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Pipe-finder: Adaptive, Lightweight Pipe Robot Integrating Origami Anisotropic Stiffness Structure

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***Abstract*—Pipeline inspection poses challenges that require robots to navigate complex environments. However, existing pipeline robots with the rigid bodies often face limitations in terms of efficiency, flexibility, and adaptability considering the significant size variations and complex terrains in pipelines. This paper introduces a novel design of wheel pipeline robots that addresses these limitations by incorporating the Origami Anisotropic Stiffness Structure (OASS). Inspired by the desert iguana's skin, the OASS offers a unique combination of rigidity and flexibility in different directions, making it an ideal skeletal framework for the robot with only 146 g weight. By integrating the OASS with PLA and resin materials, we enhance the robot's support and enable it to effectively navigate diverse pipeline configurations. Experimental results demonstrate the robot's capability to maneuver through pipelines of different diameters, U-shaped turns, obstacles, and even vertical sections. This research provides a promising solution for inspection tasks in complex pipeline systems.**

I. Introduction

Pipelines are essential for transporting fluids and gases across long distances in modern society [1]. China has 17,800 km of gas pipelines under construction, valued at approximately US$21.9 billion, according to the 2022 year-end survey by the Global Gas Infrastructure Tracker [2]. However, pipelines are subject to various types of damage and deterioration over time, such as corrosion, cracks, leaks, and blockages, which causing harm to life, damaging the environment and causing property loss [3]-[6] . Therefore, it is crucial to inspect and maintain the pipeline network regularly to ensure its safety and efficiency. To address this issue, many researchers have developed various autonomous mobile robots that can perform pipeline inspection tasks in complex and changing environments. These robots need to be able to adapt to different pipe diameters, shapes, orientations, and wall conditions, as well as to overcome obstacles and turns [7]-[10].

Fig. 1.Pipe inspection robot: Pipe-finder based on OASS proposed in this work.

In pipeline inspection robotics, legged robots, renowned for their exceptional maneuverability in challenging environments, exhibit superior adaptability and agility [8]. On the other hand, crawler-type robots, with their straightforward mechanical structures, demonstrate effective navigation through diverse pipe configurations. Similarly, wheel-type robots are notable for their efficient and reliable locomotion. However, the complex structure of pipeline networks, including pipes with different diameters and multiple bends, poses a significant challenge when it comes to accomplishing successful inspection tasks [9]. Most of the current pipe robots have limited adaptability to irregular terrains or surfaces due to the rigid body [10-12]. Secondly, their bulky structure restricts their ability to navigate through varied-sized pipelines, lacking the necessary flexibility [13]. Third, despite the presence of adaptive mechanisms to ensure continuous traction on the wheels, the inclusion of redundant actuators and rigid structures often results in excessive complexity and weight of the robot's structure [14]-[17].

TABLE I. Comparison of Pipeline Wheel Robots

Wheel robot	Min. Diameter (mm)	Max. Diameter (mm)	Expansion Ratio (Max Dia. /Min Dia.)
PIR [20]	90	130	1.40
FAMPER [21]	127	157	1.23
Flat wheel[14]	80	100	1.25
Mini robot[22]	140	200	1.42
Pipe-finder (Our work)	50	150	3

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Building upon these challenges, a potential solution lies in utilizing soft robotics and implementing the Origami Anisotropic Stiffness Structure (OASS) as the skeletal branches for wheeled pipeline robots. The OASS is a unique structure inspired by the desert iguana's skin, which exhibits both rigidity and flexibility [18]. This structure offers varied stiffness properties along different directions, making it suitable for a range of applications. Origami structures, including the OASS, have gained attention due to their lightweight nature, anisotropic stiffness and simplicity of manufacturing [19]. Despite extensive research on the geometries and mechanics of the OASS, its practical applications in robotics remain relatively unexplored. Here we integrate OASS into the pipe robot to generate expansion by the bending of the low stiffness direction and keep the robot configuration at the high stiffness direction [24]-[27].

In this study, we propose a novel design of wheel pipeline robots that incorporates the OASS as branches to address the limited adaptability and flexibility of conventional wheel-type robots in complex and varied environments. This design has been practically validated as our robot won the second place in the 2023 RoboSoft Soft Robot Locomotion Competition. In testing, our robot demonstrated the capability to navigate pipelines with diameters ranging from 50 mm to 150 mm (expansion ratio: 3, more than two times higher than previous similar robots [14][20][21][22]), maneuver through U-shape turns, overcome obstacles, finishing a 45cm length vertical pipeline in 52 seconds, and even handle pipelines with flexible walls. These results highlight the potential of our robot to serve as an inspection robot in complex pipeline systems.

In the next section, we describe the overall design principle and fabrication details. In section III, the control system of

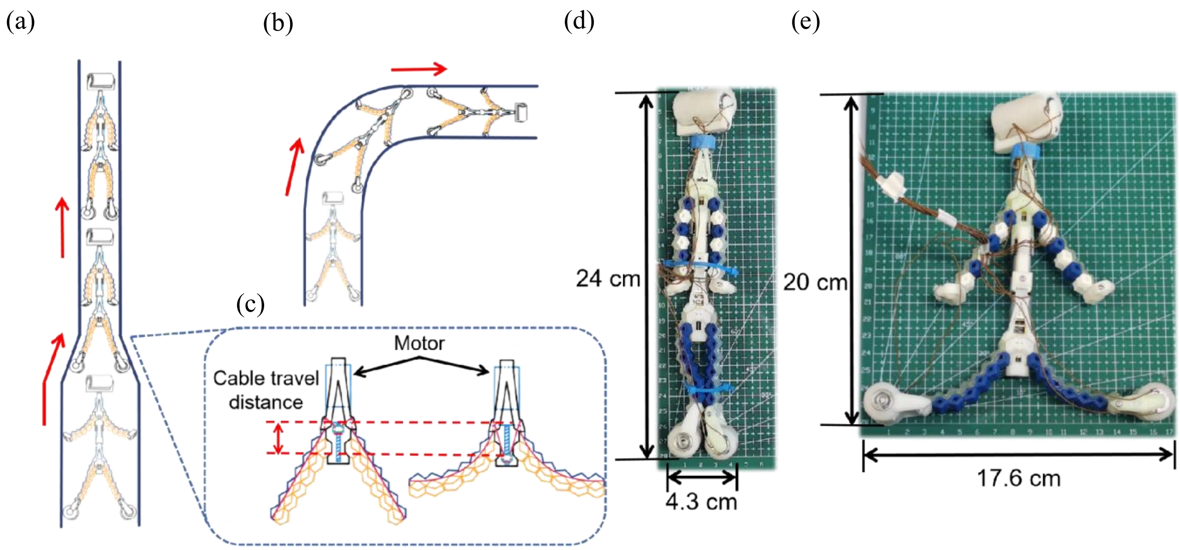

Fig. 2. (a) Schematic diagram of diameter-changing operation, where the robot controls limb bending transformation through the motor in figure (c) pulling the cable when the pipe diameter reduces. (b) Schematic diagram of curved path operation, passively adapting to the pipe changes through the flexible OASS. (d) and (e) illustrate the extensional robot size variation based on OASS, with a minimum diameter of 4.3 cm and a maximum of 17.6 cm (maximum travel of the motor).

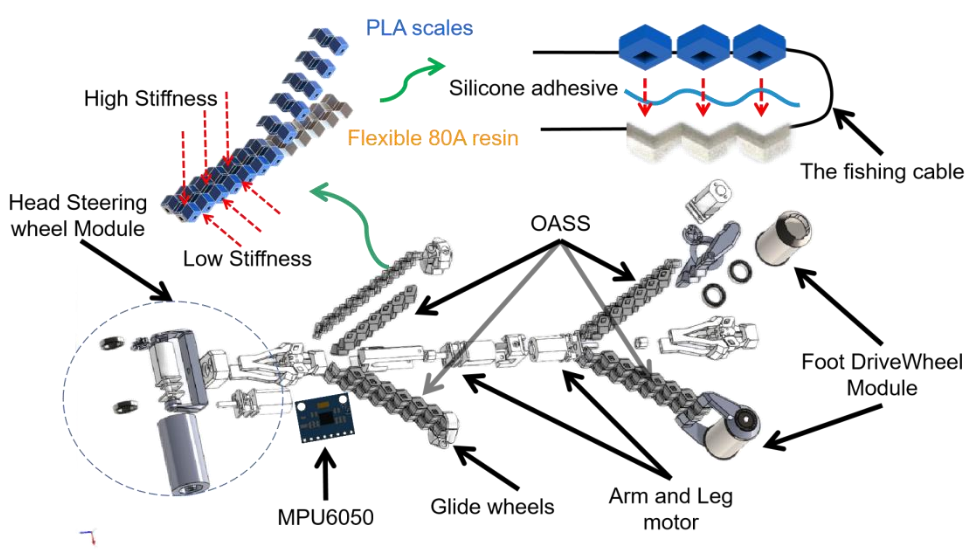

Fig. 3. Concept design and fabrication of Pipe-finder.

robot is discussed. In section IV, the modeling of the Pipe-Finder robot is detailed. In section V, we evaluate the robot by pipeline tests and loading tests. In section VI, we conclude this paper.

II. Pipe-finder Development

A. Design and working principle

The design of our wheel pipeline robots is based on the OASS, which gives wheel-type robots three advantages. Firstly, our robots exhibit a substantial expansion ratio, enabling them to effectively accommodate a diverse range of pipe diameter variations. As presented in Table I, our robots demonstrate an expansion ratio of 3, surpassing other rigid wheel-type robots. Secondly, the OASS is made of PLA and flexible resin materials, making the robot compact, lightweight, and simple in structure. The Pipe-finder weighs only 146 g, which is lightweight compared to the average weight of 2.2 kg for wheeled pipeline robots of similar sizes [20]. Most importantly, the OASS has low bending stiffness in the axial direction, providing sufficient support for the robot to crawl upwards, as showed in Fig. 2. In the radial direction, it has high stiffness, enabling the robot to better adapt to various obstacle environments. Showed in the Fig. 3, the overall structure of our Pipe-Finder robot has a humanoid-like shape, consisting of four limbs and a head. The limbs of the robot utilize the OASS for enhanced flexibility and adaptability. The OASS is constructed using PLA plastic and Formlabs' flexible 80A resin. The rigid panels made of PLA a form scales located close to the robot's central axis, while the outer sides are composed of flexible resin material. This arrangement allows for controlled bending angles and directions driven by cables, providing the robot with expandability and improved environmental adaptability.

Each limb of the robot is equipped with an OASS, allowing the robot to adjust its volume and contact force with the pipe walls, as showed in Fig. 2(c). Rear driving wheels are fixed at the ends of the two legs, providing propulsion. To accommodate smaller diameter pipes, we minimize the robot's rigid structure. This is achieved by using smaller N20 motors as the driving mechanism and positioning the wheel module motors inside the wheels to save space and protect against fluid ingress. The arms of the robot have passive wheels for additional support. Linear actuation controlled by the torso motors allows the robot to adjust limb bending, modify volume, and optimize contact force with the pipe walls, enhancing friction and movement efficiency. The robot's central axis aligns with the pipe's axis, ensuring smooth passage through varying pipe widths without excessive oscillation. To enable autonomous navigation in complex terrains, a front wheel module is utilized. Integrated with an Inertial Measurement Unit (IMU), the front wheel's orientation and rotation are adjusted dynamically, ensuring continuous propulsion and minimized resistance. This design enhances the robot's adaptability and efficiency across diverse pipe environments. Our OASS-based wheel pipeline robots possess enhanced adaptability, maneuverability, and efficiency when traversing pipes with varying diameters, turn joints, vertical sections, and challenging terrains.

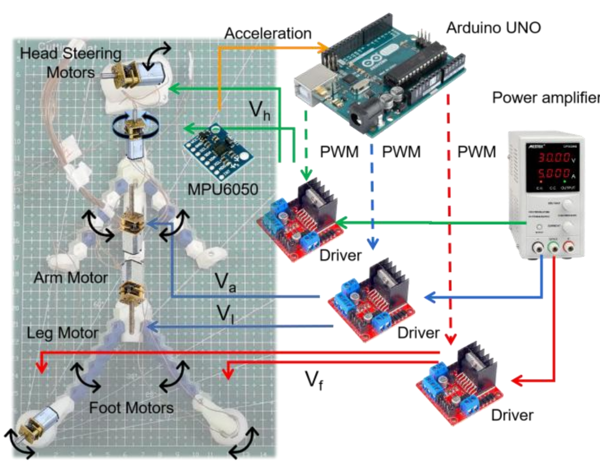

Fig. 4. Control system diagram.

B. Fabrication of Pipe-finder

The core driving unit of Pipe-finder boasts a symmetrical design. The limbs' actions are governed by two N20 screw motors, which modulate cable tension. These motors are nestled within the rollers at the limb ends, propelling the wheel assembly. The OASS fabrication entails two main elements as depicted in Fig. 3: a flexible membrane and rigid pyramid-shaped scales. The membrane, 3D printed with Formlabs' flexible 80A resin, possesses a tensile strength of 10.9 MPa and an elongation rate of 192%, furnishing the requisite elasticity for the OASS. Conversely, the rigid scales are crafted from PLA material using a Raise3D printer. The assembly process involves affixing the scales to the membrane slots via silicone adhesive, followed by threading a fishing cable through designated apertures to unite the components. This straightforward, cost-efficient process approximates a $5 expense per OASS unit. Employing these fabrication methodologies, we actualize a dependable and operational OASS, melding flexibility with rigidity, thus facilitating effective conduit locomotion.

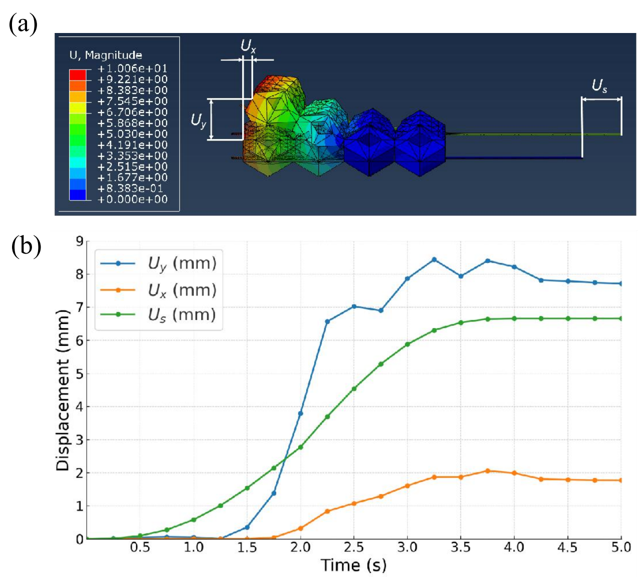

Fig. 5. (a) Finite element analysis of 4 units OASS. (b) The displacement U_x and U_y at the end of the structure are relative to the horizontal displacement of the fishing cable, which expressed by U_s.

C. *Control system*

We are using the Arduino UNO as the control board for our pipeline robot. Its advantages lie in its easy and convenient control. However, due to limitations in its pin interface, it cannot meet the requirements of controlling a robot with six drive motors and voltage distribution. To address this, we have added three motor drives to ensure a stable power supply and safe control, as showed in Fig. 4.

Since pipeline inspection robots often operate in harsh environments, integrated robots often encounter issues such as battery shortage. However, for a pipeline robot, we are able to separate and externalize the controller and the main power supply module, providing power to the robot through cables. This design not only facilitates robot maintenance and recovery but also ensures a continuous and stable power supply during operation [23]. We have also incorporated an MPU6050 to provide feedback information, allowing us to detect the orientation of pipeline the robot is currently navigating.

III. MODELING

To determine the range of pipe diameters the robot can navigate, we performed finite element analysis to simulate the variation of the OASS within the range of motor cable tension. First, we defined the parameters for the rigid scales, flexible resin layer, and fishing cable. The rigid scales were made of PLA material with a Young's modulus of 3 GPa. The flexible resin layer was characterized as follows: 1. Material: Formlabs' Flexible 80A photosensitive resin; 2. Stress at 50% elongation: 3.1 MPa, stress at 100% elongation: 6.3 MPa; 3. Based on these data, we approximated the stress-strain relationship of the material as linear and assigned a Young's modulus of 6.3 MPa. The fishing cable was composed of Nylon-66 material.

During the simulation, we fully fixed the base and the end of the fishing cable connected to the rigid structure, while smoothly pulling the end of the fishing cable attached to the flexible structure by 6 mm. Fig. 5(a) illustrates our simulation model, where Us represents the displacement of the fishing cable, i.e., the input value. The horizontal displacement at the end of the structure is denoted as Ux, and the vertical displacement is denoted as Uy. Fig. 5(b) demonstrates the relationship between the tension in the four-section OASS and the corresponding displacements. When Us changes by 6 mm, the maximum variation in Uy reaches 8.4 mm.

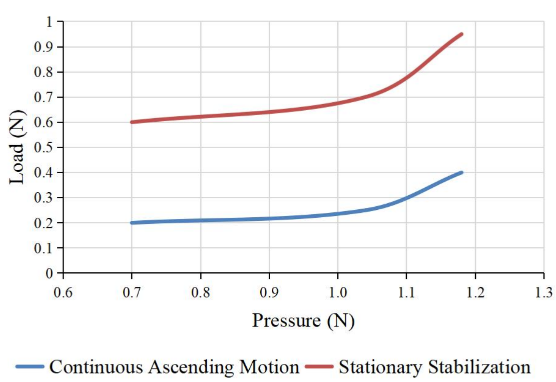

Fig. 6. The relationship between the maximum load on the robot and the pressure exerted on the wall by the robot in vertical pipeline load tests.

Based on realistic estimations, we employed 8 sections of the OASS on the robot. In this case, we achieved a Uy displacement of up to 60 mm by relaxing and tightening the input fishing cable. Considered the diameter of the rigid parts (4.3 cm) of the robot and installation angle of OASS, we inferred that our robot is capable of adapting to a diameter range from the minimum diameter to triple the maximum diameter (from 5 cm to 15 cm) of the pipes. Theoretically, our robot can navigate through pipes within this range.

IV. EXPERIMENT

To validate the capability of the OASS-based wheel pipeline robot in adapting to complex environments and traversing pipelines, we conducted a series of experiments, including load testing and pipeline traversal experiments.

A. *Load Capacity of the OASS*

In this part of experiment, we examined the robot's

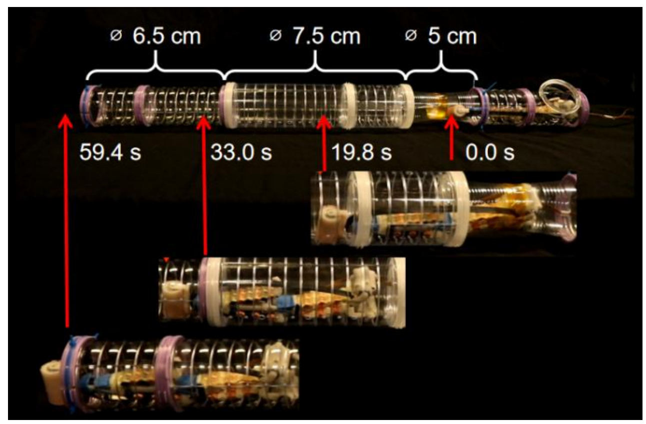

Fig. 7. Pipe diameter change scenario: pipe diameter changes from 50 mm to 75 mm to 65 mm.

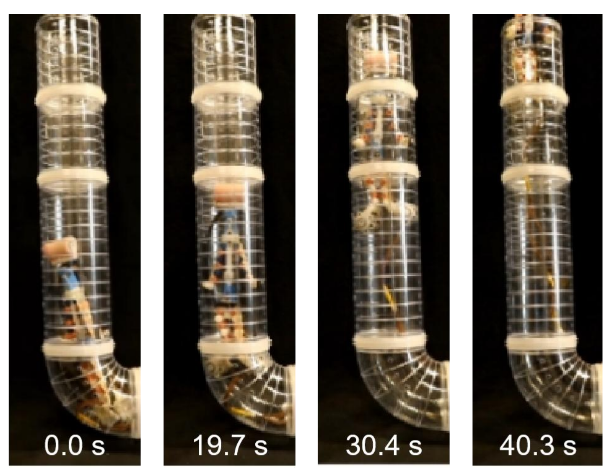

Fig. 8. Vertical pipe: vertical pipe with a length of 45 cm.

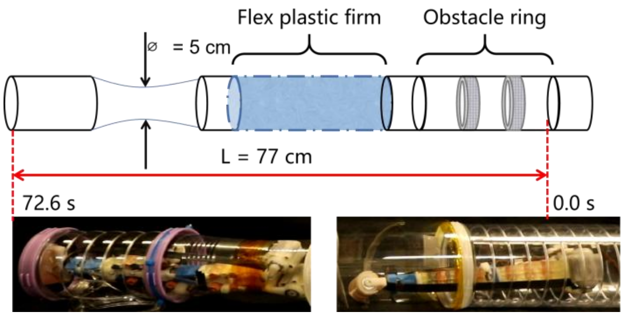

Fig. 9. Obstacle Traversal: 5 mm obstacles rings, flexible pipe wall made with flex plastic firm and 5 cm diameter gradient pipe.

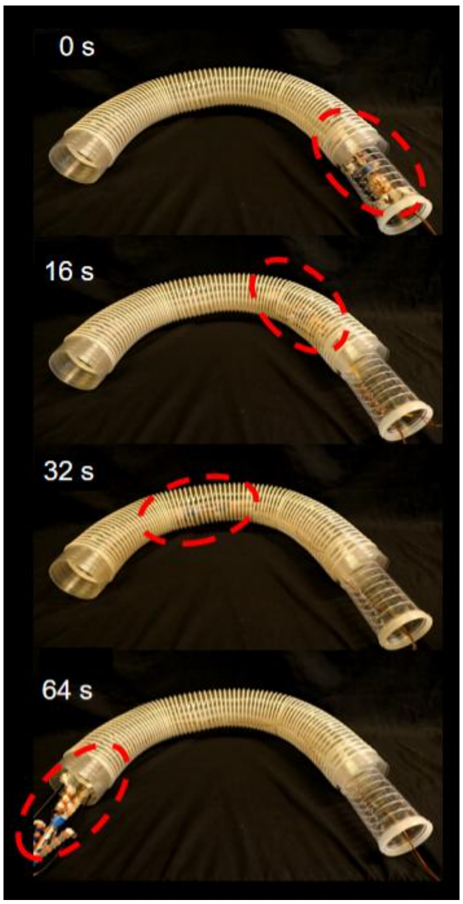

Fig. 10. Curved pipe: U-shaped bend composed of 10 cm diameter PVC ventilation pipe.

maximum load while continuously moving upward and maintaining stability to assess its load efficiency. For a specific pipe diameter, the pressure exerted by the robot's legs on the pipe wall gradually decreases and stabilizes due to the elasticity and adaptability of the OASS. The robot can maintain relatively stable pressure on the wall when the pipe diameter is less than 10 cm. However, for diameters larger than 10 cm, the leg pressure on the pipe wall starts to rapidly decrease.

To investigate the relationship between pipe diameter and pressure, we conducted vertical load tests using transparent smooth PC pipes with diameters of 6 cm, 7.5 cm, 9 cm, and 10.5 cm. A tension meter recorded the maximum load under different robot motion states, including continuous upward movement, maintaining stability (slipping in place), and downward sliding. Fig. 6 illustrates the variations in load capacity for both continuous ascending motion and stationary stabilization robot states. The maximum load shows an overall increasing trend as the leg pressure on the pipe wall increases. When the pressure is below 1 N (pipe diameter > 9.5 cm), the load stabilizes, but when the pressure exceeds 1 N (pipe diameter < 9.5 cm), the maximum load rapidly increases. For continuous forward movement, the maximum load reaches 0.6 N at a pressure of 1.27 N (corresponding to a pipe diameter of 6 cm). This indicates that the robot can adapt stably to vertical climbing scenarios with pipe diameters ranging from 5 cm to 12 cm.

B. Pipeline traversal Experiments

In the pipeline operation experiment, we designed the following four specific experimental scenarios as shown in Fig. 7, 8, 9, 10.

a) Pipe Diameter Variation: To test the robot's adaptability to different environments, we designed a series of experiments with varying pipe diameters using air ducts of different diameters (5 cm, 6.5 cm, 7.5 cm), showed in Fig. 7. The transition between different pipe diameters was abrupt. The robot contracted the OASS when passing through the 5 cm pipe, and expanded the OASS when navigating the 7.5 cm and 6.5 cm pipes, increasing the pressure against the pipe to enhance efficiency. The robot traversed smoothly without any issues, taking a total of 72.6 seconds.

b) Vertical Pipe Crawling: For vertical pipes with a 90-degree angle or larger, the robot relied on the adaptability provided by the OASS's expansion and contraction as well as the pressure against the pipe wall to ensure continuous crawling. We designed a testing environment with a vertical pipe with a radius of 7.5 cm and a length of 45 cm. We tested the climbing ability of the OASS robot from a horizontal to a vertical pipe in the Fig. 8, and it successfully crawled out of the pipe in 52 seconds.

c) Obstacle Traversal: In Fig. 9, we placed three different obstacles inside the pipe. 1. We created a sudden change in a 5 mm obstacle with adhesive thickness using 3M tape. 2. Flexible thin-film pipeline where the pipe deforms upon contact, unable to provide sufficient support force. 3. Smooth pipe with gradually changing diameter, with the minimum diameter being 5 cm. The robot experienced a brief jam when passing through the last obstacle due to slippage between the support position and the smooth pipe wall. However, by coordinating the contraction and expansion of the arms and legs controlled by the operator (arm contraction, leg expansion), the robot managed to overcome this obstacle in the end.

d) Horizontal U-shape turn: We constructed a U-shaped bend in a horizontal pipe using a PVC vacuum cleaner duct with a diameter of 10 cm and a length of approximately 1 m. The purpose of this experiment was to evaluate the adaptability of the OASS robot in navigating horizontal pipe turns. In Fig. 10, the robot successfully traversed the bend in 62 seconds, even though the ventilation pipe material was relatively soft and had edges, it did not experience any jamming.

V. CONCLUSION

In this work, we developed a lightweight, adaptive wheel robot called Pipe-Finder for pipeline inspection, utilizing the OASS as its skeletal framework. The robot's four limbs consist of OASS, enabling control over their contraction and expansion. The first two OASS in the front section are responsible for adjusting the robot's posture, while the latter section connects to two sets of wheels, providing forward drive. At the robot's head, a steerable wheel is employed for directional control. To determine the range of pipe sizes that the robot can accommodate, we conducted finite element analysis to assess the bending capabilities of the OASS. Based on these findings, we derived that the robot can navigate through pipes ranging from approximately 5 cm to 15 cm in diameter. Finally, the experimental results corroborated the simulations, demonstrating the robot's successful traversal of various pipe configurations, including a 45cm length vertical pipe, a variable-diameter pipe ranging from 5 cm to 7.5 cm to 6 cm, U-shaped bends, and obstructed pipes.

In the future, the integration of cameras and other sensors will enhance the robot's intelligence, enabling it to autonomously perform pipeline inspection tasks.

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