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Foldable Spherical Pipeline Robot: Design, Control and Simulation

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Abstract. This paper focuses on foldable pipeline inspection robots, developed to overcome the limitations of traditional rigid robots used in infrastructure maintenance and safety monitoring. Conventional robots, often exceeding 10 kg and 15 cm in diameter, struggle to access narrow or irregular pipes due to their hard metal structures. In contrast, foldable robots integrate soft materials such as silicone elastomers and shape-memory polymers with bio-inspired or origami mechanisms, allowing them to compress to a tennis-ball size—reducing volume by up to 70% and weight to under 3 kg. Structurally, the robot draws inspiration from spider locomotion, featuring six foldable legs driven by thirteen servo motors for precise motion control, achieving a linear velocity of 0.494 m/s and excellent stability on complex terrains. Electrically driven and AI-assisted, it supports both manual and autonomous modes for navigation and inspection. These robots have demonstrated remarkable adaptability in municipal, industrial, and emergency scenarios, performing tasks like detecting pipe corrosion, leaks, and deformations. Their lightweight, compact, and flexible design highlights strong potential for future applications in infrastructure, rescue, and medical fields.

Keywords: Robot, Origami, Bio-Inspired, Pipeline

1. Introduction

In recent years, the global demand for efficient infrastructure maintenance and safety monitoring has driven significant growth in the pipeline inspection robot market, with key regions such as North America and Asia experiencing compound annual growth rates exceeding 15% [1-3]. These robots are indispensable in key areas such as municipal pipeline networks (inspecting underground pipeline corrosion), natural gas pipelines (detecting explosion risk leaks)[4], and industrial ventilation systems (identifying airflow blockages). With the acceleration of urbanization and the need for more frequent inspections of old pipelines, their global production and application scale have rapidly expanded, effectively preventing accidents such as water pollution, gas explosions, and equipment overheating.However, most existing models have a major flaw: they are made of hard and rigid materials (metal alloys, reinforced plastics).

Although these materials can ensure resistance to harsh pipeline environments (high pressure, chemical corrosion), they result in bulky and heavy designs - with a minimum diameter exceeding 15 centimeters and a weight exceeding 10 kilograms [5].This makes transportation cumbersome

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(needing specialized vehicles for remote sites) and limits mobility in tight spaces. For example, in post-earthquake buildings collapsed, rigid robots get stuck when inspecting narrow gaps for survivors or small pipes. In factories, they fail to navigate intricate <8cm-diameter pipes in chemical or precision plants.

To solve this, researchers are developing foldable pipeline inspection robots [6]. These can fold into compact shapes (some as small as a tennis ball) to fit narrow openings, then unfold sensors, cameras, and movement parts inside. Key designs use soft materials (silicone elastomers, shape-memory polymers) with bio-inspired structures—like insect segmented movement or origami folds. Some mimic caterpillars for tight bends; others use origami hinges for stable expansion. Folded, they reduce volume by 70%, weighing under 3kg for easy carrying.

Soft materials and folding give these robots great flexibility, letting them adapt to irregular pipes, navigate sharp bends, and squeeze through small cracks—tasks rigid robots can't do. This opens new uses: emergency rescue (crawling rubble to deliver supplies/feeds), medical care (mini versions for minimally invasive surgery), and industrial checks (tiny aircraft coolant pipes).

This article reviews the design, manufacturing, and application of foldable pipeline robots. It studied how soft materials (elasticity, chemical resistance) and folding mechanisms (origami and biomimicry) can improve performance in narrow spaces, analyzed challenges (soft material durability, battery life), and explored future applications (artificial intelligence navigation, swarm actuators for large pipelines), with a focus on their value in unmet infrastructure, rescue, and beyond needs.

2. Structural design of folding robots

The structural, functional and actuating requirements should be considered in the design of folding robots. Consequently, several common styles of design are also developed by related researchers. Bionic design is an important research direction among them, which mimics the morphology, structure and movement logic of organisms in nature,through combining the origami structures with biological movement characteristics[7]. For example,through the translation of traditional origami patterns including Miura-ori and six-crease folding, with morphology (methods of locomotion) found in multi-legged animals such as crabs for instance, crab inspired six-legged origami robots are developed. These bionic designs can also support the robot with more flexible movements and better stability than those in complex environments. The use of origami theory is also a principal design concept of the mechanism, which leverages fundamental origami principles involving accordion and mountain-valley folding [8]. So a controlled folding and unfolding structure can be built by precisely designing the corresponding crease-pattern and choosing proper materials (e.g.,flexible polymer, thin metal sheet) 5,31. This guarantees that the pack becomes appreciably smaller on folding and has the necessary level of stability coupled with a mobility and move ability when stretched out. Modular robotics design The concept of modular transmission is one in which composition costs are reduced by a robot being divided into many standardized, reusable functional modules. These can be modulated and easily combined or rearranged for different tasks (e.g. detection, transport, assembly). One example is the Kilobots by Harvard University, that has a variety of small origami cell units towork together in synergy to fold into various shapes according to specific scenarios. Multi-material integration design focuses on the coordination of material properties, including rigid materials (for structural support), flexible materials (enabling bending and deformation) and functional materials such as based on intelligent contractile composites, pressure sensitive composites, self-healing composites etc., thatmake folding robots have more functions. For

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example, hybrids origami structure can incorporate actuation, sensing and self-healing devices being developed to newapplication domains such as robotics.

In the context of design prototypes, Figure 1 shows the Slinky robot which is a representative example of miniature folding prototype [9]. The main body of the W6R3 in Fig. 1 is achieved by fusing together two arms of an L- shaped origami and attaching two pairs of NdFeB internal magnets at either end in the case whereit is folded following a crease pattern. With the aid of the external permanent magnets, it realizes the long-range non-contact actuation and stably executes various movement modes (e.g. inchworm-like crawling, peristalsis, spring-like rolling). Its architecture is also quite basic and straight forward to reproduce. Curve Quad robot is proposed by Sung Laboratory, in United States, and it is derived fromcurved-crease origami, which has four edges in total [10]. Control can be as folding or unfolding as well one complete crawling on a single motor action basis. The triggered mechanism and transmission structure are simplified to save weight andspace, meanwhile guarantees the movement reliability in narrow space, available for mobile operations. In addition, thereexists origami robot [2-4] prototypes that are developed according to the principle of origami such as used SMAs (Shape memory alloys) as actuation material. To unfold and fold back, these robots exploit the shape recovery of SMAs activated to unfold the origami structure and folded down by elastic materials when deactivated,for automated folding unfolding operation cycles. These prototypes are frequently utilized in high volume demandand precision control applications, for example: Minimally Invasive Medical surgery and Aerospace engineering.

In terms of structural design, we drew inspiration from the walking patterns of spiders in reality and installed six foldable mechanical feet for the robot. When all mechanical feet retract, the shape becomes circular. Each mechanical foot can be folded again through hinges to enhance its ability to adapt to complex terrain, or can roll and move through a circular shape without unfolding to achieve walking function in narrow spaces. In addition, the robot is equipped with a total of 13 servo motors. A motor is located in the middle of the robot and connected through gears; it is used to control the retraction and deployment of mechanical feet, thereby changing the appearance and overall size of the robot. In addition, an additional motor is installed on each mechanical foot and connected through a hinge connection structure. These foot-operated motors are specifically designed for fine manipulation of mechanical feet, such as adjusting walking speed and deployment angle.



Figure 1. Robot 3D diagram entity and arm

As shown in Figure 1, each mechanical foot is petal-shaped, and the overall height of the mechanical foot is strictly controlled as 176mm. This size of overall height of the mechanical foot meets not only the requirement of the overall structure layout of the robot, but also the requirement of supporting the robot in different pipeline with different diameter. Besides, when the two mechanical arms on the same side are closed, the gap of the two mechanical arms is controlled as

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5mm. This small gap can prevent the dust, accumulated water and rust debris in the pipeline from entering the mechanical inside, blocking the component and causing the wear between the components, which can provide effective protection for the robot to work stably in the harsh pipeline environment.

To make the robot work stably in the different occasions, such as walking, rolling and the uneven road surface, the mechanical feet (Figure 2) of the robot adopts the design scheme of using multiple joint robotic arms cooperating with curved connecting rods. This structure forms the continuous and smooth transmission path of load, and all the loads in different occasions, such as inertial forces and supporting forces generated by the robot in the process of movement, are evenly distributed to all the components, and do not cause the deformation or fatigue damage of the structure due to the local stress concentration. In addition, the end of the mechanical foot is designed into the trapezoidal structure, and the impact force and bearing pressure when the end contacts with the ground can be further dispersed by reasonable mechanical distribution, that is, the impact force and bearing pressure generated when the end contacts with the ground are further dispersed to the whole structure, which can greatly reduce the damage, wear and other damages caused by the stress concentration in a certain area, and improve the damage resistance of the mechanical foot. This structural design not only extends the service life of the robot moving components, but also provides reliable structural basis for the long-term stable operation of the robot.



Figure 2. Robot 3D diagram robotic foot

3. Drive and control methods

In terms of driving, in order to ensure the stability of equipment operation, the device adopts electric driving mode. The electric drive system can achieve millimeter-level or even micrometer-level displacement control through pulse signals. For example, a stepper motor can accurately adjust its rotation angle according to the number of input pulses. When combined with transmission components such as ball screws and timing belts, it can convert the rotational motion of the motor into the linear expansion and contraction of the folding link, controlling the error of the link's unfolding angle within ±0.5°, which is far superior to the motion lag of pneumatic drives and the deformation accuracy limitations of shape memory materials.

This device is controlled in two ways, manual control and automatic control. This device is controlled in two ways, manual control and automatic control., Operators can perform real-time operations through visual image transmission using human-computer interaction devices such as controllers or operating software, and send control commands directly to the robot to adjust the robot's movements in real-time (such as folding/unfolding angles, forward speed, and steering) [11].

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In addition, intelligent control can be used to achieve autonomous decision-making in complex environments. Integrating technologies such as artificial intelligence (AI), machine learning, and machine vision enables robots to possess autonomous capabilities of "perception - analysis - decision-making" and handle unknown, dynamic, or unstructured scenarios (such as random obstacles in pipelines, sudden changes in diameter, and corroded areas). During the actual operation of the robot, the mechanical feet need to frequently bear dynamic loads such as ground reaction forces and inertial loads. They are highly prone to end posture deviation due to the coupling interference between loads and structural deformation, which in turn affects the accuracy of folding and unfolding. To solve this problem at the hardware level, high-performance materials such as aviation aluminum alloy 7075 or titanium alloy TC4 are preferred for the end of the mechanical feet [12]. The former has both high specific strength (tensile strength can reach more than 500MPa) and good fatigue resistance, while the latter has better corrosion resistance and low-temperature stability, which can maintain structural rigidity under complex working conditions and reduce plastic deformation caused by loads. At the same time, combined with the rectangular cross-section structure design mentioned earlier: compared with the traditional circular cross-section, the moment of inertia of the rectangular cross-section can be increased by 35%-55% (calculated based on the same cross-sectional area), which can disperse bending stress more efficiently. When the end of the mechanical foot contacts uneven ground or bears impact loads, the rectangular structure can reduce the local maximum stress by 20%-30%, significantly enhancing the resistance to bending deformation. It synergistically suppresses the coupling interference between loads and deformation from both material performance and structural form, providing reliable guarantee for the mechanical feet to accurately complete folding, unfolding and walking actions.

4. Deformation mechanism and modeling

Since the seven gears installed at the bottom of the robot are completely identical in parameters like module and number of teeth, when the servo motor delivers an angular velocity of ω to the first driving gear, all seven gears (Figure 3) will uniformly achieve the same angular velocity of ω under the condition that gear backlash is not considered.

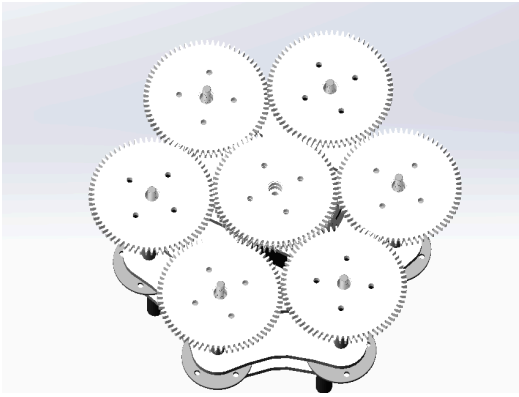

Figure 3. Bottom gear 3D diagram

Once the rotational speed of the gear connected to the curved connecting rod is known, it becomes feasible to calculate both the linear velocity and acceleration at the end of the rod through relevant mechanical formulas, considering the geometric parameters of the rod and the gear's motion characteristics.

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$$v = w * r \tag{1}$$

$$a^n = w2 * r \tag{2}$$

In this experiment, the rotational speed of the servo motor is taken as 40 revolutions per minute (rpm) for illustration. Moreover, based on the actual design dimensions of the robot, the distance from the fixed point where the connecting rod and the gear are attached to the end of the connecting rod is calculated to be 0.118 meters as shown in Figure 4.

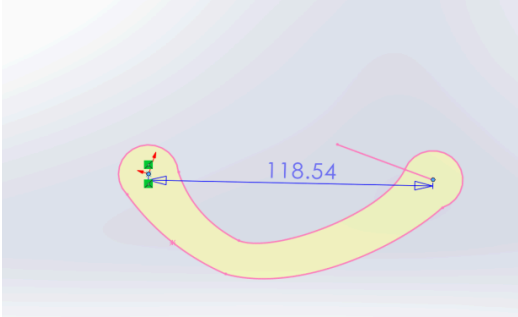

Figure 4. Bent connecting rod dimension diagram

$$\omega = \frac{40 \times 2\pi}{60} = \frac{4\pi}{3}\ \mathrm{rad/s} \tag{3}$$

$$V = \frac{4\pi}{3} \times 0.118 = 0.494\ \mathrm{m/s} \tag{4}$$

$$a^{\mathrm{n}} = \left(\frac{4\pi}{3}\right)^2 \times 0.118 = 2.07\ \mathrm{rad/s^2} \tag{5}$$

Since the required size of the robot varies in different pipelines, we can replace the connecting rods with different sizes according to the conditions of different pipelines. Figure 5 is the motion analysis diagrams under the conditions of different connecting rod lengths.

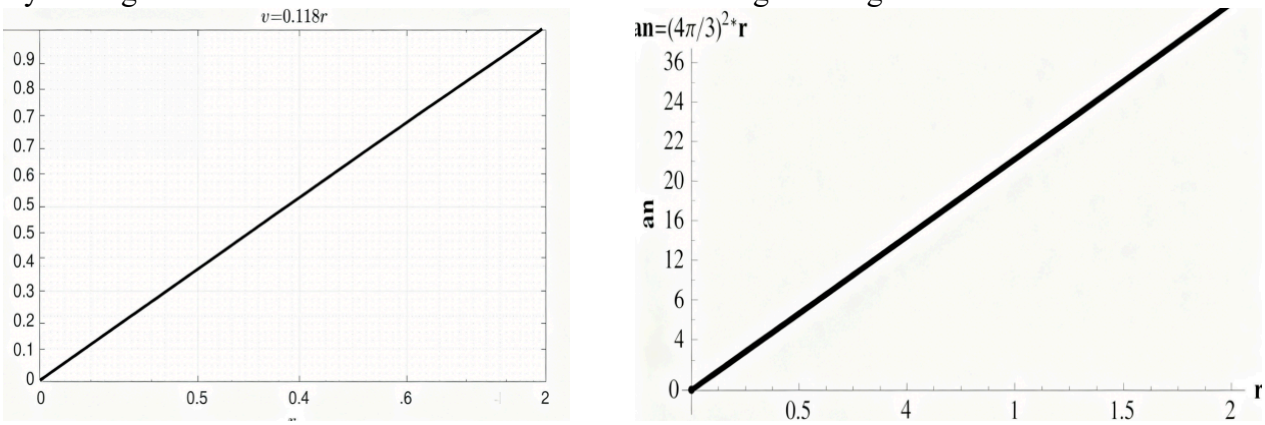

Figure 5: Motion states of different connecting rod lengths

Alternatively, when we need different motor powers to meet the machine's motion requirements, we can also obtain the Figure 6 through kinematic formulas.

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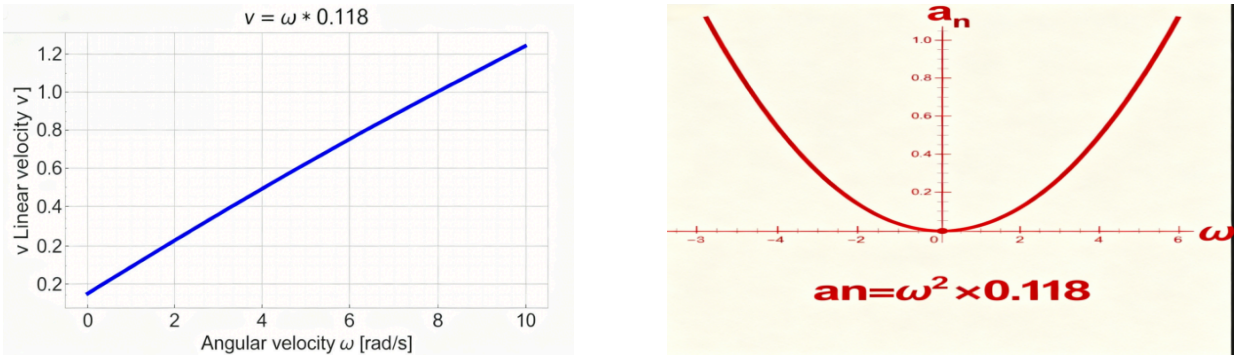

Figure 6: Motion states of different motor powers

5. Application and case study

Foldable pipeline robots have demonstrated significant application value in multiple fields. In terms of municipal sewage pipe network maintenance, Danjiangkou City uses foldable pipeline robots for routine inspections of sewage pipe networks. With their small size, they can flexibly navigate through narrow pipes and accurately capture images of potential problem points in the pipes through the "climbing while shooting" function. Once abnormal monitoring data is detected, the robots automatically go deep into the problematic pipe networks to comprehensively inspect issues such as misconnections, leaks, and damages in rainwater and sewage pipe networks, and accurately locate them. This helps in timely repairs, prevents sewage leakage, and greatly improves the efficiency and accuracy of pipe network detection. In industrial pipeline inspection scenarios, a foldable pipeline inspection robot similar to "Spider-Man" developed by Beijing Jiaotong University has been successfully applied at the Yalong River Hydropower Base and all these robots are shown in Figure 7.

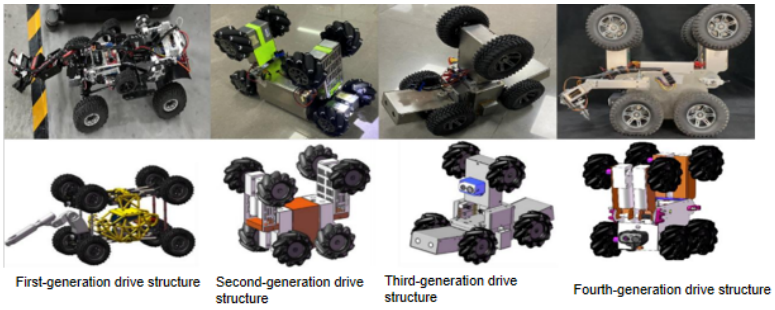

Figure 7. Iteration of the driving structure of the fourth-generation robot [13]

This robot adopts a flexible eight-wheel structure, where each wheel supports each other during operation, enabling 360-degree all-round movement. It can stably adapt to the complex structure of hydropower transmission pipelines with insulation and annular nesting, effectively solving the problems of traditional robots that are prone to movement deformation, rollover, or jamming in curved and irregular pipelines. Meanwhile, it is equipped with a laser radar and a visible light camera, allowing it to autonomously navigate and accurately identify various faults such as millimeter-level cracks, thus strongly ensuring the safe operation of industrial pipelines. Traditional pipeline robots feature fixed rigid structures with un-adjustable overall sizes. They usually need custom design for specific pipeline specifications, so one robot can only adapt to a few pipelines of

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similar sizes. If the pipeline diameter is out of the applicable range, another robot must be replaced, resulting in poor versatility. Also, their fixed sizes have strict requirements on pipeline inlets; they can't enter if the inlet size is smaller than the robot's maximum diameter.

In contrast, foldable pipeline robots use folding mechanisms like hinges and telescopic rods. Key components such as walking wheels, support arms, and detection modules can be flexibly retracted. Their folded volume is much smaller, allowing entry through narrow inlets that traditional robots can't pass. After entering, they can expand to fit pipelines of various diameters, greatly improving adaptability.

In operation, traditional robots struggle to adjust posture when facing pipeline deformations or diameter changes, often causing jams. Their fixed detection modules may fail to align with defects accurately. Foldable robots, however, adjust support components in real time via folding mechanisms to stay stable. Some detection modules can also adjust angles for better accuracy.

In terms of cost and maintenance, traditional robots require multiple devices for different pipelines, increasing purchase and transportation costs. Repairs are time-consuming due to rigid structures. Foldable robots reduce equipment quantity, save transportation space, and have modular designs for easier, cheaper maintenance.

6. Conclusion

In terms of structural design, the robot draws inspiration from the walking style of real spiders, equipped with six foldable mechanical legs. When fully retracted, it takes on a circular shape. The mechanical legs can be folded a second time via hinges to enhance adaptability to complex terrains, and when not unfolded, it can roll in its circular form to navigate narrow spaces. The robot is equipped with a total of 13 servo motors: one in the middle, connected via gears, is responsible for controlling the retraction and extension of the mechanical legs to change the robot's appearance and overall size; each mechanical leg is additionally fitted with a motor connected through a hinge, specifically for the precise control of the mechanical leg. The mechanical legs are petal-shaped, with their overall height precisely controlled at 176mm, which fits the overall structure and meets the support requirements of different pipe diameters. The gap between the two mechanical arms on each side when closed is $\leq$ 5mm, which can block impurities in the pipeline from entering, ensuring the stable operation of the robot in harsh pipeline environments.

To ensure the stable operation of the robot when walking, rolling, and adapting to complex terrains, its mechanical legs adopt a design scheme that combines multi-joint mechanical arms with curved connecting rods, constructing a continuous and smooth load transmission path. This allows various loads such as inertial forces and supporting forces generated during movement to be evenly distributed across all components, fundamentally avoiding structural deformation or fatigue damage caused by local stress concentration. At the same time, the end of the mechanical leg is optimized into a trapezoidal structure. Through reasonable mechanical distribution, it can share the impact force and bearing pressure when the end touches the ground, significantly reducing the risk of damage such as cracking and wear caused by excessive stress in a single area. This not only enhances the damage resistance of the mechanical legs but also indirectly extends the service life of the robot's core moving components, providing reliable structural guarantees for its long-term stable operation.

In terms of driving, the device adopts an electric drive mode to ensure operational stability. Its electric drive system can achieve millimeter-level or even micrometer-level displacement control through pulse signals. For example, a stepper motor can accurately adjust its rotation angle according to the number of input pulses. When combined with transmission components such as ball

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screws and synchronous belts, it can convert the rotational motion of the motor into the linear expansion and contraction of the folding connecting rod, with the error of the connecting rod's unfolding angle controlled within ± 0.5°, which outperforms the motion lag of pneumatic drives and the deformation accuracy limitations of shape memory materials. In terms of control, the device has two modes: manual control and automatic control. In manual control, operators can use human-computer interaction devices such as controllers and operating software to perform real-time operations through visual image transmission and send commands to adjust the robot's actions. Automatic control integrates technologies such as AI, machine learning, and machine vision, enabling the robot to possess the autonomous capabilities of "perception - analysis - decision-making" and handle complex scenarios. In addition, the article takes the servo motor speed of 40 rpm as an example, combined with the actual design size of the robot (the distance from the fixed point of the connecting rod and gear to the end of the connecting rod is 0.118m), and calculates that the linear velocity at the end of the connecting rod is 0.494m/s and the normal acceleration is 2.07rad/s².

Foldable pipeline robots have shown significant application value in multiple fields. In the maintenance of municipal sewage pipe networks, Danjiangkou City utilizes their small size to flexibly navigate narrow pipes, and through "climbing while shooting", they accurately capture and locate problem points in the pipes, facilitating timely repairs, preventing sewage leakage, and improving the efficiency and accuracy of pipe network detection. In industrial pipeline inspection, the spider-like foldable pipeline inspection robot developed by Beijing Jiaotong University realizes 360° all-round movement with a flexible eight-wheel structure, adapting to the complex structure of hydropower transmission pipelines. It is also equipped with laser radar and visible light cameras, which can autonomously navigate and accurately identify millimeter-level cracks and other faults, ensuring the safe operation of industrial pipelines. Compared with traditional pipeline robots, foldable pipeline robots have more advantages in terms of versatility, adaptability to the size of pipeline inlets, ability to cope with pipeline deformation or diameter changes, as well as cost and maintenance. For example, they can adapt to multiple pipe diameters, pass through narrow inlets, adjust postures in real-time, and reduce the number of equipment and maintenance costs.

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