Design of a Micro Cable Tunnel Inspection Robot

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Abstract: As the ventilation system in cable tunnel is not perfect and the environment is closed, it is easy to accumulate toxic and harmful gas. It is a serious threat to the life safety of inspection staff. Therefore, a micro cable tunnel inspection robot is designed. The whole design plan mainly includes two parts: mechanical structure design and control system design. According to the functional requirements of the tunnel inspection robot, a wheel arm structure with crawler type is proposed. Some sensors are used to collect temperature, gas and image and transmit the information to the host computer in real time. The result shows the robot with crawler wheel arm structure has the advantages of small volume, quick action and high performance-price ratio. Besides, it has high obstacle crossing and avoidance ability and can adapt to a variety of complex cable tunnel environment.

1. Introduction
With the rapid development of robot technology, the application of the robot in the power industry is more and more common. The inspection robot for cable tunnel will greatly save manpower, material and financial resources. More importantly, it can greatly reduce the damage to the inspection personnel in the harsh environment of the tunnel.

In foreign countries, the United States was the first to develop a cable tunnel inspection robot. Bing Jiang and Alanson P. Sample, University of Washington, developed a set of underground cable inspection robot named Rangers in 2005[1]. The robot is equipped with two 12V DC gear motors in the ends and designed with a single-platform multi-section modular. So it has a stable steering capability. In addition, a multi segmented structure is designed to allow the robot to carry more sensors. The robot platform is divided into two sections, which are used for the control of the robot and the data processing of the sensor. The robot, 1.2 meters in length, can walk along the cable line of the diameter of 4~8 cm, cross the obstacles encountered along the way and enter the ground to crawl along the cable to identify the location of the fault.

In China, due to more and more attention to the research and development of robot, some research institutions have made some achievements in the tunnel robot. The articulated tracked robot for cable duct was developed by Shanghai Jiao Tong University. The robot is attached to an infrared camera with PTZ and a infrared temperature sensor, in addition to various types of gas sensors. Through collecting and processing the data of these devices, the robot can understand toxic gas concentration of the tunnel in real time and test whether the cable is damaged[2][3].

In 2012, a cable tunnel patrol robot was developed by Zhejiang University. The robot has the functions of autonomous inspection, emergency handling and remote monitoring, which could sustainable work 4 hours. In addition, it is equipped with infrared cameras and temperature, gas and other sensors. It can monitor the deformation, temperature and harmful gas in the tunnel and make the case of the tunnel upload to the monitoring center in real time. Therefore, the robot can replace manual
2. **Overview of tunnel inspection robot**

Based on the analysis on the characteristics of the tunnel environment and combined with the existing technical conditions, a cable tunnel inspection robot is designed, as shown in figure 1. The features and main functions are as follows:

1. The robot body platform is 26cm length, 27cm width, 17cm height, and about 5 kg weight, which can easily enter narrow occasions.
2. The robot can move flexibly and has strong climbing and obstacle avoidance ability. It can carry out reconnaissance and patrol in the high temperature, toxic, flammable and other threats to detection personnel security occasions.
3. It has a broad visual angle.
4. It can collect temperature and harmful gas concentration, measure distance through ultrasonic wave, and send the information back to the console in real time.

![Figure 1. Cable tunnel inspection robot](image1)

![Figure 2. Structure of cable tunnel inspection robot](image2)

3. **Mechanical structure design**

3.1 **Motion structure of the body**

The robot body adopts the track wheel arm structure. The crawler type wheel arm structure is a new way to combine the wheel motion mode, walking mode and track mode. The robot with wheel arm type structure has the advantages of both wheel, walking and the crawler robot, which can achieve climbing stair, crossing ditch, obstacle, steering and other functions. So it has strong maneuverability in complex environment.

The wheel arm adopts structural control. Four wheel arms were divided into two groups. The first two wheel arms were the first group and the later two arms were the second groups. Each arm movements are consistent, and the two groups do not interfere with each other. Four tracks are divided into two groups. The left two are the first group, the two on the right are the second group. Each set of tracks is consistent, and the two groups of tracks do not interfere with each other. This control method makes the robot more stable and flexible. The wheel arm is driven by a servo motor with a speed reducer, which is convenient to measure and control, and it is advantageous to drive and control in higher precision.

The application of track increased the ability of robot obstacle. The robot can walk over a small volume of obstacles. Crossing large obstacles can be achieved by controlling the operation of personnel. In addition, the track can increase friction, so that the robot has a greater advance power and thus adapts to the more complex environment [4]-[10]. The structure design of the cable tunnel inspection robot is shown in figure 2.

3.2 **Vehicle body gait analysis**
(1) Up the stairs process:

The motion process of robot upstairs is as shown in figure 3. It shows that the maximum height of climbing stair mainly depends on the difference between the wheel arm and the big radius. The robot is designed with the wheel arm length of 200mm and the big wheel arm radius of 30mm. The maximum stair climbing height is 170mm. The actual height of the stairs is basically 160mm, so the robot have the ability to cross the floor crossing.

(2) Down the stairs process:

The motion process of robot down stairs is as shown in figure 4.

(3) Crossing ditch process:

The process of robot crossing groove is as shown in figure 5. The width of crossing groove of the robot depends on the position of its gravity center and the overall length. Robot body is 350mm length and the total length is 600mm after unfolding front and back wheel arm. The distance between the center of gravity and the front of the wheel arm is 250mm. In normal driving conditions, the maximum crossing channel width is 240mm. In the case of a larger initial speed, the robot can across a wider trench. In addition, by adjusting the expansion angle of the front wheel arm, making the robot be in a certain angle with the horizontal direction so that the robot can cross the ditch with a certain gap with the aid of inertia in case of a larger initial velocity[11][12][13].

(4) Turning process:

The robot turning process is as shown in figure 6.

1) Turn left: close the left drive (the left track does not move), open the right drive (the right track moves forward).

2) Turn right: turn off right drive (the right track does not move), open the left drive (the left track moves forward).

3) Turn left in place: drive the left track forward and drive the right track reverse.

4) Turn right in place: drive the right track forward and drive the left track reverse.
3.3 Calculate the obstacle height

The crossing obstacle process of crawler wheel arm structure robot is as shown in figure 7.

**Figure 7.** Schematic diagram of the obstacle

L-body length, a-leg length, b-center distance between two track tension wheel, h-barrier height, r-tension wheel radius, x-distance between the body's center of gravity and the chassis, \( \alpha \)-Track maximum deflection angle, \( \theta \)-robot body inclination angle.

Analyze the length relation of each part in the diagram and get:

\[
\cos \alpha \sin \theta + b/2 \sin \theta + (L/2 + r + \cos \alpha + x \sin \theta) \sin \theta = 0
\]  
(1)

That is

\[
h = L \sin \theta + b/2 \sin \theta + (L/2 + r + \cos \alpha + x \sin \theta) \sin \theta
\]

Because

\[
CD = a \sin \theta \cos \alpha + \cos \theta + r + (L/2 \cdot x \tan \theta) \cdot \sin \theta
\]

and

\[
CD = L/2 \cdot \cos \theta - x \sin \theta
\]

merge two formula above and get:

\[
L/2 \cdot \cos \theta - (a + x) \sin \theta - b/2 \cos(\alpha + \theta) - r = 0
\]  
(2)

In addition, the bottom surface of the robot platform can not be touched with the steps of the endpoint (h<EF), that is:

\[
h < b/2 \cdot \sin(\alpha + \theta) + a \cdot \cos \theta + r + (L/2 \cdot x \tan \theta) \cdot \sin \theta
\]  
(3)

In fact, when the track is full contacted with the step plane, just make \( \alpha + \theta = 90^\circ \) and the situation of \( \alpha + \theta > 90^\circ \) does not occur. So the range of \( \alpha + \theta \) is \( 0^\circ - 90^\circ \), and take \( 90^\circ \) when it is larger than \( 90^\circ \). In general, in order to make the robot cross obstacle better and more stably, the track and the step plane need to complete contact as far as possible. Generally the value of \( \alpha \) is greater than 60 degrees and \( \theta \) is also greater than 30 degrees when meeting the obstacle limits, which would make \( \alpha + \theta > 90^\circ \). So according to the above principles, take \( \alpha + \theta = 90^\circ \) in the above three types.

In this way, the formulas (1), (2), (3) can be written as:

\[
\begin{align*}
\frac{L}{2} \cdot \cos \theta - (a + x) \sin \theta - b/2 \cos(\alpha + \theta) - r &= 0 \\
h &= L \sin \theta + b/2 \\
h < b/2 + a \cos \theta + r + (L/2 + x \tan \theta) \sin \theta
\end{align*}
\]  
(4)

When calculating the maximum crossing obstacle height of the robot, it is also necessary to ensure that the bottom surface of the robot platform can not be touched with the step end points (i.e. no floor interference) when the step height is h. Suppose the body inclination angle is \( \theta' \), there is

\[
\begin{align*}
\frac{L}{2} \cdot \cos \theta' &= h \\
a \cos \theta' + r &> h
\end{align*}
\]  
(5)

After eliminating \( \theta' \), the inequality can be obtained:

\[
a \sqrt{1 - h^2/L^2} + r > h
\]  
(6)

The maximum crossing obstacle height of the robot can be obtained by formula (4) and (5). \( \theta, L, a, b \) and rare independent variables. The method for solving is as follows.

Objective function: \( h = -(L \sin \theta + b/2) \)

Equality constraints: \( L/2 \cdot \cos \theta - (a + x) \sin \theta - r = 0 \)

Inequality constraints:
\[ -h + a \cos \theta + r - (L/2 - x \tan \theta) \sin \theta < 0 \] (6)

\[ -L \sin \theta - b/2 - a/\sqrt{1 - h^2/L^2} - r < 0 \] (7)

The structure size of the track wheel arm structure robot is as follows: L=350mm, a=50mm, b=170mm, r=30mm, track maximum deflection angle \( \alpha = 75^\circ \), the distance between the body's center of gravity and the chassis is 100mm.

From the above constraints the optimal solution can be obtained for \( \theta = 0.49 \text{ rad}, h=160\text{mm} \). So, the maximum obstacle height of crawler wheel arm robot is 160mm.

4. Design of control system

The robot control system consists of three single-chip processing terminal, defined as MCU1, MCU2 and MCU3. MCU1 uses the SPI standard serial port to connect to the PTR8000 full duplex wireless communication system so that it can communicate with the host computer for data exchange; MCU2 is mainly to control the four way power motor and three dimensional rotation platform; MCU3, connected with temperature, ultrasonic measurement distance and gas detection sensors, converts the analog signal into digital signals and uploads to MCU1; MCU3 controls the image acquisition and processing system and its signal is uploaded to the host computer by 2.4G microwave transmitter. The block diagram of the control system of the robot is shown in figure 8.

In order to obtain the environmental conditions in the cable tunnel, the robot is equipped with a variety of sensors.

(1) Temperature sensor

The robot can quickly and accurately measures the temperature of the surface of the robot by the non-contact infrared temperature measurement technology, which can be used for the measurement of hot, dangerous or difficult to contact and other objects.

(2) Attitude sensor

The robot uses Holzer sensor to monitor the rotation angle of the wheel arm. Put micro cylindrical magnets magnetized on the first stage wheel of gear box and detect the rotation number of the gear by Hall sensor. MCU records the turning number of driven wheel and converts it into wheel arm angle information so that it can achieve precise control.

(3) Gas sensor

Gas sensor selects MQ-7 sensor. The detector has high sensitivity to carbon monoxide and methane, and has a long service life and high stability.

![Figure 8. Robot terminal control system](image-url)
(4) Camera
The wireless infrared camera uses 2.4G wireless transmitter ultra micro CCD chip, which has the advantages of signal stability and image anti interference. In addition, use the UTV330+ TV box to receive the image signal transmitted from the wireless camera.

(5) Motor drive circuit
The rotation and rotation direction of the DC motor is controlled by the driving circuit. Two driving schemes designed are as follows.

Scheme one:
Control four DC motor using H bridge, so each tube has a large tube pressure drop and the power consumption is large in each tube. Besides, when the PWM (pulse width modulation) there is a switching loss, so we are not able to adopt this plan.

Scheme two:
Use high power transistor to drive the DC motor, use the relay to control the rotation of motor. The scheme has the advantages of small power consumption, high efficiency and simple and practical design. This scheme is as shown in figure 9.

![Figure 9. DC motor drive mode](image)

(6) Steering gear control
The steering gear is composed of a DC motor, a reduction gear set, a sensor and a control circuit, which is used for controlling the angle and position. Control the rotation of the motor and output the torque by sending a pulse signal. At the same time, potentiometer on output shaft detects the rotation angle of the output shaft and converts it into electrical signal. The electric signal is compared with the electric signal of the input shaft angle, which can be used to control the DC motor to rotate feedback. Servo drive module uses high power MOS tube as the power element. The driving module is designed for DC motor speed control by PWM mode, which is suitable for small DC motor.

5. Conclusion
In this paper, based on the practical application and combined with the existing technical conditions, a design scheme of a micro tunnel inspection robot is proposed. Then introduce the main function, mechanical structure and control system of the robot from the whole angle. From the mechanical structure, the robot crawler wheel arm structure enriches the robot movement capability, which is more suitable for the complex terrain such as cable tunnel; From the control circuit, the circuit has the advantages of simple structure, strong anti-interference ability, stable operation of the circuit system and so on. The experimental results show that the crawler wheel arm robot not only is mobile, flexible and cost-effective, but also realizes the function of remote control robot and wireless data transmission.

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