeline inspection because it features a compact design along the pipe's transverse section, and it can adapt to the structural variations of the pipes thanks to the flexibility achievable by modifying the shaft geometry. However, the pipeline environment is inherently affected by some factors, such as oil, sediment, and rust, that can compromise the robot's locomotion, and the robot itself may contaminate the external environment. The core idea of the paper is to enable the robot to perform its inspection operations while remaining isolated from the surrounding environment through a compliant tube that encloses it.

Keywords: In-pipe inspection, Crawling Robots, Soft Robotics, Helical locomotion

1. Introduction

Pipeline transport is among the safest and economical ways of transporting fluids such as oil, water, gases, chemicals, and more [1]. However, the cyclic thermomechanical action of these fluids on the inner surfaces of the pipes can induce various forms of mechanical and chemical degradation, including corrosion, erosion, fatigue, and fracture, which may lead to significant economic and environmental consequences. Moreover, the structural complexity of pipelines, often characterized by confined and tortuous spaces, makes maintenance operations particularly costly and hazardous for human intervention.

To address these challenges, the use of robotic systems for internal pipeline inspection has significantly increased over the past decades. These robots, which are normally equipped with a camera or non-destructive testing (NDT) equipment, move inside the pipeline to conduct a pipe integrity assessment [2]. To carry out this task, an in-pipe inspection robot must exhibit key features such as efficiency, good maneuverability, reliability, and adaptability to various pipe sizes.

To meet these requirements, different types of inspection robots have been developed over the years. These solutions are based on different locomotion principles, including wheeled robots, legged robots, crawling robots, and screw-type robots. The present paper focuses on robots that exploit the rotation of a helical shaft because they feature a compact design in the transverse section of the pipe and they can adapt to the structural variations of the pipes, such as different diameters and curved profiles, thanks to the flexibility achievable by modifying the shaft geometry. In the literature, the confirmation of the efficiency of this locomotion mechanism can be found in wave-like robots, a particular type of crawling robot, which utilize wave propagation along their structure for propelling. In contrast with the conventional wheeled, legged, and screw-type robots, these wave-like robots have excellent mobility, so they can move efficiently through unstructured and confined environments. The high degrees of freedom and flexible bodies enable them to travel readily in complex and irregular terrains, making them promising for a wide range of applications such as, such as pipeline inspection for maintenance purposes and deployment in biological vessels for medical applications [3]. For example, Zarrouk et al. [4] developed a Single Actuator Wave (SAW) robot whose locomotion is based on the generation of a uniaxial, discrete, planar sinusoidal wave along a kinematic chain of links and mechanical joints. The robot can count on a minimalistic design because its motion is achieved through the rotation of a helical shaft driven by a single actuator. Yoshida et al. [5], employing the same wave generation principle, developed a mobile robot driven by a uniaxial wave locomotion mechanism, which can mechanically generate uniaxial surface waves through a single actuator that drives a helical component with discrete helical wings. The idea of rotating a helical shaft is also explored in the work of Watanabe et al. [6], who developed a bundled rotary helix drive mechanism. This mechanism generates a smooth, continuous peristaltic wave on the braided mesh tube surrounding it through the synchronized rotation of six helices around a central axis. In this context, the concept of a new robot is introduced, with a propulsion mechanism based on the actuation of a helical shaft while ensuring isolation from the surrounding environment.

2. Robot concept and functional design

Based on the studies reviewed, a robot designed based on the actuation of a helical shaft is well-suited for this application for the following reasons:

- versatility: it can be adapted to structural variations of the pipes, such as curved profiles and changes in its cross-sectional view, by modifying the geometry of the helical shaft to ensure good maneuverability;
- miniaturization: the robot is very compact along the transverse direction of the pipe, and it can be driven by a single rotary actuator, ensuring reliability and simplicity of control.

The possibility of exploiting helical locomotion within pipes seems to be reasonable. However, an environment such as that inside pipes is affected by the intrinsic presence of oil, sediment, and rust, which can compromise the functionality of the sensors and the robot’s locomotion mechanism. At the same time, the robot itself may contaminate the external environment. For these reasons, the design of a soft crawling robot is presented, which is based on the actuation of a helical shaft that moves inside a compliant tube, isolating it from the surrounding environment during its inspection operations.

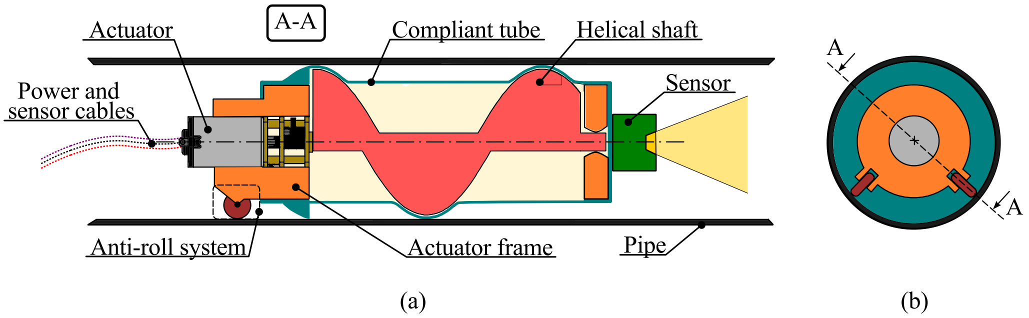

Figure 1 – Functional diagram of the robot: (a) longitudinal and (b) transverse views of the pipe

The functional diagram of the robot is illustrated in Figure 1, through longitudinal and transverse views of the pipe. The characteristic elements of the diagram are:

- actuator: it transmits the torque to the helical shaft;
- helical shaft: it receives torque from the motor shaft and interacts with the flexible tube during its rotation. Its transverse dimension is greater than that of the actuator;
- compliant tube: the isolating component that covers the entire structure of the robot and prevents it from directly interacting with the surrounding environment. It is in constant contact with the helical shaft and adapts to its profile during rotation. It is also responsible for transferring forces generated by the helical shaft to the walls of the pipe;
- actuator frame: the structural support for the robot, housing the stator of the motor and serving as the internal frame that connects the motor to the flexible tube;
- anti-roll system: it balances the reaction torque acting on the actuator frame and the possible moment of the gravitational force if the robot’s center of mass is located outside the contact area between the compliant tube and the pipe;
- sensor: the critical element for conducting the pipe integrity assessment. Normally, it consists of a camera or non-destructive testing equipment;
- power and sensor cables: they connect the motor and the sensors to a remote power source, which is located outside the robot’s operational area.

The robot's locomotion mechanism consists of the interaction between the helical shaft and the compliant tube. This soft tube is attached to the robot's frame, and it mustn't twist during the rotation of the helical shaft. For this reason, the tube must be reinforced in such a way as to provide good torsional stiffness combined with the radial and bending flexibility required to follow the profile of the helical shaft.

3. Executive design

The executive design aims to construct a prototype to verify the behaviour of the compliant tube only so the design does not include the anti-roll system and the inspection sensor. Figure 2 illustrates the constituent elements of the robot: the actuator, the actuator frame, the shaft support, the single-helix helical shaft with the indicated geometric parameters, the flanged bushing, and the compliant tube.

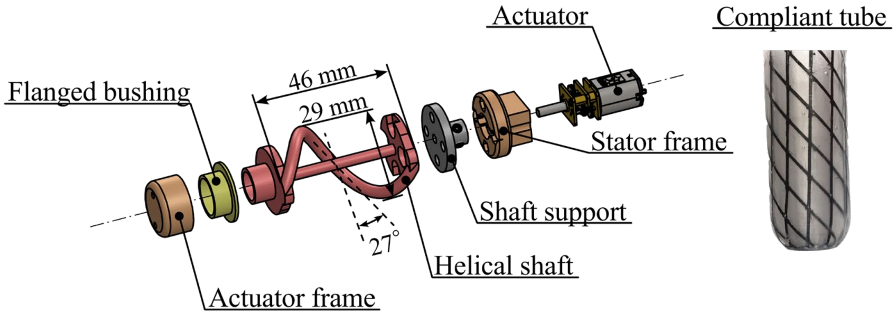

Figure 2 – The different parts of the robot. The geometric parameters of the helical shaft are indicated: the pitch p=46 mm, the diameter D=29 mm and the angle α=27°

The actuator frame is composed of two parts: one directly connected to the actuator stator, and the other positioned at the opposite end of the robot. The two parts are made rigidly together by the compliant tube, which connects them through screws. The compliant tube is fabricated with a compression molding process of AS40 silicone, using two 3D-printed PLA molds, as shown in Figure 3(b). The tube is reinforced by a 3D-printed nylon mesh using FDM technology to achieve the mechanical properties described: the mesh is designed with a single-helix reinforcement that enhances the torsional strength of the silicone tube, preventing it from twisting, but it does not significantly affect the radial and bending strength, allowing the necessary deformation.

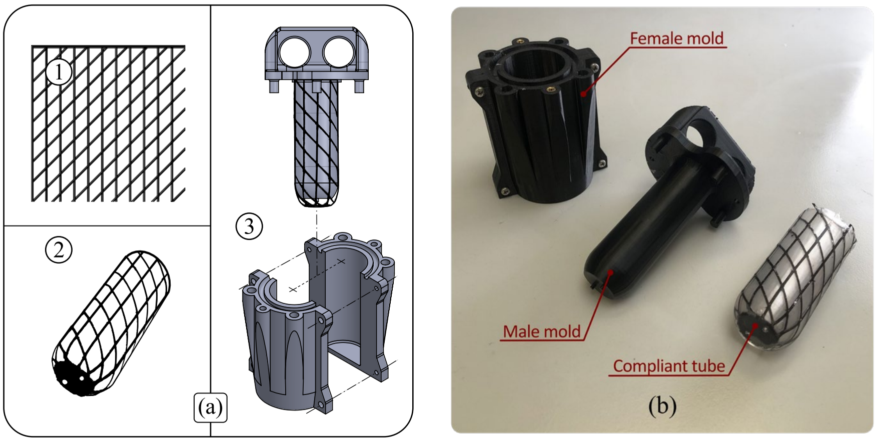

Figure 3 – The compliant tube fabrication process: (a) the different fabrication phases and (b) the PLA 3D printed molds and the produced compliant tube

The manufacturing process, illustrated in Figure 3(a), consists of three main phases:

- in the first phase (1), the reinforcement mesh is 3D-printed;
- in the second phase (2), the mesh is welded to achieve the required cylindrical geometry;
- the third phase (3) involves the compression molding process, following the assembly of the two parts that form the female mold and the positioning of the reinforcement mesh onto the male mold. After molding, the silicone undergoes a curing treatment in an oven to enhance its strength and durability.

4. Prototyping

A preliminary robot prototype was constructed to verify the functionality of the proposed design, with particular attention to the behaviour of the compliant tube. All the components described in the executive design, except for the shaft support and the flanged bushing, were 3D-printed with FDM technology. A test motor was used, while the compliant tube was fixed to the motor stator using a 3D-printed clamp. An experimental test was conducted: Figure 4 shows three instants of the helical shaft's rotation inside the tube according to the indicated angular velocity ω. Thanks to a blue marker drawn on the tube's surface, it is possible to highlight how its angular position remains constant during continuous rotation. This behaviour demonstrates that the tube does not twist significantly, making it promising for future developments.

Figure 4 – Evaluation of the compliant tube's behaviour

As a supplementary result, the robot's locomotion capability on a horizontal plane was evaluated: the robot’s stator frame was kept fixed to the plane while the helical shaft rotated. The compliant tube followed the rotation of the shaft, and it was in contact with a sheet of paper in the geometric center of the latter. The sheet of paper was free to move relative to the plane, and to assess its displacement, a cross-shaped marker was drawn on it. Therefore, the robot is attached to the fixed reference frame $\{O_G, X_G, Y_G\}$ of the plane, while the sheet is attached to the mobile reference frame $\{O_M, X_M, Y_M\}$. Figure 5(a) shows the discrete trajectory of the origin O_M, according to the indicated angular velocity ω, where the subscript *i* refers to the initial configuration, while the subscript *f* refers to the final one. Figure 5(b) shows the initial and final pose of the mobile reference frame. The motion of the sheet is essentially translational, and its trajectory is linear. Still, the angle θ identified with respect to the X_G axis is different from the helix angle α, and this is probably due to the slippage that was evident during the test. This result constitutes a first verification of the physical principle of operation of the robot, which still requires significant further development, especially on the compliant part of the robot.

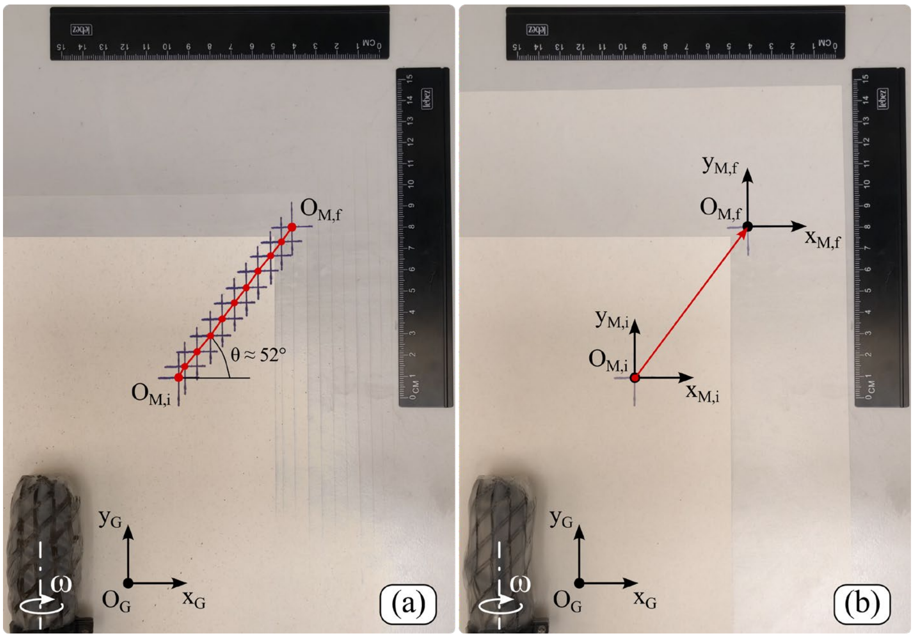

Figure 5 – Evaluation of robot's locomotion capability: (a) discrete trajectory of the origin O_M of the mobile reference system $\{O_M, X_M, Y_M\}$ and (b) initial and final pose of $\{O_M, X_M, Y_M\}$ with respect to the fixed reference system $\{O_G, X_G, Y_G\}$

5. Conclusion

This paper presented the preliminary design of a novel helical motion-based soft crawling robot for in-pipe inspection. The robot uses the rotation of a helical shaft as its locomotion principle, which is a propulsion mechanism that, based on the literature, has the characteristics to be suitable for an application such as pipe inspection. The innovative aspect of the robot lies in the interaction of the helical shaft with a flexible tube that covers the robot and isolates it from the surrounding environment, preventing mutual contamination. Therefore, a preliminary design of the robot has been developed, with particular attention to the flexible tube. The latter must exhibit adequate torsional resistance to prevent twisting during the rotation of the shaft while maintaining a certain radial and bending compliance to adapt to the shaft's profile. To meet these requirements, a manufacturing process was conducted involving the compression molding of AS40 silicone reinforced with a nylon 3D-printed single-helix helical mesh. A prototype of the robot was constructed with the primary goal of evaluating the behaviour of the compliant tube, and it was found that the desired mechanical characteristics were achieved. A supplementary result was obtained from the first verification of the physical principle of operation of the robot, confirming its ability to move on a horizontal plane. However, further development and refinement work are still needed, especially on the deformable part of the robot, to create a prototype capable of moving inside a pipe.

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