Development and Design of Self-Adaptive Variable Diameter Robot for In-Pipe Inspection

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Abstract. Pipeline defects such as aging, corrosion and cracks may result in the structural failure of industry pipelines, causing environmental pollution, energy waste and even catastrophic accidents of explosion. In-pipe inspection robots are regarded as an expected non-destructive testing tool of analyzing and evaluating in-pipe defects. This paper built a simple variable-diameter pipeline platform based on real pipeline environment. The movement of robots was analyzed to meet the functional requirements of variable diameter and obstacle-crossing. A design scheme of automated in-pipe robot with self-adaptive various diameter mechanism was developed, where a parallelogram connecting rod mechanism combining spring and feed screw nut pair was employed to adapt the diameter change of pipelines from 200mm to 250mm, actively and forcibly. Moreover, a digital camera device was equipped to perform on-line macro detections and in-pipe image acquirements. The results indicate that designed robot system has good various diameter properties. The work provides a reference for subsequent designs of in-pipe inspection robots.

1. Introduction

Structural integrity of pipelines is a major concern for ensuring safe production and efficient operation, as the channel of fluid transportation in petroleum, chemical, energy, natural gas, nuclear power and other process industries. Under the long-term action of chemical effects and physical loads from working media, generated pipeline defects such as aging, corrosion and cracks may result in structural failure of pipelines, causing environmental pollution, energy waste and even catastrophic accidents of explosion [1-2]. Therefore, the efficient and accurate defect detection of pipelines is significantly necessary work.

Conventional in-pipe inspections of full-scale excavation and random sampling method are carried out by inspectors using advanced non-destructive testing techniques, which have disadvantages of heavy workload and low efficiency [3]. In addition, limited working space, complex working environment and high danger don’t allow inspectors to enter inspected pipelines. For such difficulties, the in-pipe robot with inspection instruments and devices is developed and expected to be an effective and reliable in-pipe inspection tool. The aforehand repair or replacement of pipelines under the assistance of in-pipe robots not only can guarantee the safety of people's life health and property, but save a lot of costs.
With the development of sensor level, image processing, control and communication technology, the research of foreign in-pipe robots has presented fruitful achievements. In our country, the current research is also being conducted prosperously, though the start time is late [4]. Most of these in-pipe robots are developed for constant diameter pipelines, however, the working environment of in-pipe robots is various and the diameter of pipelines is not constant, such as variable diameter tubes or T-tubes [5]. Furthermore, there are often some bellied obstacles in industry pipelines. These means that in-pipe robots should have the function of adjusting radius distance of itself. The ability of self-adaptive variable diameter also has gradually become an important indicator to measure the performance of in-pipe robots.

Research on the self-adaptive variable diameter mechanism of in-pipe inspection robots is an interesting topic. In order to study the variable diameter maneuverability of robots in the real working environment, this paper firstly built a simple variable-diameter pipeline platform. Then the movement of robots in pipelines is analyzed to meet the functional requirements of variable diameter and obstacle-crossing. A design scheme of telescopic variable diameter mechanism driven by motor and controlled by computer program code is proposed, which realizes the adaptation to the inner wall diameter in a variable-diameter pipeline, and provides a reference for subsequent designs of in-pipe inspection robots.

2. Inspection Robot Design Scheme

Inspection robots with non-destructive testing technology are effective and reliable tool to defend against pipeline failures. Current research task is to design an in-pipe inspection robot that can automatically move forward, backward, turn, cross obstacles and adjust radius dimensions under manual control in pipelines. Based on the application characteristics of industry pipeline inspection, the modular design method including the variable diameter function module, the climb function module, the obstacle-crossing function module and the video detection function module is adopted to meet the design requirements of the in-pipe inspection robot. A system consisting of the robot body, camera, illumination lamp, image processing and PC is schemed in this work.

The large-scale variable diameter behavior of the designed robot is driven by the improved automatic variable diameter mechanism, which is controlled by the sensor feedback value and the control algorithm. Due to the presences of concavo-convex pits, sludge and scale formation on the inner wall of industry pipelines, the designed mechanism also requires the ability of small range radius adjustment to cross obstacles in pipelines. In view of the fact that the crawler wheel provides more adhesion forces and traction properties for robots, and have good performances of climbing, obstacle-crossing and operation stability, the crawler-type way is used in the climbing driven mechanism of the designed robot. In addition, macroscopic video devices are equipped for visually detecting defects of in-pipes.

The design of the designed inspection robot needs comprehensive tests and analyzes to quantitatively understand and evaluate its performance, so as to improve the design, determine the scheme and study the action behavior in depth. We put up a variable diameter test platform of inspection robots for simulating the real variable diameter environment of industry pipelines, where two pipes with the inner diameter size of DN200 and DN250 are connected by a size joint, as shown in Figure 1. The distribution of the pipeline is designed according to real working conditions of complex industry pipelines. The platform can simulate various movement obstacles of the in-pipe inspection robot, and perform action behavior tests, such as the variable diameter ability and obstacle-crossing ability.
3. Self-Adaptive Variable Diameter Mechanism

Most in-pipe various diameter robots use spring units to provide support and clamping force for crawler wheels, keeping mechanism stability in pipelines with different diameter sizes. That is a forced adjustment method depends on the spring stiffness and deformation, with small range adaptation to pipe diameter. The variable diameter mechanism with feed screw nut pair, an active adjustment device not only compact in structure but needs less driving force, can stretch and contract in large range in the radius direction. Based on above various diameter properties, a new mechanical structure and movement mode of robots are improved. A parallelogram connecting rod mechanism combining spring and feed screw nut pair is employed to adapt the size change of pipelines, which is a variable diameter device with both active and forced adjustment. The action of the mechanism enables three independent crawlers supported by connecting rods to well adapt the tube diameter change from 200mm to 250mm. The schematic of the mechanism is shown in Figure 2.

![Variable diameter mechanism structure of the designed Robot.](image)

The design has three sets of crawler wheels distributed with an interval of 120 ° in the circumferential direction. Three spring sliders connected with parallelogram connecting rods are fixed on the same screw nut pair. At the size joint of pipelines, the motor of feed screw nut pair mechanism drives the nut to push spring sliders under the control of remote system controller. Connecting rods connected with crawler wheels stretch and contract in forced forces of three spring sliders. These
behaviors realize the adaptability to different pipe diameter. Three compression springs with suitable stiffness are mounted on the location between the feed screw nut pair and sliders. When the feed screw nut pair is self-locked, connecting rods can stretch and contract in a small range due to the flexible deformation of compression springs. This serve the designed robot as a buffering function for obstacles of concavo-convex pits, sludge and scale formation on the inner wall of industry pipelines. In summary, the variable diameter behavior of the robot is completed under composite operations of feed screw nut and spring deformation. The mechanical structure is simple, guarantees sufficient adhesion force and provides better adaptation to pipe diameter change for robots.

The speed of all wheels of the robot is the same value when walking in straight pipelines. Robots with no differential drive unit is difficult to smoothly cross bend pipe, so the differential structure should be adopted in the design of robots [6]. The speeds of three sets of crawlers are controlled and adjusted by three independent motors based on the principle of differential control, which allows the bend-crossing posture of the robot to be suitably adjusted, and improves the flexibility and stability during its motion.

The robot's control system consists of two central processing units, namely the CPU integrated on the robot body as the slave controller and the CPU of the external control box as the main controller. Two CPU boards of Fujitsu MB90F549G Single-Chip Microcomputer communicate though CAN bus. Of these, the control system scheme of the robot body is shown in Fig. 3.

![Control System of the Robot Body](image)

**Figure 3.** Control system of the robot body.

The robot body control is a variable-diameter and differential closed-loop control system based on the of three pressure values on crawlers. The increase of all three crawler pressures implies that the robot climbs from a large-diameter pipe to a small-diameter pipe, on the contrary, the robot climbs from a small-diameter pipe to a large-diameter pipe. In these cases, the corresponding adaptive variable diameter is driven by the feed screw nut. The measured pressure of outside wheels greater than inside wheels reveals that the robot moves to the bend position where the rotational speed of the outside motor is required to be higher than inside motor due to longer curve distance. More than three flexible and bendable FSR400 film pressure sensors are mounted on each crawler, ensuring that one sensor measures the effective pressure at least.

### 4. Video device and real-time transmission technology

The visual detection technology of image acquisition and processing is a common method to monitor pipeline conditions. The digital camera device with wide-angle lens and high-gloss illumination is installed in the front of the robot for performing on-line macro detections and acquiring in-pipe defect images. The acquired images of corrosion, surface defects, pipe deformation, and leakage in pipelines is transmitted to the graphical user interface of the control console in real time and stored in the
computer for easy of physical positioning and subsequent defect processing operations. The visual video transmission system uses CAN bus to realize high-speed data transmission, whose overall structure is shown in Figure 4.

**Figure 4.** Visual video transmission system

5. Conclusion
The effective inspection method is the demand of in-pipe non-destructive testing. In-pipe inspection robots are inspiringly regarded as an expected tool to analyze and evaluate in-pipe defects. With the development of sensor level, image processing, control and communication technology, the research on in-pipe robots has presented fruitful achievements. However, the working environment of in-pipe robots is various and the diameter of pipelines is not constant, such as variable diameter tubes or T-tubes. This paper proposed a self-adaptive various diameter design scheme of automated in-pipe robot. A parallelogram connecting rod mechanism combining spring and feed screw nut pair was employed to adapt the diameter change of pipelines, actively and forcibly. The designed robot has good various diameter properties, which provides a reference for subsequent designs of in-pipe inspection robots.

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