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A novel mobile robot for finned tubes inspection

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SUMMARY

A novel mobile robot FTIR (Finned Tube Inspection Robot) for finned tube inspecting is presented in this paper. FTIR can move in both x- and y-direction on the top layer of the tubing that is installed in layers. The snake-like arms mounted on the robot can be lowered into the narrow space between the tubes and the tubing can be inspected through the device installed in the end of the arms. The moving mechanisms, inspecting device applied in narrow space and control system are introduced.

KEYWORDS: Finned tube inspection; Snake-like arm; Robot.

1. INTRODUCTION

In China, more than 80% of the electricity is supplied by thermal power plants. Heat exchanger tubing is the key equipment of power plants. Based on recent statistics, boiler accidents are 40% in all the equipment accidents, and 70% of the boiler accidents are caused by heat exchanger tubing, especially finned tubing. A finned tube is one having fins around its outer surface in order to maximize heat transfer to the surrounding air by supplying a large surface area. Once the accident occurs the thermal generator set is forced to stop working, thus resulting in a great loss. For example, if a 300 MW thermal generator set stops working, it would lose millions of Yuans per day.[1] There are two reasons resulting in the high accidents on finned exchanger tubing in boiler: One is the adverse conditions of high pressure and high temperature; the other is that it is very difficult to inspect some tubes by people due to their special installation. In recent years, intelligent robots have been developed around the world. One purpose to develop these robots is to employ them to work in environments dangerous or inaccessible for humans. Thus, it is necessary to inspect the finned exchanger tubing in boiler with intelligent robots.

Many scientists are interested in tube robots and boiler inspection; they focus their research on such fields as in-pipe, outer-pipe and boiler tube inspection. The research on an in-pipe inspection robot is of particular interest to the locomotion and location mechanism.[2–12] The research on outer-pipe inspection robot emphasizes particularly the inspection of tubes in a plane.[13] The research on boiler tube inspection focuses on the methods of inspection, including ultrasonic, eddy current, magnetic flux leakage and laser optics, etc.[14–26] But one of the main problems in the inspection of boiler heat exchanger tubing, especially that installed in layers in a narrow space, is how to design a moving device that can take the sensors to the whole the inspection site and that is small enough to act freely in a narrow space between the tubes; however, there is almost no research on these devices. A novel Finned Tube Inspect Robot (FTIR) has been developed in order to inspect the finned heat exchanger tubing installed in layers in a boiler with a narrow space among the tubes.

The paper is organized as follows: The overview of FTIR is described in Section 2; The moving mechanisms of FTIR are introduced in Section 3; The rotating and sliding structure of upper platform in FTIR is introduced in Section 4; A snake-like arm is presented in Section 5; The inspecting devices are shown in Section 6 The control system is described in Section 7; The conclusion is in Section 8.

2. THE OVERVIEW OF FTIR

The FTIR is shown in Figure 1. It can move in both x- and y-directions on the top surface of the tubing and reach any position on the surface. The snake-like arms fixed on the upper platform can be lowered into the narrow space between the tubes. Tubing failures can be inspected with the small inspecting devices mounted at the end of the snake-like arms, and the edge of the tubing can also be inspected by sliding and rotating of the upper platform. A supervisor

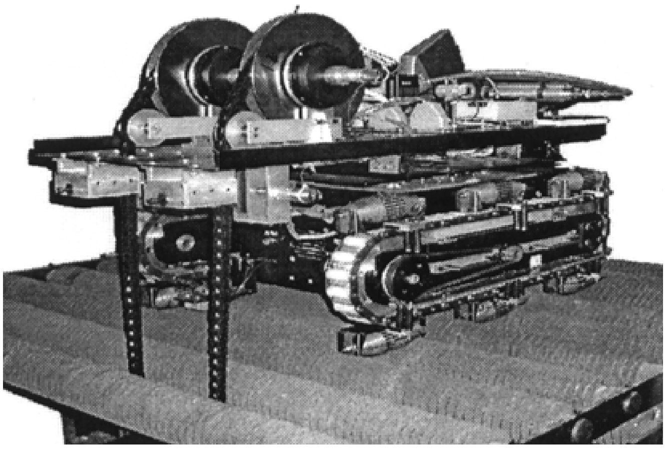

Fig. 1. The overview of FTIR.

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can control the FTIR and obtain the inspecting information by the wireless LAN (Local Area Network).

3. THE MOVING MECHANISM OF FDTR

The moving mechanisms of FDTR include x- and y-directions moving mechanism, an error compensating device for movement, and the mechanism of y-direction driving and speed inspection.

3.1. X- and y-direction moving mechanism

A x- and y-direction moving mechanism is shown in Figure 2. X-direction is defined as the direction perpendicular to the axis of the tubing, and the y-direction as parallel to the axis.

H is the output of the driving motor. A is sprocket wheel in which a harmonic speed reducer is installed. The chain is specially designed and it's pitch is one fourth the distance of the two next tubes. B is timing belt; C is the small wheel, and twelve small wheels are mounted on the chain symmetrically. By precisely calculating the skeleton line of the small wheel, the small wheels don't interfere with the tubing in the x-direction movement. D is the adjustment mechanism of the chain. E is a board with an electrode and guide path on it; three sets of electrodes are fixed in a special place; F is the electrode on the small wheel. The small wheel works only when F is in contact with the electrode on E. F slides into E along the guide path on E. G is the inspected tubing. There is a set of moving mechanisms on each side of FTIR, as shown in Figure 1. The x-direction movement of FTIR is driven by H, and FTIR can move in the y-direction when the small wheels rotate. The small wheel is driven by a motor inside it. The inner structure of the small wheel is shown in Figure 3.

3.2. The structure of error compensating for movement

Because an installation error of tubing is unavoidable, some small wheels can't contact the tube fully and the force exerted on each wheel is different; thus FTIR can't move exactly, hence a structure for error compensating is designed. The structure is shown in Figure 4, including lateral error compensation structure and longitudinal error compensation structure. The error can be compensated by the elasticity of the structure. The small wheels can touch the tubes fully when moving, as a result of adopting the structure of error compensating.

3.3. Y-direction driving and speed inspecting structure

The small wheels move with the chain when FTIR moves over the tubes; as a result, the power wires of motor in the wheel will twist together. In order to avoid the twisting of the power wire a novel mode of wire connection is invented, in which E and F in Figure 3 are involved. E is stationary and F slides into E along the guide path on E when FTIR moves in a x-direction. F can contact the electrode on E tightly due to the elastic pressure mechanism inside F.

It is difficult to measure the speed and the moved distance of the small wheel with the rotary encoder because the motor is installed inside the wheel. A reflected photoelectric sensor is applied instead of the rotary encoder (shown in Figure 5). The numbers and the width of the stripes depend on the resolution and inspection requirements. The relationship between the width and the numbers of the stripes is given by:

$$W = \pi D / N \geq d$$

where W is the width of the stripes, N is the numbers of the stripes, D is the diameter of the small wheel, and $d = 6.25$ mm is the inspection resolution. In this paper, by setting D to 50 mm and N to 40, W is 3.925 mm. In order to distinguish the rotation direction, the phase difference of the two sensors should be one-fourth cycle. One cycle is defined as follows:

One cycle = one white strip + one black strip.

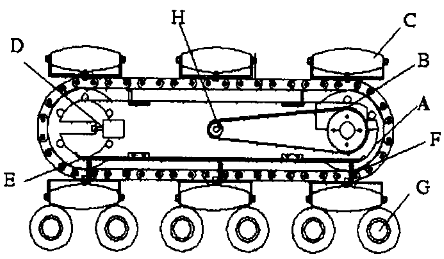

Fig. 2. The moving mechanisms.

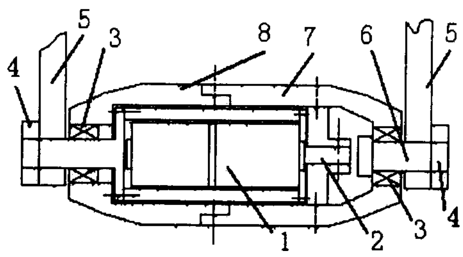

Fig. 3. The inner structure of the small wheel. (1) motor; (2) output of the motor; (3) bearing; (4) fastening nut; (5) supporting frame; (6) supporting shaft; (7, 8) shell of the small wheel.

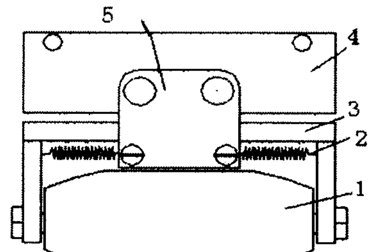

Fig. 4. The structure of error compensating. (1) the small wheel; (2) spring; (3) supporting system; (4) spring board; (5) connector.

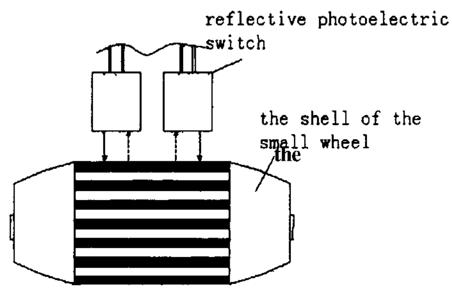

Fig. 5. Method of speed measuring.

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4. THE ROTATION AND SLIDE MECHANISM ON THE UPPER PLATFORM

The FTIR can't be at the tubing edge because of its big size, so the edge becomes the blind zone of inspecting. For the sake of inspecting, the rotation and slide mechanism on the upper part of the FTIR are designed, as is shown in Figure 6. The rotation plate-form can rotate from −90° to +90°, and the slide platform can slide to and fro. The sensors can be carried to any site of tubing edge due to the rotating and sliding of the platforms and the action of the snake-like arm (shown in Figure 7), hence there is no blind zone in the inspection.

5. THE STRUCTURE OF SNAKE-LIKE ARM

Because the tubing is installed in layers, the inspection device must be capable of reaching the deep layer of the tubing. A snake-like mechanism is designed which can carry the inspection device into the deeper layer of the tube. The snake-like mechanism is illustrated in Figure 7.

One end of the snake-like arm is fixed on the shaft of the reel wheel and there is an inspection device (shown in Figures 8, 9 and 10) on the other end. A rotary encoder is mounted on the drag wheel. The snake-like arm is driven by the drag wheel and the reel wheel together, and it's position in working can be obtained with the rotary encoder. The snake-like arm is pressed onto the drag wheel at a suitable pressure with a compressing apparatus.

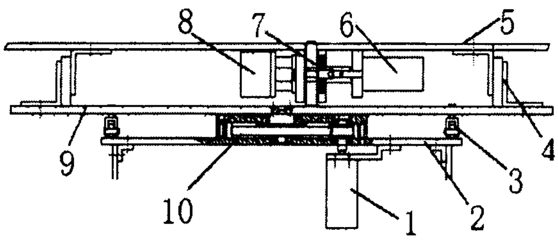

Fig. 6. Rotation and slide platform. (1, 6) motor; (2) shell of FDTR; (3) roll bearing; (4) slide rail; (5) slide platform; (7) gear and timing belt; (8) encoder; (9) rotation platform; (10) rotation gear cluster.

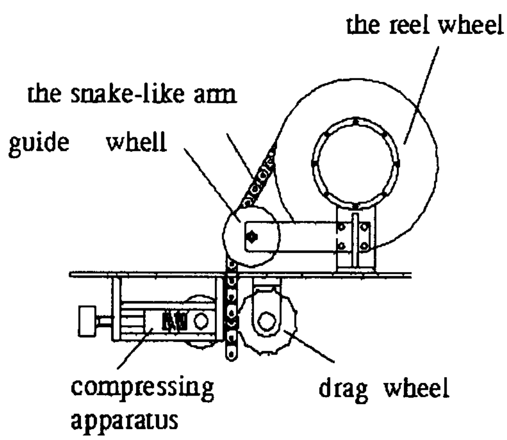

Fig. 7. The snake-like arm mechanism.

6. THE INSPECTING DEVICES

There are three kinds of sensors on the end of the snake-like arm: CCD device for image scanning, ultrasonic sensor for thickness measuring and stain gauge transducer for diameter deformation measuring. The inspection devices are specially designed and manufactured so that they are small enough to act freely in the narrow space between the tubes.

The special inspection devices are shown in Figures 8, 9 and 10. A CCD probe is installed in the center of the CCD

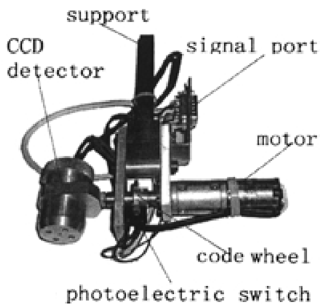

Fig. 8. The CCD device.

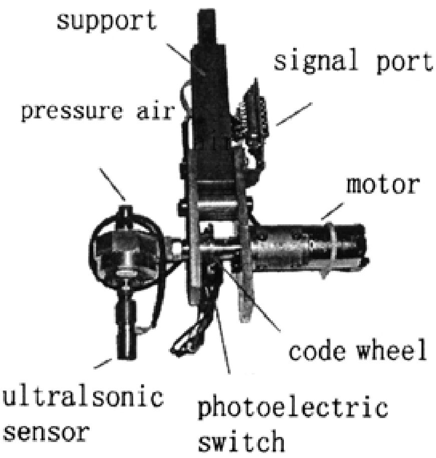

Fig. 9. The Ultrasonic sensor.

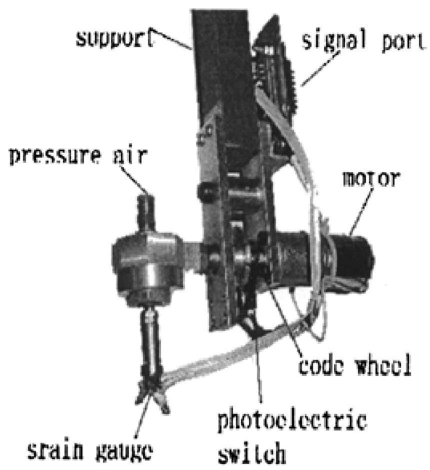

Fig. 10. The strain gauge transducer.

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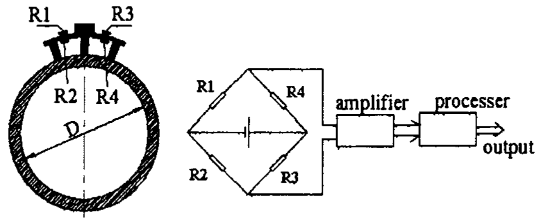

Fig. 11. The principle of the strain gauge.

device, and four LEDs are around the CCD probe symmetrically as a light source. The inspected surface can be lit uniformly without reflection by choosing a certain LED parameter suitable for the environment of the boiler. The intensity of illumination can be changed by adjusting the electric current flowing into the LED. The outside diameter and the length of the ultrasonic sensor is 8 mm and 12 mm respectively; it has an arched surface, so it can fully contact the tube surface. It is difficult to insert the couplant into the tube surface, so a special cavity is designed in the ultrasonic sensor which is full of couplant, and the couplant can leak out to the tube surface automatically. The principle of the strain gauge transducer is illustrated in Figure 11. Three probe contacts with the tube and the probe are connected with an elastic girder on which four strain gauges are pasted like a bridge. The elastic girder deforms differently when a different diameter tube is measured, thus resulting in a different output of the strain gauge transducer. The strain gauge transducer is sensitive to 0.01 mm of deformation. The ultrasonic sensor and strain gauge are driven to and fro toward the tube surface by high pressure air. The inspection devices can rotate by being driven by a motor, and the position information can be obtained with a photoelectric switch and coder wheel.

7. THE CONTROL SYSTEM

Because of the hostile conditions in the boiler, inspectors cannot be there. A wireless LAN is used so that inspectors can control the robot and obtain the inspection information remotely. The control system is shown in Figure 12.

The control system is a multilevel distribution system. The host controller is in charge of the whole inspection. During the inspection, the CCD first works to scan the tube surface in order to know whether there are faults and what they are. If there are any faults, the ultrasonic sensor and strain gauge transducer can ascertain their extents. All actuators and transducers are controlled by a host controller; on the other hand they return inspection information to the host controller. The information exchanges between the actuators, transducers and the host controller is realized via a communication controller. The communication controller communicates with the host controller via the wireless LAN. At the same time it communicates with actuators and transducers via a RS-232 data-communication standard. In order to ensure the clarity of the pictures, special wireless transmission instruments are used for the image data.

8. CONCLUSION

A robot FTIR is introduced in this paper. It can be used to inspect the heat exchanger pressure tubing with fins on it's outer surface in the boiler. The tubes are installed in layers and there are narrow space among the tubes. The problem of moving in both x- and y-directions on finned tubes is solved. The problem of interference between the inspection devices and the boiler due to the narrow space and deep layer is also solved by using a snake-like arm. A special small ultrasonic sensor is designed in order to solve the problem of a narrow inspection space and the difficulty of inserting the couplant onto the tube surface. The supervisor can control the robot and obtain the inspection information by the wireless LAN. At present, the robot is being tested in the Huangtai power plant in the Shangdong province.

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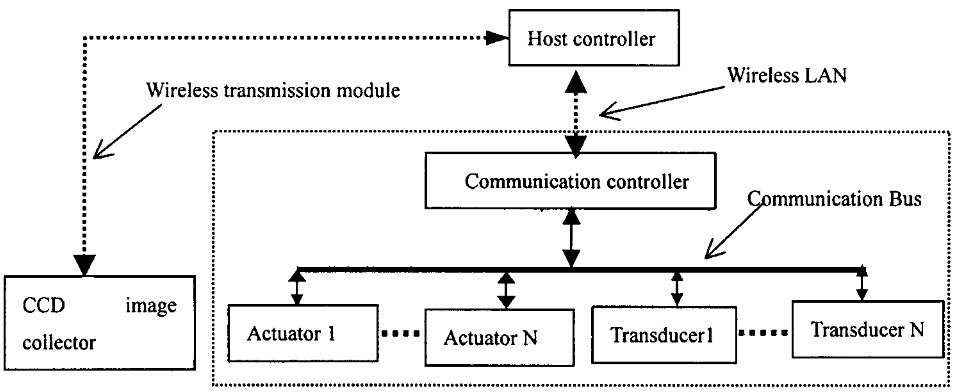

Fig. 12. The diagrammatic sketch of the control system.

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