Design And Development of a Bio-Inspired Worm Robot for Pipe Inspection

Dr.K.K.Arun[1], Mithilesh B[2], Anuranjith R[3], Dinush R[4], Gowtham Dharmalingam D[4]
[1,2,3,4]*Kumaraguru College of Technology, Coimbatore - 641049*

***Abstract*— The integrity of modern pipeline infrastructure is critical for safety and continuous operation. Traditional inspection methods are often costly, time-consuming, and carry inherent risks in hazardous or confined environments. This project addresses these limitations by developing a soft, modular, worm-inspired robot specifically engineered for navigating and inspecting pipelines of varying diameters and complex geometries, including elbows and vertical sections. Drawing inspiration from the peristaltic motion of the earthworm, the robot employs a sequence of radial gripping and axial elongation/contraction to achieve stable, high-traction locomotion. The key design innovation lies in its underactuated or pneumatic/Shape Memory Alloy-based soft modular segments, which allow for passive adaptation to diameter changes. The prototype integrates a miniaturized Non-Destructive Evaluation sensor suite for detecting internal defects. Successful realization of this project provides a highly flexible, cost-effective, and robust robotic platform for autonomous pipeline inspection, significantly enhancing infrastructure maintenance and reducing human risk.**

***Index Terms*— Bio-inspired, Peristaltic Motion, Pipe Inspection, Soft Robotics, Non-Destructive Evaluation.**

I. INTRODUCTION

Pipelines constitute the circulatory system of modern infrastructure, forming the backbone of global energy, water, and industrial supply networks. They are responsible for the efficient and large-scale transportation of essential resources such as water, natural gas, crude oil, and refined petroleum products. The structural integrity and operational reliability of these pipelines are therefore of utmost importance; any failure can lead to catastrophic consequences including supply disruption, economic losses, environmental contamination, and even threats to human life.

Despite their critical role, the inspection, monitoring, and maintenance of pipeline systems remain complex engineering challenges. Many sections are buried underground, submerged underwater, or located in confined spaces, making direct human access difficult or impossible. Traditional techniques are labor-intensive, time-consuming, and limited to accessible regions. Moreover, conventional rigid inspection devices struggle to adapt to the intricate geometries of real-world pipeline systems, which include varying diameters, multiple bends, elbows, junctions, and vertical or inclined sections. This lack of uniformity restricts the mobility of rigid tools, which are prone to getting stuck. Innovations such as soft robotics, modular inspection crawlers, and sensor-integrated systems offer promising solutions, enabling continuous monitoring and predictive maintenance.

A. Background

The imperative for autonomous pipe inspection stems from the limitations of hydrostatically operated Pipeline Inspection Gauges (PIGs) and tethered remotely operated vehicles (ROVs). PIGs require uniform pipe geometries and cannot navigate highly variable diameters, while tethered systems suffer from drag and entanglement. There is a clear need for untethered, miniaturized, flexible, and adaptable inspection systems.

II. LITERATURE REVIEW

A literature survey provides context by identifying gaps in current knowledge and establishing a theoretical foundation. Key research includes the study of earthworm-inspired soft robots, which highlights locomotion principles and confined space advantages. Tanaka (1989) developed foundational mathematical models for peristaltic movement, linking contraction waves to forward motion. Recent work by Consumi et al. (2022) discusses antagonistic actuation for robust peristaltic waves.

Other studies focus on pneumatic soft burrowing robots that emphasize radial expansion for anchoring, and origami-inspired structures for flexible, deployable segments. Additionally, researchers have explored modular mesh designs and cable-driven hoops for locomotion in constrained environments. However, gaps remain in achieving stable locomotion in wet, slippery, or vertical segments using low-power sensing.

III. PROBLEM IDENTIFICATION

The central problem addressed is the lack of a suitable autonomous inspection mechanism capable of navigating pipes with Varying Internal Diameters (VIDs), tight radius bends, and complex vertical configurations.

Core issues include: 1) Inadequate adaptability of conventional rigid devices (PIGs, wheeled systems) to non-uniform geometries, leading to jammed tools and incomplete data. 2) Lack of stable locomotion required to traverse vertical or slippery segments, preventing the effective deployment of essential Non-Destructive Evaluation (NDE) sensors. 3) High operational risk and downtime associated with manual inspection or taking pipelines offline.

IV. DESIGN AND DEVELOPMENT

The "Flap System" or Radial Expansion and Anchoring Mechanism is the most critical mechanical subsystem. Drawing inspiration from earthworm anchoring, it generates propulsive force through controlled body deformation.

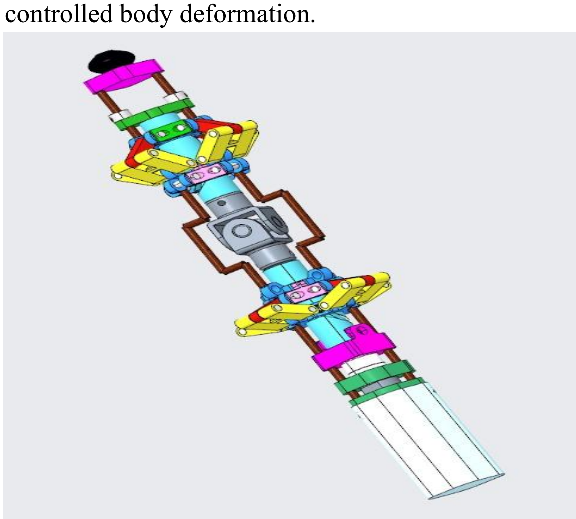

Fig. 1. Worm Robot CAD Model Assembly and Isometric View

The complete system was designed using SolidWorks. Each component, including linkage arms, central shaft, Universal Coupling and structural frames, was modeled to ensure proper alignment and functional fit. Motion Study tools simulated the conversion of linear actuator displacement into radial expansion, confirming smooth operation and establishing wall contact for anchoring.

V. COMPONENT BREAKDOWN

The mechanical structure consists of: 1) Central Shaft (Aluminium 6061-T6): The main structural member transmitting actuation forces. 2) Segment Frame (Nylon/ ABS): Modular units housing the linkage mechanisms. 3) Linkage Mechanism (Aluminium Rod): Converts linear motion to radial expansion for gripping. 4) Motor Assembly:

High-torque micro-servos or mini motors for synchronized expansion. 5) Flexible Outer Sleeve (Silicone/TPU): Mimics the worm's soft body and provides protection. 6) Gripping Pads (Neoprene/Nitrile Rubber): Enhances traction against the pipe wall. 7) Control Unit (Arduino/ESP32): Coordinates the movement cycles and synchronizes sensors.

VI. WORKING PRINCIPLE

Operation is based on peristaltic locomotion, involving a cyclic sequence: 1) Anchoring (Radial Expansion): One segment expands to press against the wall, creating a firm grip. 2) Elongation (Axial Extension): Unanchored segments extend to push the front section forward. 3) Contraction and Release: The rear segment releases its grip and is pulled forward, completing the cycle.

As the robot moves, it performs real-time inspection. Camera modules transmit live video for visual anomalies, while integrated Infrared and Ultrasonic sensors perform non-destructive evaluation to detect leaks, wall thickness variations, or internal cracks.

VII. ENGINEERING APPLICATIONS

The robot is applicable across various sectors: 1) Pipeline Inspection in oil, gas, and water distribution. 2) Municipal Infrastructure monitoring for sewage and drainage systems. 3) Nuclear and Hazardous

Environment inspection where human intervention is risky. 4) Aerospace and Marine applications for inspecting aircraft fuel lines and submarine piping.

VIII. LIMITATIONS AND RESEARCH GAPS

Current designs often lack mechanical adaptability to surface roughness and sudden geometry changes in real pipelines. High energy consumption and the slow response of certain actuators (like SMAs) restrict continuous operation.

Project-specific limitations include dependence on friction, which makes operation in extremely wet or oily pipes challenging. Furthermore, payload constraints limit the robot to qualitative inspection sensors rather than heavy quantitative tools. Battery life also restricts the mission range, especially during power-intensive vertical climbs.

IX. CONCLUSION AND FUTURE SCOPE

The bio-inspired worm robot provides an innovative solution for autonomous pipe inspection. Its modular design overcomes the limitations of rigid systems, offering flexibility and adaptability to varying diameters. Future scope includes miniaturization, AI-driven defect detection, and enhanced traction mechanisms for diverse pipe materials.

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