Investigation on the System Design of Automatic Inspection Robot and Its Motion Adjustment Algorithm

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Abstract

In this paper, a kind of automatic inspection climbing robot was developed to improve the work efficiency of ultrasonic tandem weld seam detection on high pressure chemical containers. The robot powered by four independently magnetic wheels, utilizing magnetic belt to navigate and examine using fiber sensor. The structure of robot is compact; it has very high precision to position and navigation. A new navigation method and an algorithm of error adjustment is proposed, it is proven effective in actual use. The structure and the motion-adjusting algorithm about the robot is mainly discussed with actual experiment.

Keywords: Ultrasonic tandem detection, Motion adjusting algorithm, automatic inspection robot

I. Introduction

To inspect the flaw of the container loop weld seam, so many methods are tried, and the ultrasonic tandem method is regarded as one of the most efficient way. In this paper, we designed an automatic ultrasonic tandem inspection robot, which is used to a refinery hydrogenation reactor container. With the demand of JB4730-94 “Pressure Container Nondestructive Testing”, the ultrasonic tandem inspection method should make sure that the middle bunch of a transmit probe and a receive probe must keep in a plane perpendicular, and at the center line of weld seam, it receive and transmit probes in isometry[1]. It is difficult to manipulate by manually examine, poorly repeat and compare weakly, so it is significant to research the climbing robot which detect by ultrasonic and automatic inspect. In this paper, a special robot designed for Nanjing refinery factory is proposed and its main mechanism structure, control system and motion adjusting algorithm is also discussed.

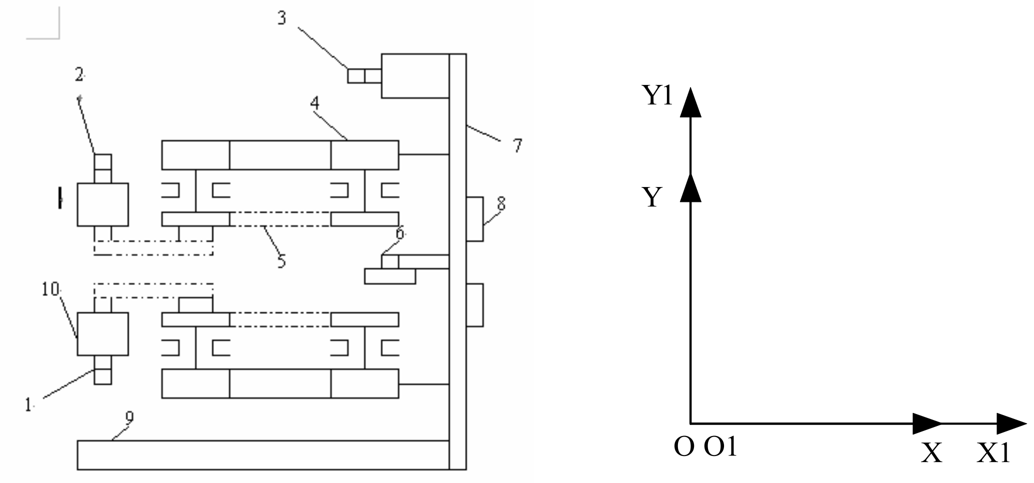
Ⅱ. Total Structure and Design

A. Structure

The inspection robot include guide track mobile, right and left magnetic wheel mobile [2] according to the work demand, as is shown in Fig.1 (a). Tab.1 illustrate the technology specification. The inspection robot was keep on the surface of container depending on the four magnetic wheel forces, two wheels were placed on right and left sides of robot, which is driven by two AC servo motors and slowdown through harmonious retarder and synchronization dentiform belt. The movement of magnetic wheels make robot to go ahead, back off and circumvolve, which adjust the position of robot. Two wheels are driven by dentiform belt [4,5]; they were active wheels too, which form two freedom of robot. Another motor driven by AC servomotor with retarder and synchronization dentiform belt form the third freedom of robot. Two moveable modules were respectively mounted on the both dentiform belt, consequently, they can bring the probes mounted on the modules to move positive and negative direction relatively symmetrically.

The reference frame $O_1X_1Y_1$of robot is defined as Fig.1 (b). In the reference frame, point O_1 locates symmetry center point of four wheels, point O_1X_1 is symmetry centerline of left and right wheels, O_1Y_1 parallel guide track of tandem scan probes.

In Fig.1 (b), axis OX fixed on the surface of container, with superposition of tandem scan based line; perpendicular with axis OY, O and O_1 are in the same point. Tandem scan based line located usual 0.5 span distance from detection surface, which is symmetry based line of receive and transmit probes isometry movement, when robot inspects. In this paper, left mean the positive direction of Y_1, right mean the negative direction of Y_1.



(a) (b)

Fig.1 Robot structure and Coordinates;
1, 2, 3 motor, 4 magnetic wheel, 5 dentiform belt, 6 photoelectric encoder + small wheel, 7 guide track, 8 module and tandem scan probe, 9 sensor box, 10 harmonious retarder

Tab.1 Technique Reference

Outline Size	No guide track：435mm(L)×450mm(W)×130mm(H)
	Include guide track：435mm(L)×730mm(W)×130mm(H)
Weight	20kg
Magnetic force	200kg (4 wheels in total)
Movement Scope	X direction >=15m
	Y direction <=400mm
Speed	X direction nominal speed 95mm/s(0~70mm/s adjustable)
	Y direction nominal speed 330mm/s(0~2000mm/s adjustable)
Sensor	4 guide sensors and a sensor marked position，type：BFRX，precision 0.2mm

	Photoelectric proximity sensor
	Photoelectric Encoder，Japanese NEMICON ovw2-25-2MD

B. *Guidance System based Sensors*

In this paper, four fiber sensors were used, which are sensitive for color, to guarantee the x-axis precision. Another photoelectric encoder, which was driven by free small wheel adhered to surface, is used to detect movement distance of the x direction.
A Guided belt was placed refer to the tandem based line of weld seam, and a magnetic belt with smooth surface is the bottom layer. For navigation, a white color belt with fixed width was placed on the magnetic belt.

Plane layout of sensors was illustrated in Fig.2. O1’x1’y1’ is reference frame of sensors box, correspond with $x_1^{'}$ fixed on robot’s body, middle symmetry line of sensors parallel with x axis, $y_1^{'}$ pass sensor1 and sensor2, $o_1^{'}$ is zero point of sensor frame. $o^{'}x^{'}y^{'}$ is reference frame of guide belt, $x^{'}$ axis parallel with x axis and superposition with middle line of guide belt, equivalent to the coordinates of fixed on the container’s wall, $o^{'}$ and $o_1^{'}$ is the same point on $x_1^{'}$ axis when no position deviation and angle deviation, $y^{'}$ perpendicular with $x^{'}$. In the Fig.2, the function of sensor 1 and sensor 2 is to limit the deviation of y axis when robot move along with x axis, the function of sensor3 and sensor 4 is to limit the deviation angle of robot relative with x axis’s direction. Once the deviation appeared, at least one sensor react the phenomenon, then computer send messages to adjust the pose of robot based the status of sensors.

The function of fiber sensor 5 is to decrease the accumulate error when the robot move forward along of axis x, which is marked every 200mm distance along the guided belt, once sensor 5 meet the road mark, the current position of robot was obtained through photoelectric encoder, and calculate the error between current position and real position, after this, set the current position as the real position to avoid the shortcoming of accumulate error after long distance.

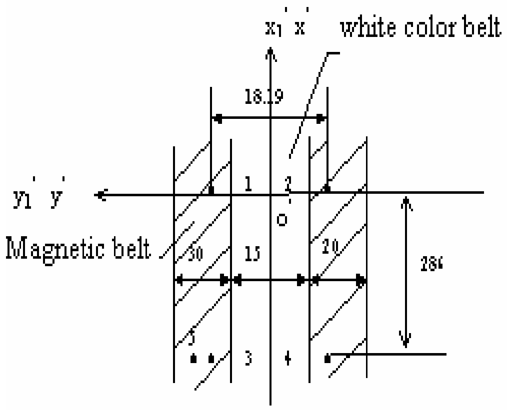


Fig.2 The plane layout of sensors

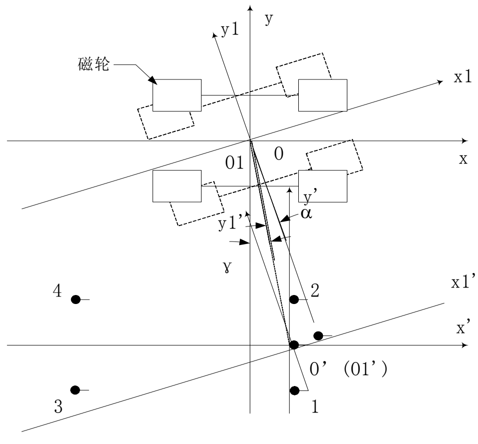


Fig.3 Adjusting movement

Ⅲ. Control System

The simple structure of robot control system in Fig.4, in which, industry computer realizes track planning, store scanning data and analyze the data of weld seam flaw. GT-400SV motion control card based PCI bus is control unit of servo AC motor, which accomplishes speed and position close-loop of three motor shafts. Ultrasonic detect card transfer the data from ultrasonic probe to computer, the signals of fiber sensors, photoelectric encoder and limit switch were connected to motion control card through connecting card. Servo amplifier and servo motor are products of Panasonic MINAS A series, Servo amplifier structured speed and current close-loop to get high precision of robot controlling. Frame of control system software illustrated Fig.5, where GUI is plain and in favor of debugging and running, the information from GT-400 SV transferred were displayed in the GUI to monitor.

Task module realizes different task, such as zero position initialising, position and angle adjusting and position marked of x axis direction etc, including warning and error dealing too. In GUI window, you can choose operation mode, hand control and automatic control, accomplishing itself pose correcting while robot is running. During this process, program is monitoring status of system running and deal with the troubles of system.

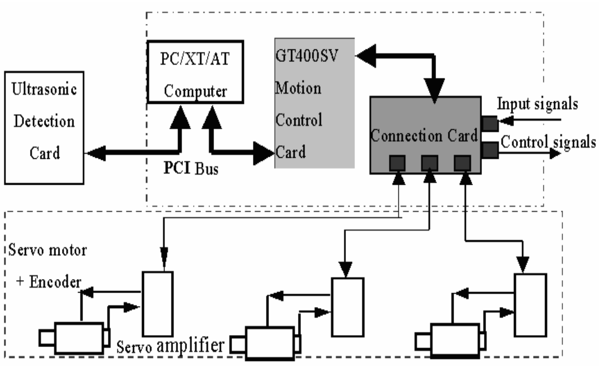


Fig.4 Hardware Frame of Control System

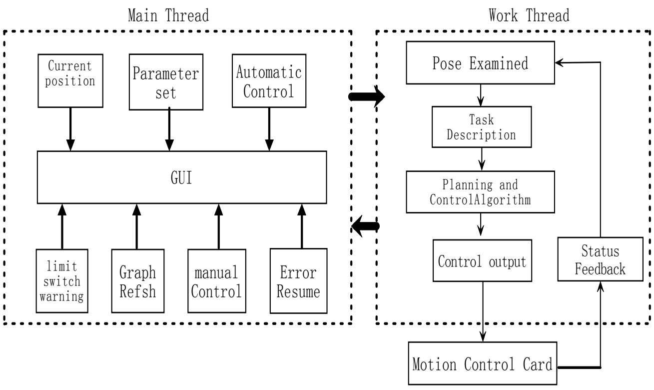


Fig.5 Software Frame of Control System

Ⅳ. Movement Process

A. Scan Motion

The robot receives and transmits probes in isometry, inverse phase and movement with constant velocity relatively tandem based line, called scan motion, probes mounted on the modules in Fig.1 (a). The scan motion can be described as: robot searched zero position, circle step motion forward - probes expand - robot step forward – probes contract; during these steps, system entered adjusting process once deviation appeared.

B. Adjusting Motion

In order to meet the precision of ultrasonic tandem scan, robot must adjust its pose based on sensors' status in time. Four fiber sensors in the Fig.4 indicate usually red color, when robot deviate the guide belt, fiber sensor's probe deviate the area of white color guide belt from the area of black guide belt, and the indicator of fiber sensor deviated don't light, then robot correct the pose of robot based the status of four sensors, according to the deviation of position and angle, the status of sensors can divide 15 pose, for example: ○●○●, ○●●○ etc, ○ means the dark of indicator, ● means light. Robot can reach the demand precision of position and angle by adjusting motion, the motion have position adjusting and angle adjusting.

C. Position Deviation Adjusting

The position deviation adjustment include have four steps:(a) robot rotate a φ_1 angle across the centre of the dotted line, as is shown in Fig.3, solid line indicate position of zero deviation; (b) move forward x_1 distance forward the direction; (c) stop and rotate inversely φ_2 angle across the centre; (d) back to the initial position x_0 along the x direction.

Consequently, the robot can fulfil the motion of y direction at the same x position. In this paper, the distance of $o_1o_1^{'}$ is l, the angle between $o_1o_1^{'}$ and y_1 axis is γ, l,γ are the parameters of robot structure, α is the rotation angle of robot, the level distance of robot from $o_1^{'}$ to $y^{'}$ is ΔX, the perpendicular distance of robot from $o_1^{'}$ to $x^{'}$ is ΔY; every step as followed:

(1) Robot rotate φ_1 angle and $\alpha = \varphi_1$, perpendicular offset ΔY_{φ_1}, level offset ΔX_{φ_1}

$$\Delta X_{\varphi_1} = l\sin(\varphi_1 + \gamma) - l\sin\gamma \tag{1}$$

$$\Delta Y_{\varphi_1} = l\cos\gamma - l\cos(\varphi_1 + \gamma) \tag{2}$$

(2) Robot produces perpendicular offset ΔY_{x_1} and level offset ΔX_{x_1} by forwarding x_1 distance followed the direction.

$$\Delta X_{x_1} = x_1\cos\varphi_1 \tag{3}$$

$$\Delta Y_{x_1} = x_1\sin\varphi_1 \tag{4}$$

(3) Robot produces perpendicular offset ΔY_{φ_2} and the level offset by inversing φ_2

$$\Delta X_{\varphi_2} = -\left[l\sin(\varphi_2 + \gamma) - l\sin\gamma\right] \tag{5}$$

$$\Delta Y_{\varphi_2} = -\left[l\cos\gamma - l\cos(\varphi_2 + \gamma)\right] \tag{6}$$

$\alpha = \varphi_2 - \varphi_1$, if $\varphi_2 = \varphi_1$, then "α＝0" means the finish of angle adjusting.

(3) In order to compensate the offset of robot in x direction, robot must back ΔX_{1b} and keep the perpendicular offset of robot $\Delta Y_{bX_1} = 0$.

Level offset: $\Delta X_{1b} = -\Delta X_{x_1} = -x_1\cos\varphi_1$

Conclude, for adjusting ΔY offset, the relation of rotation angle and motion distance as followed:

$$\Delta X = \Delta X_{\varphi_1} + \Delta X_{x_1} + \Delta X_{\varphi_2} + \Delta X_{1b} = 0 \tag{7}$$

$$\Delta Y = \Delta Y_{\varphi_1} + \Delta Y_{x_1} + \Delta Y_{\varphi_2} + \Delta Y_{bX_1} = x_1\sin\varphi_1 \tag{8}$$

Here, the offset have something to do with the rotation angle, under the constant offset, x_1 is bigger, φ_1 is smaller, so it must be selected on practice, considering that robot must get ride of friction while rotating, the consumed power of the motor is greatly, φ_1 can't be too big, if x_1 is too big, the time of robot adjusting need too long, as a result of setting these parameters according to a concrete circumstance.

D. *Angle Deviation Adjusting*

The adjusting process of angle deviation is follows:

(1) Compensating ΔY_{φ_1} can be finished by first three steps of position adjusting, then robot rotate φ_2 and go forward x_2 distance followed the rotated direction, inverse φ_2 angle.

$$\Delta Y_{\varphi_1} = x_2\sin\varphi_2 \quad \text{i.e.} \quad l\cos\gamma - l\cos(\varphi_1 + \gamma) = x_2\sin\varphi_2 \tag{9}$$

According to the deduce of position adjusting, in the process robot produce level offset $\Delta X' = x_2\cos\varphi_2$, at the moment, in total offset in x direction is $\Delta X_{total} = \Delta X_{\varphi_1} + \Delta X'$.

Compensating ΔX_{total}, robot go backward $X_{back} = -\Delta X_{total}$, then

$$X_{back} = l\sin(\varphi_1 + \gamma) - l\sin\gamma + x_2\cos\varphi_2 \quad (10)$$

E. Position and Angle Deviation Adjusting

The mode of position and angle deviation adjusting can be divided two steps, first adjusting position according to mode of position deviation, then adjusting angle according the mode of angle adjusting, the concrete way and deduce can reference above process.

In practical adjustment, the deviation of robot is different because of the left partial and right partial of robot influenced by gravity and friction, it must be compensated properly.

Ⅴ. Conclusions

In this paper, a special automatic inspection robot climbing on the wall was proposed, which is experimented on the surface of cylinder container with the radius 1700mm. The motion trajectory of climbing robot's probes is shown in Fig.6 (a), which reveals the motion process of probes and the adjusting process of robot. The robot is running on the surface of container, which is shown in Fig.6 (b). The motion deviation of the basis line is shown in Fig.6(c), in which the deviation is –1mm to 1.5mm. This performance can meet the requirement of ultrasonic tandem scan; it is proved that the method of ultrasonic tandem scan is effective. The application in lab and scene show that the wall robot with above symmetrical magnetic structure is feasible, it realizes scanning motion and adjusting motion, and reaches the movement precision of ultrasonic tandem scan required, and it has simple structure, cheap, very good markets prospect.

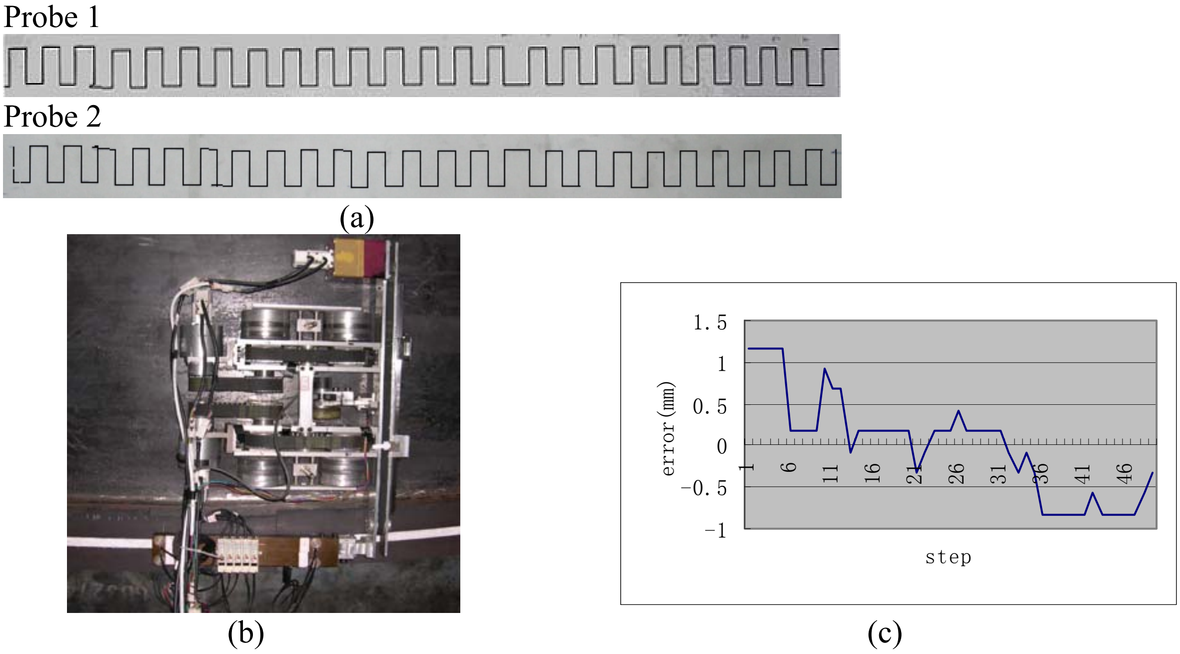


Fig.6 (a) trajectory of probes motion; (b) running scene of specimen; (c) deviation relatively tandem based line in y direction

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