

CONTROL METHOD OF A MACHINE VISION-BASED ROBOT FOR PUMP PIPE INSPECTION

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Abstract: The pump pipe detection robot is used to detect the blockage of the concrete pump pipe, and it is an important equipment to ensure the safe and efficient transportation of the pump pipe. Currently, traditional inspection relies heavily on manual experience, which is not only time-consuming and inaccurate but also severely impacts construction progress and may even cause economic losses. To achieve precise and efficient blockage detection, this paper designs a machine vision-based pipeline detection robot control system. The core of this system utilizes optical fiber as the communication medium, fully leveraging its high bandwidth, low latency, and electromagnetic interference resistance to enable efficient and reliable transmission of robot control commands and high-definition image data.

Keywords: Pipeline robot; Control system; Fiber optic communication; Machine vision

1 INTRODUCTION

As a critical component of concrete delivery systems, pump pipes undertake high-pressure, long-distance concrete transportation tasks in the construction of high-rise buildings and large bridges[1]. The operational status of concrete pump pipes directly impacts construction continuity and project schedules. During actual use, factors such as operator error, pumping equipment issues, and concrete selection often lead to pump pipe blockages[2]. Manual blockage clearance is not only inefficient and inaccurate but also causes project delays and economic losses[3]. Therefore, employing a pump pipe detection robot equipped with machine vision for blockage detection offers advantages such as real-time capability and high inspection efficiency. However, pump pipe robots face challenges in remote control and signal transmission, including high signal latency and low transmission bandwidth. For inspection tasks involving small-diameter pipes, long distances, and vertical working conditions, inspection robots urgently require a suitable control system to address these current issues.

Pipeline robots have reached a relatively mature stage, with both remote control technology and machine vision technology seeing extensive development and application. The reliability of pipeline robot control and communication is crucial for ensuring their long-term, efficient operation. Scholars have conducted extensive research in areas such as pipeline robot control system design, communication architecture, and transmission protocols, achieving significant progress. Kazeminasab et al. proposed a pipeline robot system based on wireless relay nodes and multi-stage motion control algorithms, supporting real-time data transmission and motion switching during long-distance inspections[4]. Bai et al. designed an underwater bionic vehicle motion system (UBVMS) that interacts with a ground control console via TCP/IP communication[5]. Han et al. developed an articulated pipeline robot system based on CAN bus and distributed architecture[6], achieving efficient inter-node communication. Nguyen et al. proposed a pufferfish-inspired soft robot with an external air source and wired communication to enable its adaptive movement in variable-diameter pipelines[7]. Jeon et al. developed a wheeled robot integrating multi-motor cooperative control and wireless communication modules for large-diameter water pipe inspection and remote monitoring[8]. Liu et al. designed a multi-gait snake robot with centralized control via a host computer and CAN bus[9], generating complex motions through the trunk curve method. Zhen et al. developed a pneumatic pipeline robot capable of crawling through variable-diameter pipes[10], utilizing centralized control via a 485 bus between a subordinate device and a host PC. Luo Jiman et al. achieved closed-loop regulation of support leg pressure using fuzzy PID and an STM32 controller[11], significantly enhancing the robot's motion stability and interference resistance. In machine vision, Liu Simo proposed an obstacle avoidance strategy for pipeline robots by integrating stereo vision with ant colony optimization[12], enabling obstacle recognition and intelligent path planning based on 3D reconstruction. Kabir et al. developed a visual system based on Mask R-CNN and LiDAR cameras[13], achieving high-precision instance segmentation and distance measurement of rocks inside pipelines under complex lighting conditions. Yang Wanting investigated machine vision-based automatic identification and classification methods for pipeline weld defects using image enhancement[14], segmentation, and morphological processing.

In summary, although existing research provides ample references in areas such as control methods and machine vision, studies in the field of concrete pump pipe inspection robots remain largely unexplored. To achieve stable operation in long-distance, small-diameter, vertical metal pipelines while effectively addressing challenges such as communication latency, metal shielding interference, and cable dragging, the control system of the pump pipe detection robot must exhibit high stability, strong anti-interference capabilities, and low latency. To this end, this study specifically designed a highly reliable control system and experimentally validated its outstanding performance.

2 CONTROL SYSTEM FOR PUMP PIPE DETECTION ROBOT

2.1 Control System Framework

The control system framework for the pump pipe detection robot is illustrated in Figure 1. The system operates by transmitting control commands from a PC terminal. These commands are converted into optical signals by a ground-based optical transceiver, then transmitted via fiber optic cable to a sky-based optical transceiver. The sky-end optical transceiver converts the optical signal into a digital signal, which is then sent to the control board. The control board parses the control commands and outputs two identical-frequency PWM signals to drive two brushless motors. These two PWM signals can be set to different duty cycles. The pulse signals from the Hall sensors of the two motors are captured and counted by the control board, which calculates the rotational speed and sends it to the sky-end optical transceiver. The sky-end optical transceiver converts the feedback information and image data into optical signals, transmitting them in real-time to the ground-end optical transceiver. The ground-end optical transceiver converts the optical signals back into digital signals and sends them to the PC terminal.

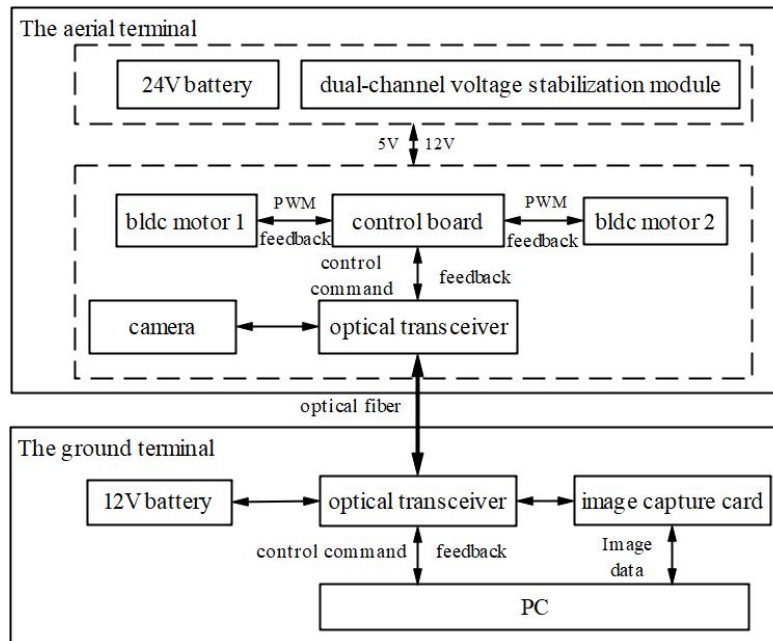


Figure 1 Pump Pipe Detection Robot Control System Framework

2.2 Composition of The Control Hardware

The main hardware composition of the pipeline robot control system is illustrated in Figure 2. The aerial terminal consists of the robot body, control board, optical transceiver, dual-channel voltage stabilization module, and 24V battery; the ground terminal includes an optical transceiver, image capture card, 12V battery, and PC terminal. Communication between the ground terminal and the aerial terminal is transmitted via optical fiber media. The robot body, as the main equipment for performing pipeline inspection tasks, is composed of a wheeled support mechanism, a diameter-variable mechanism, a camera, two brushless motors, and other components, capable of completing operations such as patrol inspection and image data collection under remote commands. The control board serves as the main controller of the robot, responsible for receiving instructions from the ground terminal, controlling the robot's movement, and sending information such as the robot's movement speed to the ground terminal.

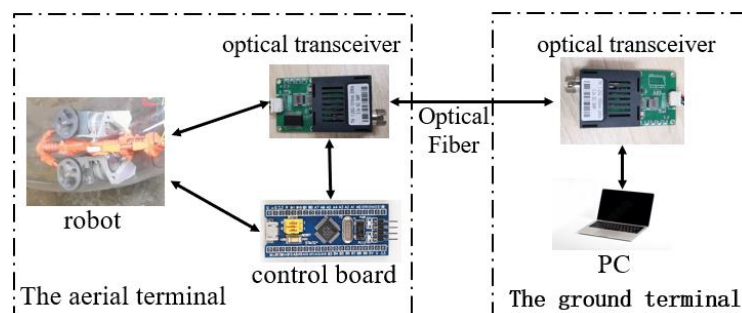


Figure 2 The Main Hardware Components of the Control System

The control board utilizes the STM32F103C8T6 minimal system board, integrating a rich array of timers,

communication interfaces, and analog functions to fully meet the device's control and communication requirements. The system transmits one analog video signal and one TTL-level signal via the optical transceiver unit, used for image data and control commands respectively. The optical transceiver utilizes an FC fiber optic interface, offering high bandwidth, high reliability, and strong electromagnetic interference resistance to establish stable, long-lasting fiber connections. Brushless motors are adopted, with a rated voltage of 12V, a no-load speed of up to 6000rpm, and a rated power of 6W. The camera utilizes an analog signal camera with a resolution of 720P. The image capture card acquires analog video signals and converts them into digital image signals. This capture card supports both 1080P and 720P resolutions. Additionally, the system is equipped with a voltage stabilization module, which can convert the externally input 24V voltage into 12V and 5V to provide stable power supply for the control board, optical transceiver, and camera respectively.

3 CONTROL SOFTWARE AND MACHINE VISION ALGORITHMS

3.1 Control Software

To achieve precise motion control and status monitoring for the detection robot, an embedded control software based on the STM32F103C8T6 microcontroller was designed. This software adopts a layered architecture and modular design, integrating core functions such as motor drive, sensor feedback, and communication management to ensure system real-time performance, reliability, and maintainability.

The control software employs a four-layer hierarchical architecture, as illustrated in Figure 3. The hardware driver layer directly manipulates STM32 peripheral registers to initialize and implement low-level drivers for GPIO, timers (TIM1/2/4), serial port (USART1), and interrupt controller (NVIC), providing a unified hardware access interface for upper layers. The hardware abstraction layer encapsulates functions such as motor control, encoder acquisition, direction switching, and serial communication. The functional module layer contains core modules including PWM control, rotational speed calculation, command parsing, and state management. These modules respectively handle dual-motor speed regulation, encoder pulse processing, serial command execution, and system state maintenance. The application layer implements task management through main loop scheduling, coordinates the work of various modules, and completes the full-process business logic of robot control.

The system employs a hybrid scheduling mechanism combining interrupts and polling to ensure real-time response for critical tasks. A SysTick timer is configured to generate a 1 ms time base, which is used for the periodic triggering of rotational speed calculation and status reporting. Encoder input capture interrupts (TIM2/TIM4) are assigned the highest priority to guarantee accuracy in motor pulse counting; serial port receive interrupts (USART1) enable timely response to control commands and prevent data loss.

The communication protocol employs plaintext ASCII format, supporting both multi-parameter batch processing and real-time response. The control commands sent by the host computer contain target duty cycle and steering information, and the slave computer returns an acknowledgment message after execution; Simultaneously, the system proactively reports operational status including motor speed, direction, and cumulative pulse count at 1-second intervals. To improve system reliability, multiple measures such as parameter boundary checking, software timeout judgment, and hardware status monitoring are implemented at the software level, ensuring that the system can achieve safe shutdown or state recovery in cases such as communication abnormalities, sensor failures, or control parameter out-of-bounds.

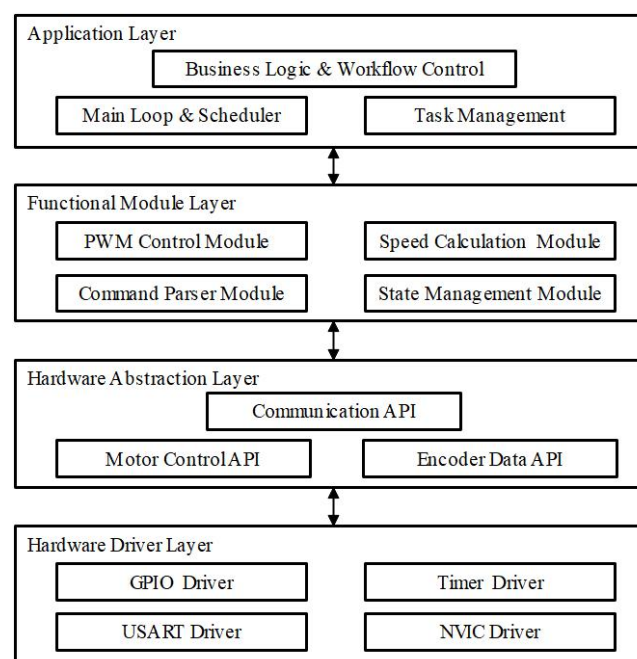


Figure 3 Control Software Architecture

3.2 Machine Vision Algorithms

This study adopts a machine vision algorithm based on Hough circle transform to achieve the detection of circular obstacles in pipelines and the judgment of passing ability. Through three main steps—image preprocessing, edge detection, and circle recognition—the algorithm can accurately identify circular obstacles in pipelines and determine whether the robot can pass safely according to their radius dimensions.

Prior to circular detection, input images undergo Gaussian filtering to eliminate noise interference. The core Gaussian filter formula is:

$$G(x, y) = \frac{1}{2\pi\sigma^2} e^{-\frac{x^2+y^2}{2\sigma^2}} \quad (1)$$

where (x, y) represents pixel coordinates and σ denotes the standard deviation. This formula defines a two-dimensional Gaussian kernel function, which smooths the image through convolution operation. While retaining edge information, it effectively suppresses noise and provides a high-quality input image for subsequent edge detection.

The core idea of Hough circle transform is to convert the problem of circle detection in the image space into the problem of peak detection in the parameter space. For an edge point (x_i, y_i) in the image space, it will be transformed into a three-dimensional conical surface after transformation, and the circle equation it satisfies in the parameter space (a, b, r) is:

$$(x_i - a)^2 + (y_i - b)^2 = r^2 \quad (2)$$

where (a, b) represents the coordinates of the center of the circle and r denotes the radius. The conical surfaces of points on the same circle in the parameter space will have the same intersection point (a, b, r) , and the task of Hough circle detection is to find this point to determine the circle in the image. The Hough transform finds all satisfying pixels by traversing the image, and its formula is expressed as:

$$P = \{(x_0, y_0, r): (x_i - x_0)^2 + (y_i - y_0)^2 = r^2\} \quad (3)$$

where (x_0, y_0) represents possible coordinates of the circle center. The algorithm conducts cumulative voting in the parameter space to find parameter combinations with votes exceeding the threshold, thereby determining the circles present in the image.

4 EXPERIMENTAL VALIDATION

4.1 Motion Control Experiment

The experiment tests the robot's communication and control capabilities, and is conducted on a pipeline experimental platform with an inner diameter of 120 mm. Control commands are sent through the PC terminal to control the robot to walk, climb, turn and hover in the pipeline. As shown in Figure 4, the robot can walk horizontally, climb vertically, pass through elbows and hover in the pipeline, and can receive commands to adjust speed and move backward.



(a) Robot through a bend pip



(b) The robot climbs vertically

Figure 4 The Robot Runs in the Pipeline

4.2 Image Signal Transmission Experiment

The robot is put into the pipeline for operation in the experiment. Equipped with a camera, the robot collects images synchronously. The captured real-time images are transmitted to the ground via optical fiber. The ground PC control terminal receives and displays the video. With a transmission rate of 1 gigabit per second, the optical fiber ensures high-speed, stable and smooth data transmission. Figure 5 shows the comparative images taken by the robot at different distances from obstacles in the pipeline, all with an image resolution of 1280×720.

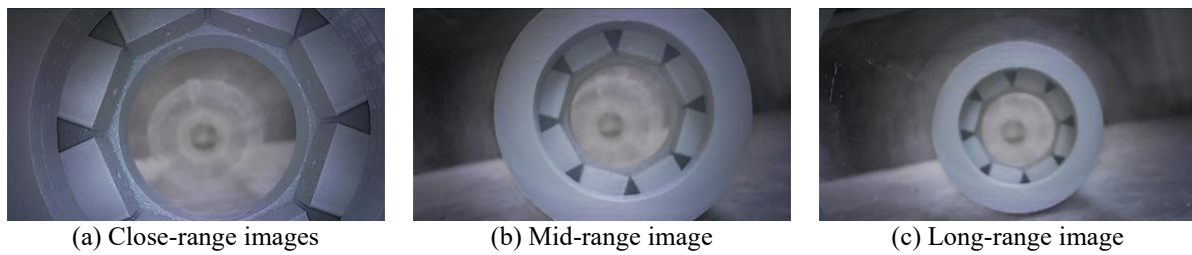


Figure 5 Inside the Pipeline Image

4.3 Visual Detection Experiment

Images were collected in a pipeline environment with real pipe diameters in the experiment to verify the algorithm's effectiveness. Figure 6 shows the detection results of circular obstacles in the pipeline. The algorithm can accurately identify contours, marking passable ones with green circles and impassable ones with red circles. This method provides a reliable basis for robot navigation and effective visual perception support for autonomous inspection tasks.

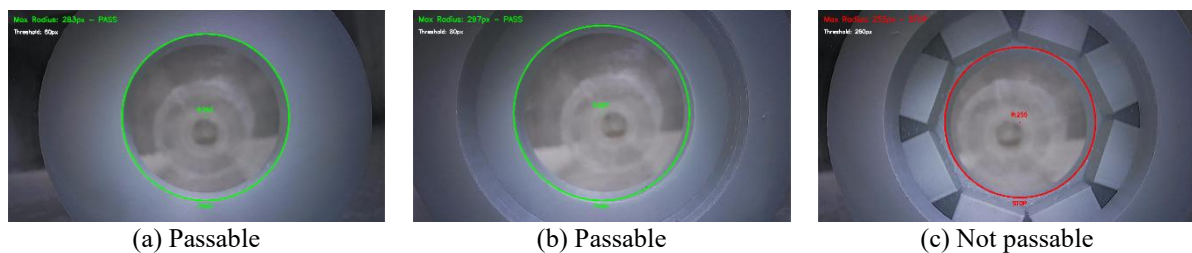


Figure 6 Obstacle Detection Results in Pipeline

5 CONCLUSION

This paper addresses the problems of difficulty and low efficiency in clogging detection of concrete pump pipes, and designs a pipeline inspection robot control system based on machine vision. Through the construction of a pipeline testing platform, experiments were conducted on the robot's motion control, image transmission, and visual detection capabilities. experimental results show that: the system can transmit control commands via optical fiber to control the robot to complete actions such as walking, climbing, turning and hovering in the pipeline; the robot can capture the clogging status inside the pipeline and transmit images back to the PC terminal in real time, stably and with low latency through optical fiber; the visual algorithm can effectively identify the size of circular obstacles, providing a key basis for the robot's passage decision-making.

COMPETING INTERESTS

The authors have no relevant financial or non-financial interests to disclose.

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