High precision 3D measurement method of pipeline on complex working conditions research

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Abstract—The research object of this paper is high-precision 3D structure measurement of thin pipe workpiece with working temperature ranged from -50 °C to +70 °C and pipe diameter range from 20 mm to 100 mm. Measurement method is based on the principle of circular structure light vision detection. Due to the strict temperature environment requirement and limited measurement space of the inner surface of pipeline. A CMOS camera module based on customized optical lens is designed. Matched with camera temperature compensation device. Motion guide rail of telescopic arm is equipped with high precision servo motor and grating ruler are used for accurate measurement. Experimental results show that the measurement system meets the design requirements of accuracy ≤ 0.02 mm, repeatability ≤ 5% FS (0.5 mm), and strain test error ≤ 5%.

1. INTRODUCTION

Regular inspection of the inner surface of the pipeline can prevent pipeline accidents and provide a scientific basis for reasonable maintenance. Meanwhile, it can reduce pipeline maintenance costs and environmental pollution, avoid unnecessary economic losses, and has significance meaning in industrial production and national defense industry. For inner surface of large diameters such as sewage and oil transportation, detection space of the inner surface is large, the volume requirement of the sensor is not very demanding, and driving of the sensor is relatively simple. The detection methods mainly include ultrasonic detection, magnetic flux leakage detection, and laser ray method [1,2,3]. These detection techniques require multiple transmissions and receptions of signals near a section of the pipeline to complete the inspection of the pipeline section. The detection efficiency is low, and indirect, has no visibility, and is susceptible to noise. Prone to false inspection.

Due to the limitations of above methods, photoelectric detection technology is suitable for detection of the inner surface of pipelines, and develops toward the rapid identification of defects, accurate 3D measurement of the inner surface of the pipeline, and visual display of wall defects in 3D images. At present, the photoelectric detection methods used for pipeline detection mainly include internal video camera method, laser scanning method, visual inspection method and detection method based on photoelectric sensitive devices [4,5]. Among them, visual inspection technology is more and more applied to the inner surface detection of pipeline structures due to its advantages such as visibility and large amount of information.

In this paper, the detection space of the inner surface of thin pipe with pipe diameter ranging from 20mm to 100mm is narrow, and the volume requirement of the sensor is strict. Because the circular structure light detection method can achieve accurate 3D measurement, the system structure is simple,
and the system installation requirements are not high, and the applicability is strong [6]. This paper is based on the principle of circular structure light vision detection. Internal surface structure information is captured by the camera, and 3D mathematical model of the calibration is used to realize high-precision 3D measurement of pipeline’s inner surface.

2. CIRCULAR STRUCTURE LIGHT VISION DETECTION SYSTEM

2.1 Principle of Circular Structure Light

The principle of circular structure light vision detection is shown in Figure 1. The system consists of a camera module, a laser source and a pipeline to be tested. Arranged along the axial direction of the pipe [7,8]. Laser and Camera distance depends on the divergence angle of the laser projector, pipe diameter and camera focal length.

![Figure 1. Schematic diagram of a circular structure light detection system](image)

2.2 Pipeline Inwall Circular Structure Light Vision Detection Model

The model of the circular structure light vision detection system is shown in Figure 2 [9]. The camera model established in this paper mainly includes the following two steps of transformation.

- Transformation relationship between 3d world coordinates and camera coordinates. R is Unit orthogonal rotation transformation matrix. T is translation vector.

\[
\begin{bmatrix}
x_c \\
y_c \\
z_c
\end{bmatrix} = \begin{bmatrix}
x_w \\
y_w \\
z_w
\end{bmatrix} + T \tag{1}
\]

- Transformation of camera coordinates and image coordinates. \( f \) is focal length of lens.

\[
\begin{aligned}
x_u &= f \frac{x_c}{z_c} \\
y_u &= f \frac{y_c}{z_c}
\end{aligned} \tag{2}
\]

\( OX_CY_CZ_C \) is camera coordinate system, \( OXY \) is camera image plane, \( OO_C \) is camera focal length. Point \( P \) is on intersection line of the conical surface intersects with surface of the object to be measured, while 3D coordinates are the measurement results of detection system.

The 3D coordinates \( O_WX_WY_WZ_W \) are finally based on the external parameter conversion of the camera.

![Figure 2. Circular structure light vision detection system model](image)

2.3 Circular Structure Light Image Calibration

Since cross section of the pipe is usually circular, for light projection characteristics of circular structure, the light emitted by circular structure light projector and inner surface of the pipe are usually circular. And the diameter of circle is limited by the structural light emission angle and the inner diameter of the pipe. Therefore, a black and white circular plane target is designed based on circular structure light projection shape to calibrate the camera [10].
Ring plane target is shown in Figure 3. The target consists of black and white concentric rings. The corners of circular target on the black and white intersection are the calibration points. 3D coordinates are calculated from the radius of the circle and the Fan - shaped central angle.

![Figure 3](image_url)

**Figure 3. Circular structure light vision detection system model**

3. **SYSTEM INSPECTION WORK PLAN PROCESS**

System structural block diagram is shown in Figure 4. The laser emits a circular structure light that intersects with the pipeline to be measured produce a bright light bar. The camera captures the image of the inner wall of the pipe and extracts the feature information, finally obtained a complete measurement cross section.

Moved the pipe in the axial direction to take an image of the inner surface at different sections. Based on the distortion correction model, the circular strip image on the inner surface of the pipeline is corrected. Sub-pixel contour extraction algorithm is designed to obtain the high-precision inner wall contour.

All inner wall profiles acquired in the axial direction are combined to obtain 3D vector data of the inner surface of the pipe structure. Accurate 3D information on the inner surface of the pipe can be measured after calibrating the positional relationship between the cone plane and the camera and its laser. Then processed by a computer to finally obtain 3D information of the surface of all the objects to be measured.

![Figure 4](image_url)

**Figure 4. System measurement scheme**

4. **SYSTEM HARDWARE STRUCTURE**

According to the characteristics of pipeline structure, a 3D visual pipeline internal surface inspection system based on circular structure is designed. The system uses a Mini CMOS camera to capture the circular structure light strips of the inner surface structure information of the pipeline. Use accurately calibrated 3D mathematical model to achieve high-precision 3D measurement of the inner surface of the pipeline. System device design is shown in Figure 5:

![Figure 5](image_url)

**Figure 5. System measurement scheme**

Compared with other photoelectric detection methods, this scheme can realize 3D accurate measurement, has the characteristics of simple structure, convenient installation, no need coaxial positioning device, and strong applicability advantage etc.
4.1 Camera Lens Module
Depending on the length of the pipe to be tested (< 360mm) and the accuracy of the measurement (< 0.02mm), CMOS SENSOR is required to meet 5 million resolutions and 20 FPS. The device selection parameters of CMOS SENSOR are shown in Table 1.

**TABLE1 CMOS TECHNICAL PARAMETER**

| Contents        | Specifications         |
|-----------------|------------------------|
| Module Size     | 43MM*8MM*7.2MM         |
| Sensor Type     | LIHAPPE8 56(1/4")     |
| Array Size      | 2592*1944              |
| Pixel Size      | 1.4µm*1.4µm            |

To meet requirements of measuring object, focal depth of the designed lens is 15mm -100mm. Device selection parameters and information of the lens are shown in Table 2.

**TABLE2 LENS TECHNICAL PARAMETERS**

| Contents         | Specifications         |
|------------------|------------------------|
| Lens Construction| 4P+IR                  |
| FOV              | 70°                    |
| TV Distortion    | <1%                    |
| Relative Illumination | 38.50%              |
| IR Filter        | 650 ± 10nm             |

4.2 Temperature Control
Camera temperature compensation equipment has been added for low temperature environments inside the pipeline. The temperature control scheme adopts the PID temperature control system which widely used in industry, with combination of quartz cotton insulation and graphene film heating scheme ensures the camera module operate at the allowable temperature range, meanwhile ensure lens size meet size requirements (diameter <30mm). Specifications are shown in Table 3.

**TABLE3 LENS TECHNICAL PARAMETERS**

| Contents                   | Specifications          |
|----------------------------|-------------------------|
| Millivolt signal           | 0-100mV                 |
| Current signal             | 0-20mA                  |
| cold junction compensation | ±1°C                    |
| sampling resolution        | 0.5s                    |
| measurement accuracy       | ±0.2%FS                 |

4.3 Telescopic Arm/Motion Guide
To achieve high-precision concentric motion, the motion guide rail and its supporting structure require high rigidity. Needs to have low movement error and return error. Therefore, considering the cost performance and stability factors, this project uses a two-track screw large flat slide with a 0.001mm grating to assemble a high-precision motion platform [11]. High-rigidity telescopic arm structure is installed on the working platform. After calculation and analysis, the comprehensive motion control of the system can achieve 0.005mm accuracy.

4.4 Motion Control System
A full closed loop control system [12, 13] is used on the platform designed in this project. The AC servo system is composed of power inverter, PWM-Pulse Width Modulation, position control, speed control components etc. The system diagram is shown in Figure 6.
The encoder adopts high-precision coding motor, which can achieve measurement accuracy of 0.002mm. Position detection adopts high-precision grating ruler for absolute position measurement, which can achieve measurement accuracy of 0.001mm.

Figure 6. Schematic diagram of a full-closed control system

5. EXPERIMENT RESULT

Data collected by the visual 3D inspection system was compared to a standard laser scanner, each section was measured 5 times. See diagram in Figure 7. The left picture is the image captured by camera before pre-process and the right is pixel size of pipeline circle sections.

Roundness errors are 0.015mm and 0.013mm. Diameter and roundness errors are within 1μm and the results are very similar. The measurement data has a variation of less than 0.6μm, and the standard deviation is within 0.2μm.

Figure 7. Diagram of pipeline circle sections

From the whole experimental process and results, the measurement results of the system can be designed with accuracy requirements and the stability of the system is high.

6. CONCLUSION

In this paper, a circular structure light vision detection mode is proposed for measuring the inner surface of a pipe with limited space, which has the characteristics of fast measurement speed and high precision. A 3D visual inspection system for circular structure of pipeline inner surface is built, effectively solved the problem of 3D measurement in confined space.

Measurement experiment for industrial pipe surface results showed the system solution proposed in this paper can realized 3D measurement of pipeline inner surface. Achieve pipeline diameter measurement 0.015mm accuracy which proving have good applicability for 3D measurement of confined space.

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REFERENCES
[1] YUAN HM. Question and answer of the pipeline inspection technologies [ M]. Beijing: China Petrochemical Press, 2010: 100-105 (in Chinese).
[2] DURAN O, ALTHOEFER K, SENEVIRATNE LD. Pipe inspection Using a laser-based transducer and automated analysis techniques [J]. IEEE /ASME Transactions on Mechatronics, 2003, 8(3): 401-409.

[3] JIANG CJ, JU XM. The development and actuality of oil-gas pipeline Detection technologies[J]. Inner Mongolia Petrochemical Industry, 2008, 40(3): 83-86 (in Chinese).

[4] GOM EZ F, AL THOEFE RK, SENEV IRATN E. Mo-deling of ultrasound sensor for pipe inspection [J]. IEEE, 2003, 2(9): 14-19.

[5] DURAN O, ALT HOEFORE K, LAKM AL D, et a lA sensor for pipe inspection: model, analysis and Image ex traction [J]. International Conference on Image Processing 2003, 3: 597-600.

[6] SENEV IRA TNELAKM AL D. Pipe inspection using a laser-based Transducer and automated analysis techniques [J]. IEEE, ASM E Transactions on Mechalronics, 2003, 8(3): 401-409.

[7] HE Jun-ji. 3D Shape inspection for inside surface of Microminiature workpiece [D]. Beijing: Beijing University of Aeronautic and Astronautic, 2004. (in Chinese)

[8] LI Jiang-xiong, WU En-qi, KE Ying-lin. New inner Surface pro file sensor for mini Diameter pipes [J]. Journal of Zhejiang University, 2006, 40 (9): 1619-1623. (in Chinese)

[9] Wang Ying, Zhang Rui. In-pipe Surface circular structured Light 3D vision inspection system [J]. Infrared and Laser Engineering, 2014, 43(3): 891-896. (in Chinese)

[10] Scaramuzza D, Martinelli A, Siegwart R.A toolbox for Easily calibrating omnidirectional cameras[C] IEEE International Conference on Intelligent Systems, 2006(6): 5695-5701.

[11] Fragenzu Direct oral anticoagulants for the treatment of cancer Associated venous thromboembolism" [J]. Phlebologie, 2017, 46 (06).

[12] EA Postnova. Optimal Motion Control of the System Modeled by Double Integrator of Fractional Order [J]. Automation and Remote Control, 2019, 80(4).

[13] Shahzad Zaman, Paolo Barge, Paolo Gay. Cost-effective visual odometry system for vehicle motion control in agricultural environments [J]. Computers and Electronics in Agriculture, 2019, 162.