Design and Analysis of Modular Mobile Robot with Magnetic Wheels

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Abstract: - In the paper, a modular climbing-wall mobile robot with four magnetic wheels is presented. It can move on the vertical steel wall and inspect the weld seam. First, the structure of the mobile robot is analyzed. It is modular, which consists of a light manipulator module, an ultrasonic probes module and a weld testing sensors module. Then, the magnetic wheels are designed and analysed. One magnetic wheel consists of two pieces of magnet and three pieces of pure steel plates. Second, the motion of the robot on the vertical cylindrical vessel is analysed in detail. The position deviation and angle deviation are adjusted with the geometric method. At last, the experiments of the modular climbing-wall robot on real vertical steel vessel are shown to verify the above motion analysis and design requirements at Nanjing refinery factory in China. It is of high reliability and simple control.

Key-Words: - Mobile robot, Magnetic wheel, Motion, Modular, Structure

1 Introduction

A robot capable of moving on a vertical wall has been looked forward to for a long time [1]. By developing for several decades, the climbing-wall mobile robot has a wide application in different fields, such as the inspection and maintenance of storage tanks in nuclear power plants and petrochemical enterprises [2-4], ship hull welding and cleaning [5], rescue robots for fire fighting or danger environments [6], the cleaning of high-rise buildings [7,8], et al. The climbing-wall mobile robot needs special adhesion mechanism to support it to absorb on the vertical walls. According to the adhesion mechanism, the climbing-wall mobile robots can be divided into four groups: magnetic adhesion, vacuum sucker, propeller [9], and dry adhesion using nanofabrication techniques [10]. Such as the miniature robot-Crawler [11], the wall-climbing robot for inspection in nuclear power plants [3], the SURFY[12,13] and so on, they used vacuum suction cups to adhere to the wall. According to the locomotion mechanism, the climbing-wall mobile robots can be divided into four groups: wheeled locomotion [14], tracked locomotion [15], legged locomotion [16], and locomotion based on arms and grippers [17]. Different adhesion mechanism and different locomotion mechanism can be combined together to form different types of climbing-wall mobile robots. Nishi [9] developed the wheeled climbing-wall robot, using single vacuum sucking cup. The climbing robot is supported by two suction feet which can hold on smooth and non-porous surfaces. It moves on the wall with the wheels. Based on their first legged climbing wall robot with vacuum adhesion mechanism, Tomoake et al [18] developed the second adaptive climbing-wall robot. Some climbing robot has legs. Each leg has claw to climb the surface, such as the tree-climbing robot—RiSE [19]. A three-limbed climbing robot in vertical natural terrain is given in [20]. The robot can climb real, vertical natural terrain, being applied for military and civilian used as search, rescue, planetary exploration and so on. A quadruped walking and climbing robot for NDT (non-destructive testing) is put forward in [21]. The quadruped robot, called “MRWALL SPECT III”, can walk in planes as well as climb walls with suction pads and carry an ultrasonic NDT tool for inspection of the large surface of industrial utilities. Hagen developed tracked locomotion climbing-wall robot with magnetic adhesion mechanism [22].

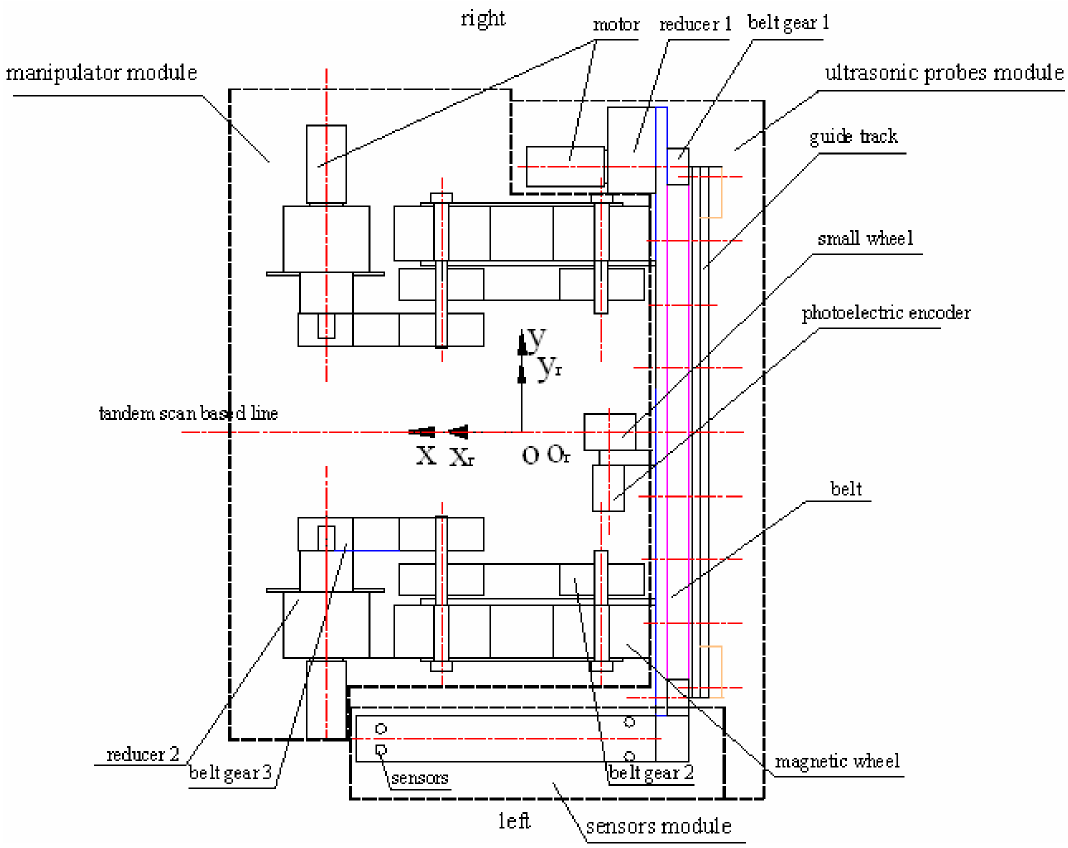
The mobile robot with ultrasonic scanning is a useful device that can be applied to nuclear power plants [23] to protecting nuclear workers in highly contaminated areas or hostile environments, reduce human exposure not only to radiation, but also to hot, humid and oxygen-deficient atmospheres. In nuclear power plants, the reactor pressure vessels are one of the most important pieces of equipment in view of its function and safety. The vessels are constructed by welding large rolled plates, forged sections or nozzle pipes together. In order to assure the integrity of the vessel, these welds should be periodically inspected using sensors [24]. Such inspections have been performed using a conventional inspection machine with the manual method. In order to automate and cut human's cost, some systems are designed and some climbing-wall mobile robots with magnetic wheels are developed. Kim [24-26] developed an underwater mobile robot with magnetic wheels for the ultrasonic examination of the reactor vessel weld. By the aid of floats, the weight of the robot became zero in water. So the motion analysis in water was simpler than that in air. Sogi [27] developed an inspection robot to detect the weld seam for spherical storage tanks with the time of flight diffraction mode. Shang presented a wheeled robot for the real time inspection of long weld lines in the up-down motion [28]. Fischer described a mobile climbing robot on magnetic wheels for inspecting the interior surfaces in gas tanks [29]. The structure of the climbing robot on magnetic wheels was complicated. They did not analyse how to adjust the position and angle deviation on the vertical wall in the horizontal motion.

In the paper, we have developed a novel, modular mobile robot with four magnetic wheels to detect the weld seam for the vertical cylindrical steel vessel with the tandem scan mode. The structure of the robot is modular, so it is easy to exchange, repair and manufacture modules to low its cost. With the geometric method, the position deviation and angle deviation are adjusted and the motion control is finished on the vertical steel vessel. Then, we utilize ultrasonic tandem way to automatically inspect the flaw of the weld seam.

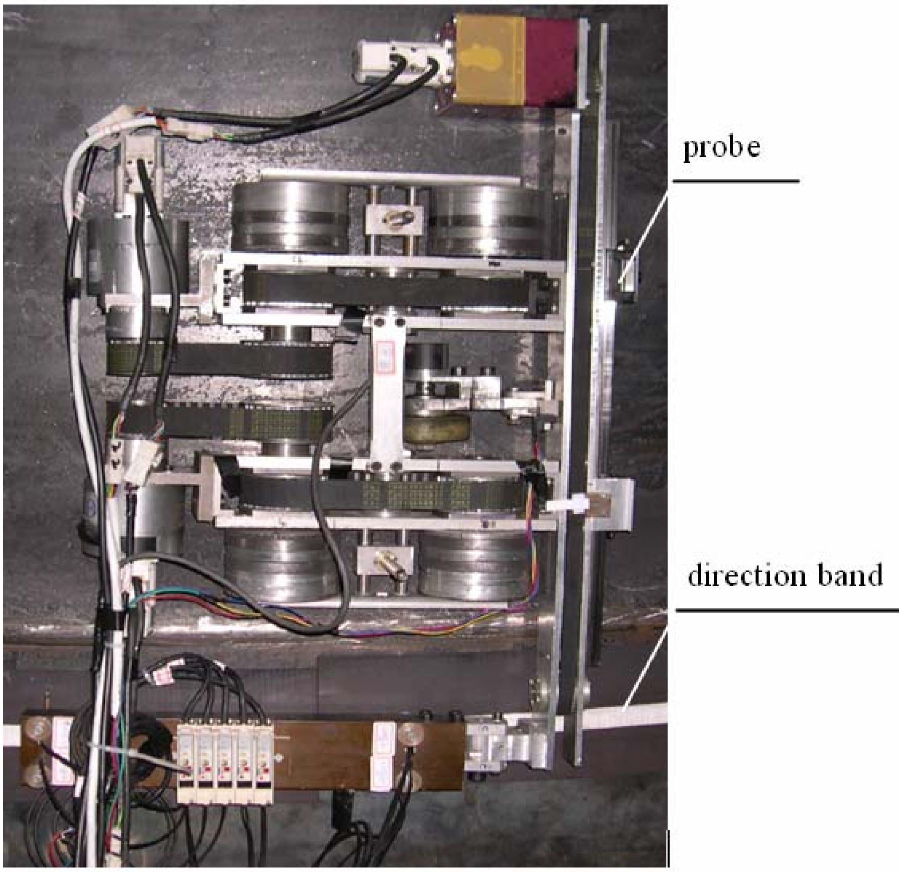
2 Design of a Modular Mobile Robot with Magnetic Wheels

The reactor pressure vessel has a cylindrical shape. It has many welds such as a circumferential seam, a weld of nozzles to the upper shell, a weld of flange to the upper shell and so on. When inspecting the welds of a vessel wall, the robot is moved to the outer vertical wall of a reactor pressure vessel. A modular mobile robot is designed to finish the task of inspecting the welds of a vertical steel vessel wall.

The modular mobile robot consists of a light manipulator module, an ultrasonic probes module attached to its end effector and a weld testing sensors module (Fig.1). The robot has three degrees of freedom which are translation, rotation and probes' consecutive translation.



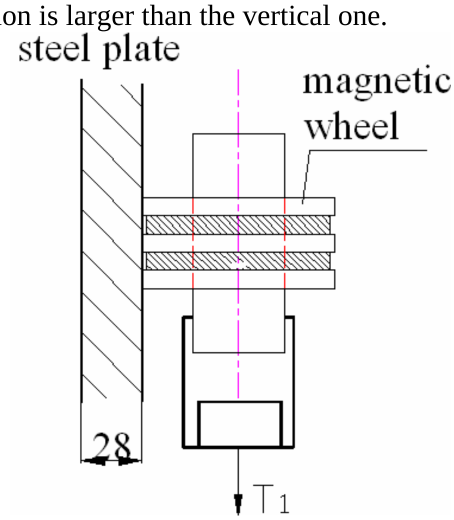
(a)



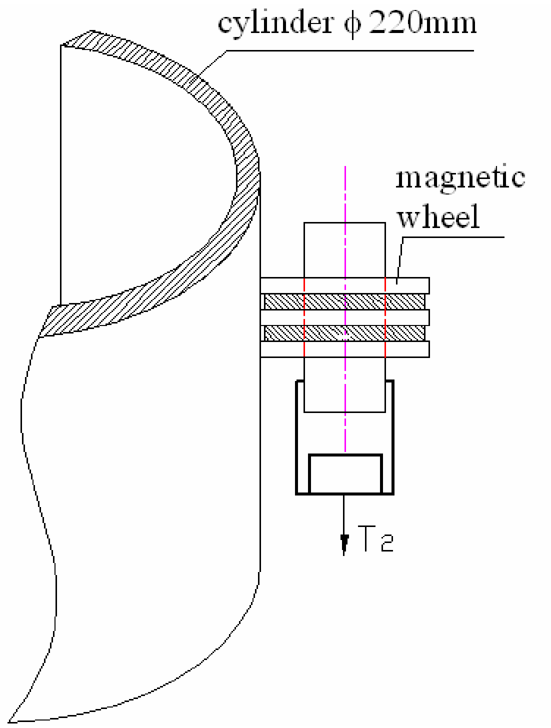
(b)

Fig.1 The structure of the modular mobile robot

The manipulator module mainly consists of the robot body plate, magnetic wheels, DC servo motors. The reactor pressure vessel is composed of carbon steel and clothed with austenitic stainless steel. In order to climb the vertical wall of the vessel, the robot has four magnetic wheels. Each magnetic wheel consists of two pieces of magnet and three pieces of pure steel plates. The ring shaped magnet has N and S poles on each side of the magnet. Its inner diameter is $\phi 50$ mm and the outer diameter is $\phi 100$ mm. The circular pure steel plates are attached on each side of the magnet to maximize the attraction force to the vertical steel wall. Its inner diameter is $\phi 50$ mm and the outer diameter is $\phi 105$ mm. The magnetic wheel was made to adhere to the surface of a cylinder. Its attraction was tested. There different trials were performed (Fig.2 a, b, c). In Fig.2 a, the magnetic wheel adhered to the surface of a painted steel plate. The attraction was 36.5 Kg. In Fig. 2 b, the magnetic wheel adhered to the coarse and painted cylindrical surface. The diameter of the cylinder is 220mm. We can obtain the attraction was 41.3Kg. In Fig. 2 c, the magnetic wheel horizontally adhered to the coarse and painted cylinder surface. The attraction was 130Kg （Table 1）. From the trials, we can see that many factors affect the attraction. For example, how to deal with the attractive surface, coarse or fine? How to put the magnetic wheel on the wall, horizontally or vertically? From Fig. 2 b and c, the horizontal attraction is larger than the vertical one.



(a)



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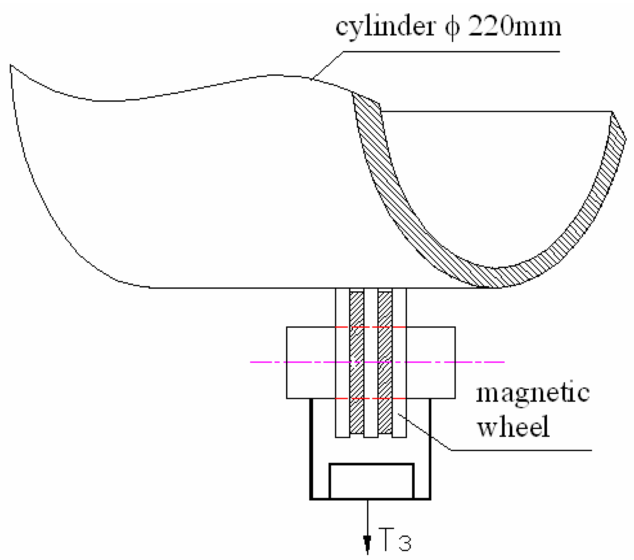


(c)

Fig.2 Trials on the magnetic wheel's attraction

Table 1 ATTRACTIONS IN FIGURE 2

One magnetic wheel			Attraction(Kg) (in Fig.2)		
	inner diameter (mm)	outer diameter (mm)	a	b	c
ring shaped magnet	$\phi 50$	$\phi 100$	36.5	41.3	130
pure steel plate	$\phi 50$	$\phi 105$			

According to the trials, the total attraction of four magnetic wheels is more than 100Kg. Because the attraction of the inspection robot needs 80Kg, in order to reduce the weight, we must reduce the diameters of the magnetic wheels. According to the experiments, when the weight of the magnetic wheel reduces 1Kg, the magnetic force reduces 23%. So the inner diameter of the ring shaped magnet is $\phi 50$ mm and the outer diameter is $\phi 91$ mm. The inner diameter of the circular pure steel plates is $\phi 50$ mm and the outer diameter is $\phi 93$ mm. Thus the magnetic wheel is designed in Fig.3. It is about 2.5 Kg. Smooth rubber is clothed around the magnet to prevent slippage on the vertical wall. The robot with four magnetic wheels mounted on the parallel links with the robot body plate is about 20 Kg, as shown in Fig.1 and its technology specification illustrated in Table 2. It makes the robot body parallel to the cylindrical wall. The four wheels are driven by two DC servo motors so that the robot has enough driven force when the robot swerves and one wheel is out of the wall. The robot can control the linear velocity and the angular velocity by the sum and difference of the velocities of the left and the right driving wheels.

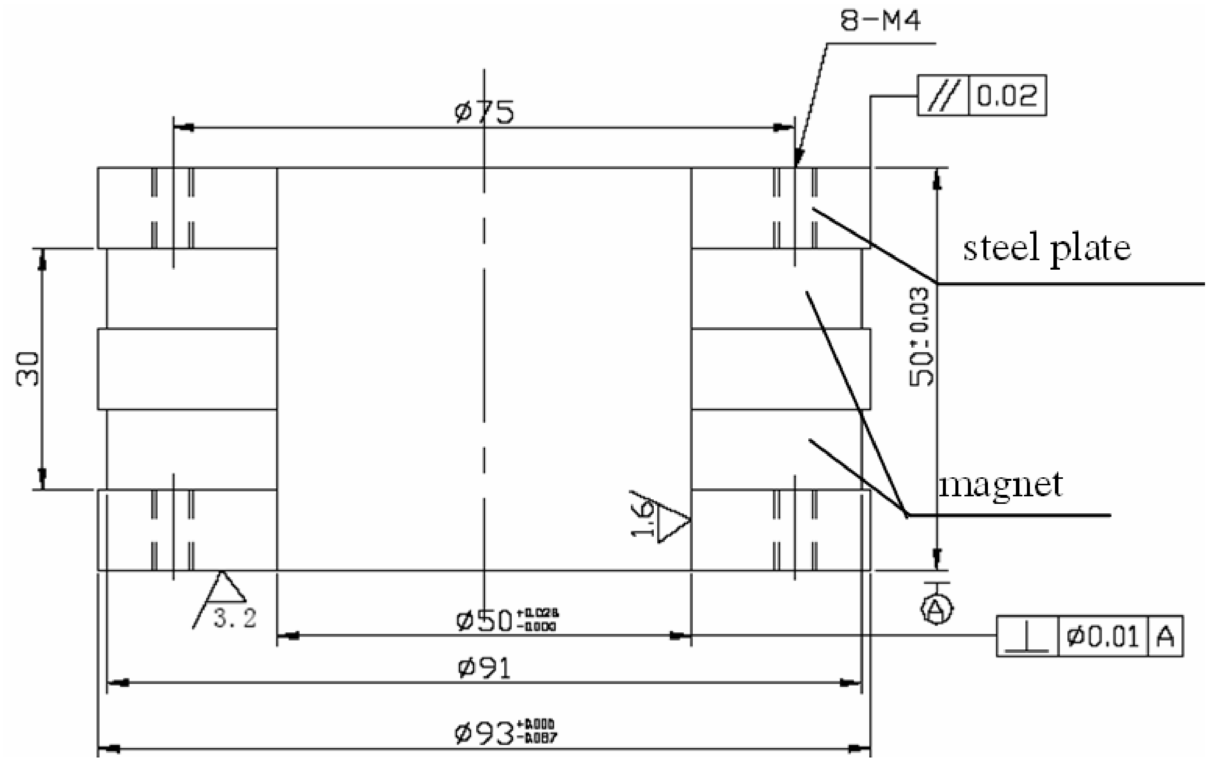


Fig.3 The structure of one magnetic wheel

The ultrasonic probes module mainly consists of motor, belt, belt gears, guide track, probes (Fig.1). When the motor works, the belt gears rotate and the belt works. So the probes work. It is used to scan the weld seam.

The robot is induced by the weld test sensors module which has four optical fiber sensors 1,2,3,4 fixed in the left of the robot. The bottom of the sensors module has a spring to adapt to different cylindrical curvatures. At the beginning, the robot is put on the wall and the sensors module is parallel to the weld direction band. The robot walks along the direction tape and detects the deviation with the information of sensors, and moves in the appropriate direction to make this deviation zero.

In order to inspect the welds accurately, the robot should move exactly to the given position. However, controlling the robot's exact movements on the vertical cylindrical wall is not a simple process. The robot's position and direction are determined by the sum and difference of the velocities of the left and the right wheel, which are driven by two DC servo motors. Because of gravity, the robot will slide on the vertical wall. Then the robot will deviate from its given position. So we must adjust the position and the pose of the modular mobile robot.

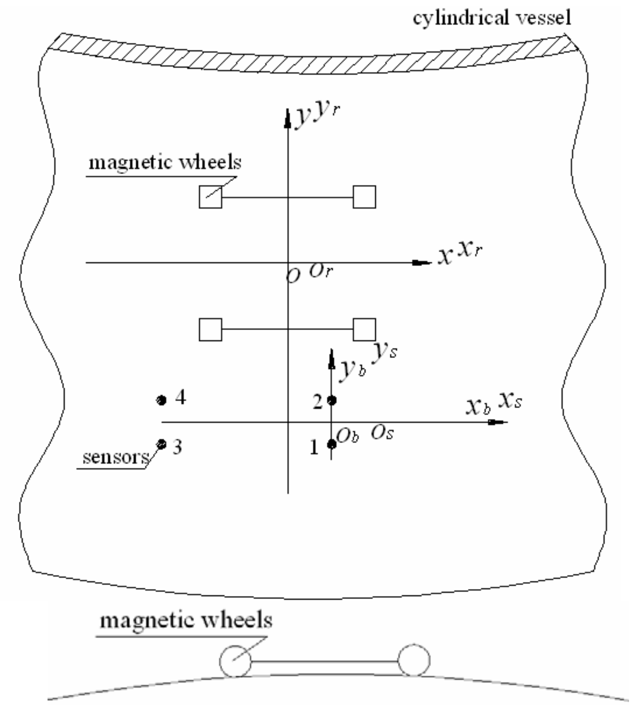
Table 2 SPECIFICATIONS

Outline Size	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 speed: 95mm/s(0~70mm/s adjustable)	
	y direction speed: 330mm/s(0~2000mm/s adjustable)	

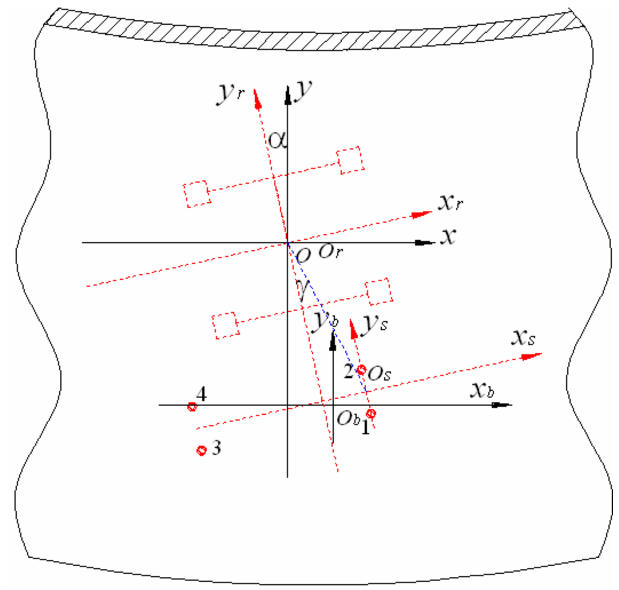
3 Analysis and Adjusting of Motion on Vertical Wall

The coordinates of the robot, $o_rx_ry_r$ is illustrated in Fig.1, Fig.4. Point o_r is the symmetry center point of four wheels, the axis o_rx_r is the symmetry center line of the left wheels and the right wheels. The axis o_ry_r is parallel to the guide track of the tandem scan probes. In Fig.1, Fig.4, the axis ox fixed on the surface of the vertical vessel is the tandem scan based line. o and o_r are the same point. In Fig.4, $o_sx_sy_s$ is the coordinates of the sensors module. The axis o_sy_s is through sensor 1 and sensor 2. Point o_s is in the middle of sensor 1 and sensor 2. The axis o_sx_s

is parallel to sensor 1 and sensor 3. $o_bx_by_b$ is the coordinates of the direction band. Before the motion of the robot, the coordinates $o_sx_sy_s$ and $o_bx_by_b$ are at the same place. When the robot works, the coordinate systems $o_rx_ry_r$ and $o_sx_sy_s$ will change.



(a)



(b)

Fig.4 Motion analysis

In order to meet the need of the ultrasonic tandem scan, the robot must adjust its pose based on the sensors' status in time. The layout of the sensors is shown in Fig. 5. In the Fig.4, four fiber sensors usually show the red color. When the robot deviates from the direction bend, the fiber sensors don't show the red color. The robot corrects its pose based on the status of four sensors. According to the deviation of the position and the angle, the status of sensors can be divided into 16 kinds, for example: ○●○●, ○●●○ etc. Here ○ means the dark of indicator, ● means light. The robot can reach the demand positions and angles by adjusting its motion. It includes the position deviation adjusting and the angle deviation adjusting.

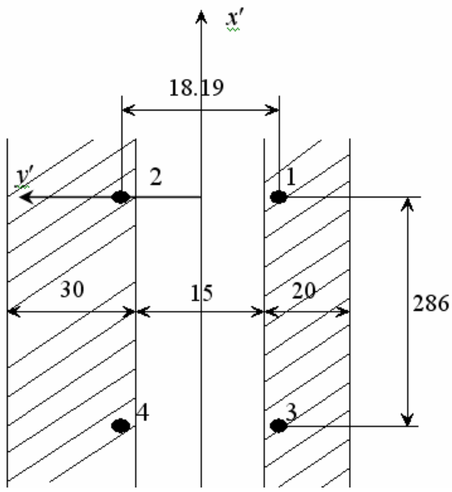


Fig.5 The layout of the sensors

3.1 Position Deviation Adjusting

The adjusting process of the position deviation has four steps.

(a) The robot rotates an angle φ_1 about its center o. It arrives at the dotted line position displayed in the Fig.4 b. The solid line indicates the original position without deviation;

(b) The robot moves forward x_1 in the direction o_rx_r;

(c) The robot stops and rotates a converse angle φ_2 about its center;

(d) The robot backs off the original position x_0 in the axis ox direction. Thus, the robot can fulfil the motion of y direction while the position of x direction is constant. Here the distance of o_ro_s is l; the angle between the o_ro_s axis and the y_r axis is γ; l, γ are the structure parameters of the robot; α is the rotation angle of the robot; the level distance from o_s to the y_b axis is Δx; the perpendicular distance from o_s to the x_b axis is Δy. We can obtain

1) The robot rotates the angle φ_1

$$\alpha = \varphi_1 \quad (1)$$

The level offset $\Delta x(\varphi_1)$ is

$$\Delta x(\varphi_1) = l\sin(\varphi_1 + \gamma) - l\sin\gamma \quad (2)$$

The perpendicular offset $\Delta y(\varphi_1)$ is

$$\Delta y(\varphi_1) = l\cos\gamma - l\cos(\varphi_1 + \gamma) \quad (3)$$

2) The robot moves forward x_1 in the direction o_1x_1. The perpendicular offset $\Delta y(x_1)$ and the level offset $\Delta x(x_1)$ are

$$\Delta x(x_1) = x_1\cos\varphi_1 \quad (4)$$

$$\Delta y(x_1) = x_1\sin\varphi_1 \quad (5)$$

3) The robot rotates a converse angle φ_2.

$$\alpha = \varphi_2 - \varphi_1 \quad (6)$$

The perpendicular offset $\Delta y(\varphi_2)$ and the level offset $\Delta x(\varphi_2)$ are

$$\Delta x(\varphi_2) = -[l\sin(\varphi_2 + \gamma) - l\sin\gamma] \quad (7)$$

$$\Delta y(\varphi_2) = -[l\cos\gamma - l\cos(\varphi_2 + \gamma)] \quad (8)$$

If $\varphi_2 = \varphi_1$, $\alpha = 0$, which means the angle adjusting is finished.

4) In order to compensate the offset in the axis ox direction, the robot must back off Δx_{1b}. The perpendicular offset $\Delta y_{x_{1b}}$ and the level offset Δx_{1b} are

$$\Delta x_{1b} = -\Delta x(x_1) = -x_1\cos\varphi_1 \quad (9)$$

$$\Delta y_{X_{1b}} = 0 \quad (10)$$

In conclude, the total level offset and the perpendicular offset are

$$\Delta x = \Delta x(\varphi_1) + \Delta x(x_x) + \Delta x(\varphi_2) + \Delta x_{1b} = 0 \quad (11)$$

$$\Delta y = \Delta y(\varphi_1) + \Delta y(x_1) + \Delta y(\varphi_2) + \Delta y_{X_{1b}} = x_1\sin\varphi_1 \quad (12)$$

3.2 Angle Deviation Adjusting

The adjusting process on the angle deviation is shown:

1) The robot rotates the angle φ_1. The position offset is shown in Eq.(2) and Eq.(3).

2) Compensating $\Delta y(\varphi_1)$ with the step (a) (b) (c) in section *A*, we can obtain

$$l\cos\gamma - l\cos(\varphi_1 + \gamma) = x_2\sin\varphi_2 \quad (13)$$

In the process, the robot produces the level offset

$$\Delta x' = x_2\cos\varphi_2 \quad (14)$$

The total offset in the axis ox direction is

$$\Delta x_{total} = \Delta x(\varphi_1) + \Delta x' \quad (15)$$

3) Compensating Δx_{total}. The robot goes backward

$$x_{back} = -\Delta x_{total} \quad (16)$$

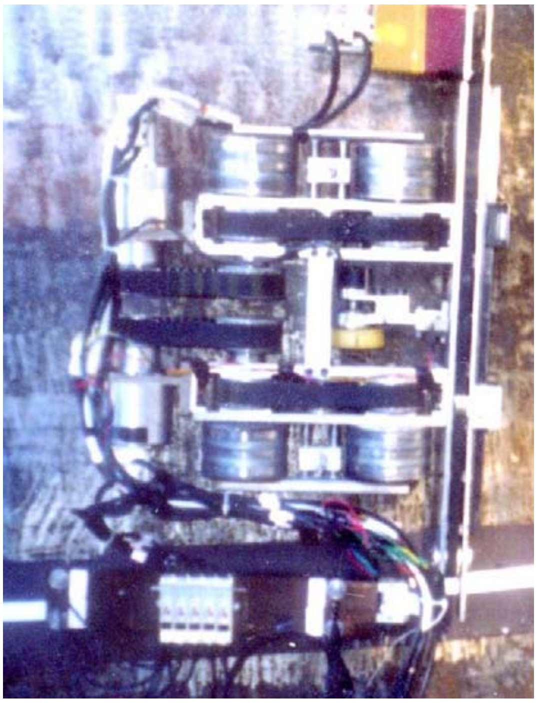
so

$$x_{back} = l\sin(\varphi_1 + \gamma) - l\sin\gamma + x_2\cos\varphi_2 \quad (17)$$

In practical adjusting process, influenced by the gravity and the friction, the deviation of the robot is different when the robot deviates to the left and the right. It must be compensated properly.

4 Experiments

We have the experiments in the real vertical vessel at Nanjing refinery factory in China. The diameter of the cylindrical vessel is 3.4 meter and its thickness is 0.2 meter. Firstly, the direction band is attracted on the wall of the cylindrical vessel. Secondly, the modular mobile robot is put on the wall. The original position and orientation of the robot are calibrated. Then, the control system works. The modular mobile robot moves on the cylindrical vertical steel wall (Fig. 5). At the beginning, the robot tilts to the right (Fig. 5 (a)). Because of the gravity, the robot flips when it moves. After a while, it tilts to the left (Fig.5 (b)) with the above adjusting method.



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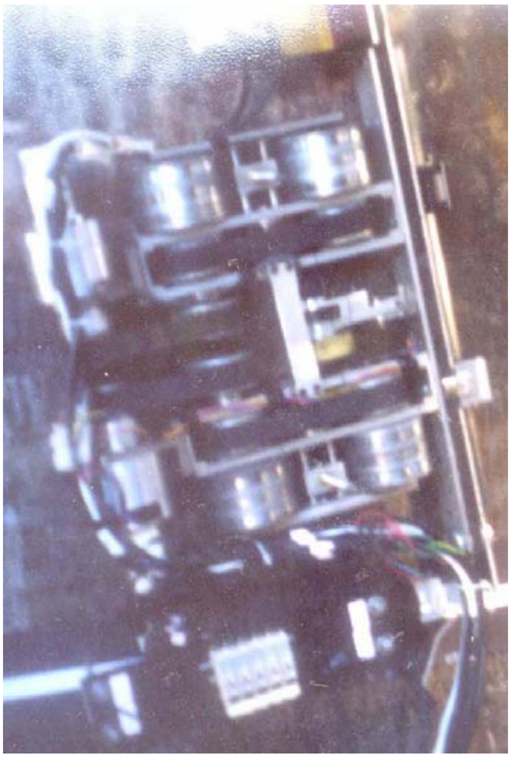

(b)

Fig. 5 The motion of the robot on the cylindrical vessel

The velocity of the inspection robot is 4mm / s. The motion distance is 1000mm. The adjusted time is 110s. The motion trajectory of the robot is shown in Fig.6. In the Fig.6, x represents the displacement in the level direction; y represents the deviation displacement; t_1, t_2 are the adjusted times, respectively. From Fig. 6, according to the above motion analysis, the pose of the robot can be adjusted. The robot moves along the tandem scan based line. The motion error is less than 1mm.

With the above deviation adjusting method, the position repeatability is 1.52mm in the x-axis direction and 0.0087mm in the y-axis direction. The motion trajectory of climbing robot's probes illustrated Fig.7 reveals the motion process of probes and the adjusting process of robot. The motion trajectory of the robot deviating from the tandem scan base line is shown in Fig.8. The deviation range is among –1mm and 1.5 mm, which can assure the scanned precision of the seam.

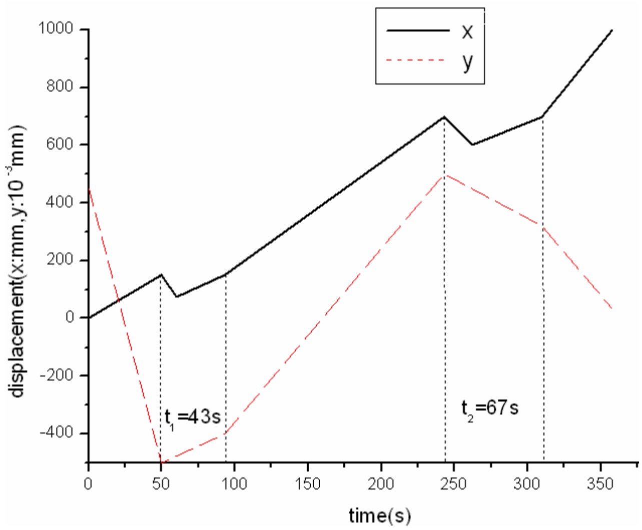

Fig. 6 The motion trajectory of the robot

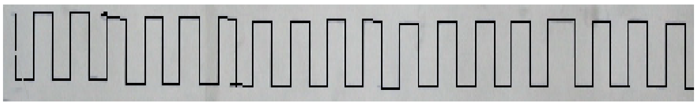

Fig.7 Trajectory of probes motion

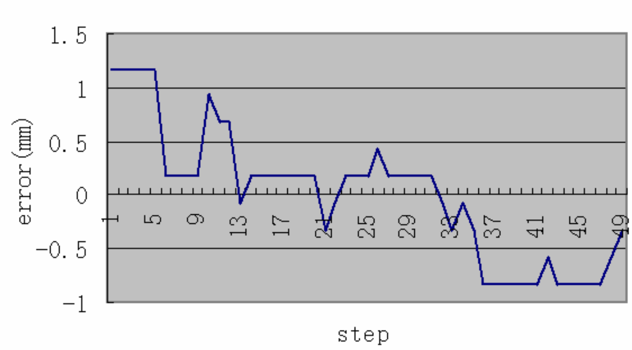

Fig.8 The deviation from the tandem scan base line in the y-axis direction

5 Conclusion

A modular mobile robot with four magnetic wheels is presented to detect the weld seam for the vertical cylindrical steel vessel with the tandem scan mode. The robot consists of a light manipulator module, an ultrasonic probes module and a weld testing sensors module. The manipulator module mainly consists of the robot body plate, magnetic wheels, DC servo motors. The ultrasonic probes module mainly consists of motor, belt, belt gears, guide track, probes. The weld testing sensors module mainly consists of four optical fiber sensors. The magnetic wheels are designed, which consists of two pieces of magnet and three pieces of pure steel plates. Then, the motion of the robot on the vertical cylindrical vessel is analyzed in detail. The position deviation and the angle deviation are adjusted with the geometric method. At last, the experiments are shown to verify the above analysis on the motion deviation adjusting, which can control the wall climbing robot simply.

The robot is used practically for the reactor vessel inspection instead of old conventional machines in danger environment. Because of its modular structure, it is convenience of maintenance when assembling and disassembling.

Acknowledgements

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