Development of automatic inspection device for pipe inner surface

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Abstract: Aiming at the problem of 3D measurement of the inner surface of pipe, this paper develops a new structure of pipe inspection device inside the pipe based on the principle of laser triangulation. The device is composed of motion mechanism and image acquisition system. The three-dimensional shape of the inner surface is reconstructed the image pixel offset. The detection device driven by the motion mechanism can realize the automatic detection of different positions. The experiment shows the steps of the three-dimensional measurement of the inner surface of the pipe, verifies the feasibility of this method.

1. Introduction

The internal space of pipe is small, and it is difficult for high-precision testing equipment to be placed inside such parts for direct measurement. The traditional measurement of the geometric parameters of the inner surface of the pipe mainly relies on contact measurement methods, and the measurement process is complicated, time-consuming, and low in accuracy[1]. Non-contact measurement represented by structured light optical detection methods can achieve rapid, high-precision measurement and three-dimensional reconstruction of the inner surface of the pipe, which is a current research hotspot. In recent years, the developed pipe inner surface detection system generally adopts the circular structured light measurement[2], fringe projection[3] and laser interference[4] to pursue higher measurement efficiency. In these research, the direction of the CCD camera in the above system is parallel to the direction of the pipeline axis. It is difficult to perform 3D analysis when the central area of the captured optical image is irradiated to the depth of the pipe, a large amount of pixel area is wasted, and the resolution of 3D reconstruction is limited.

To improve the resolution of the detection of the pipe inner surface, this paper applies the multi-line structured light technique to the detection of the inner surface of pipe and develops a detection system for the inner surface of the pipe. This system is composed of the motion mechanism and the image acquisition system. The detection point cloud of the pipe inner surface is obtained by the pixel offset calculated, and the motion mechanism is used to detect the entire inner surface of the pipe.

2. Measurement Principle

When the structured light projector projects the structured light onto the surface of the measured object at a certain angle, the light plane intersects with the surface of the object to be measured to form a characteristic light strip containing the geometric information of the object, as shown in Figure 1.
The detection system adopts the optical path design structure of the oblique laser triangulation method. In this structure, the grating is projected onto the surface of the object under test at a certain angle of incidence, so that the CCD camera can capture the height difference of the surface of the object under test in the imaging area. The structured light strip produced by the change shifts the image. The offset distance \( h' \) of the structured light bar and the height \( h \) of the sudden change of the surface of the object have a certain linear relationship under the circumstance of ignoring the influence of lens distortion. According to the principle of oblique optical triangulation, assuming the height change of the measured object surface is \( h \) and the physical distance between two pixels on the CCD sensor is \( h' \), the relationship between \( h \) and \( h' \) is shown in equation (1):

\[
h = \frac{ah'\cos \theta_1}{b \sin(\theta_1 + \theta_2) - h'\cos(\theta_1 + \theta_2)}
\]

Where \( a \) is the distance from the intersection of the structured optical axis and the optical axis of the receiving camera lens to the main surface of the receiving camera lens; \( b \) is the distance from the main surface of the receiving camera lens to the imaging center point, \( \theta_1 \) is the included angle of the normal of the measured surface, \( \theta_2 \) is the included angle between the optical axis of the camera lens and the normal of the measured surface. Assuming that the height difference \( h \) between a measured plane \( m \) and the reference plane \( n \) is known, the linear relationship between \( h \) and \( h' \) can be solved to complete the calibration of the detection system.

3. System Configuration
The connection and control relationship between the various components of the measurement system is shown in Figure 2. Among them, the system works in conjunction with the image acquisition system and the motion mechanism to realize movement in the pipe. The motion mechanism outputs power according to the instructions of the industrial computer. Under the command of the control module, the power of the stepper motor is converted into the reciprocating linear motion of the measurement system in the pipe along the axis, and the image acquisition system rotational movement around the axis. The structured light strip projected by the structured light projector reaches the inner surface of the pipe and is modulated by the inner surface. The CCD camera acquires the structured light strip image of the pipe inner surface and uploads it to the industrial computer for image analysis and processing. Obtain the structural information of the surface features of the pipe, and accurately calculate the geometric feature parameters of the pipe through the acquired three-dimensional reconstruction.

3.1. Motion mechanism

The overall structure of the motion mechanism is shown in Figure 3. The motion mechanism uses the guide plate to ensure the axis of the measurement system is exactly the same as the axis of the pipe. The motion mechanism contains two stepping motors, which receive the signals of the industrial computer and during the working process, and provide driving torque for different motion forms respectively.

3.2. Image acquisition system

The structured light projection path of the image acquisition system is shown in Figure 4. Limited by the narrow space inside the pipeline, the laser light source, CCD camera, reflector and other components are integrated together. The structured light source is projected on the inner surface of the pipe at an angle of $2\alpha$ by using the oblique projection, that is, the structured grating projected in the horizontal direction is reflected by the reflector and then obliquely shot to the inner surface of the pipe at an angle of $2\alpha$ to reduce the radial size of the image acquisition system.
Thus the system's height difference measurement formula is transformed into:

\[ h = \frac{a h' \cos \alpha}{b \sin \alpha - h' \cos \alpha} \]  

(2)

In our system, \( a=110 \text{mm}, b=33 \text{mm}, \alpha=22.5^\circ \), the distance difference in pipe could be calculated by the offset of the light stripes in image.

4. Measurement experiment

In the experiment, a pipe with a band-shaped protrusion pipe is used for detection experiment. The processing process of the inner surface of the pipe is as follows: First, the Canny operator is used to perform edge segmentation on the collected image, and the detection area are divided into 3 regions as shown in Figure 5 (a). Then the region B is selected as the linear fitting area, the centroid of structured light strips are extracted to fit the straight line equation as shown by the thick yellow line in Figure 5 (b), the result of the linear fitting is shown as the thin solid red line in Figure 5 (c). Finally, calculate the vertical image distance between the corresponding centroid coordinates and the fitting straight line equation in the three regions, and combine the centroid coordinates to obtain the 3D reconstruction of the detected pipe as shown in Figure 5 (d).
5. Conclusion
We have developed a pipeline inner surface detection device, which enables the CCD camera to image perpendicular to the inner surface of the pipeline through a reflector, and performs a three-dimensional reconstruction of the geometric shape of the inner surface of the pipe. The system proposed in this paper can improve the resolution of the reconstruction of the pipe inner surface, and could realize the automatic detection of the inner surface of the pipe through the motion mechanism.

References
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