Development of inspection robot for in-service steel tubular poles

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Abstract. The development of an inspection robot for in-service steel tubular poles is described in the article. Based on the design requirement analysis to the steel tubular poles used in China, the design requirement is presented. By compared with the deferent technology, TOFD technique and magnetic wheel are chosen to use in the project. On the other hand, with unique design of separation and reconnecting device, it made the robot can climb the poles, hold on the poles, do the inspection work in both vertical and horizontal direction. The field test proved that the robot can be widely used for the inspection work of in-service steel tubular poles after a few work in future.

1. Introduction

Steel tubular poles are widely used in 10~220 kV transmission lines because of the advantages of less space demand, beautiful appearance, excellent capacity etc. The typical geometry of tubular pole is shown in figure 1. The pole is conical and made up of several shell sections. The sections are assembled together by flanges or welds. Each section is about 10m length and made from 6-22mm thick rolled steel plate. Therefore, there are many vertical welds and horizontal welds on steel tubular poles.

Figure 1. Steel tubular pole in China

Figure 2. A strengthened steel tubular pole

In China, the manufacturing standard of the steel tubular poles accepts some flaws in welds. At the same time, in early years, because of the low manufacturing level, there are lots of defects in the weld in part of the steel tubular poles, such as crack, lack of penetration, slag inclusion, lack of fusion. These defects may enlarge and damage the safety of the pole in long time running. Some failures of the steel tubular poles were occurred in China. Figure 2 is showing a tubular pole which has amounts of defects and is strengthened to ensure its safety. In order to ensure the safety of the poles, the maintenance department regularly implements the ultrasonic tests to the poles, masters the status of the defects in the welds and assesses the security of the poles. But the test work is dangerous and inefficiency because of that the poles are tall. Therefore, developing an inspection robot for in-service steel tubular poles is efficient.

Because of the in-creasing demands of climbing robots in the field of vertical structures, many climbing robots have been developed to accomplish the technical work. In general, climbing robots need to be developed depending on the desired tasks and the field of application. So there has no one climbing robot suitable for the detection to the in-service steel tubular poles. This paper thus reports the development of the first prototype of the inspection robot for in-service steel poles.

The paper is organized as follows. The design requirement is described in section 2. In section 3, the key design and components of the robot are presented and discussed. In section 4, the experimental results are showed .Finally, the conclusion is given in section 5.

2. Design Requirements

The final design work has been based mostly on the robot's capability to climb the poles and do the inspection work with the inspection device.

2.1 Fundamental characteristics of the tubular poles

The geometry and material properties of the tubular poles r is the foundation of the whole design. Through the survey on the 10-220kV transmission lines in Jiangsu Province of China, the fundamental characteristics of the tubular poles is shown in Table 1.

Table 1. Fundamental characteristics of tubular poles

Items	Information
Materials	Q235,Q345,Q420,Q460*
Thickness	6-22mm
Diameter	300-2200mm
Section form	Circle, polygon(always dodecagon，sixteen edge shape etc.)
Surface coating	Hot galvanizing
Thickness of coating	About 100 μ m

Note: Q235,Q345,Q420 and Q460 are the material grades of carbon constructional steel in China.

2.2 Design Requirements

According to the fundamental characteristics of the tubular poles and the task of the project, the following requirements were established:

Usability: The robot has good sensitivity and it can be used to detect the flaws in the welds of in-service tubular poles.

Safety: The robot can firmly adhere to the surface of the tubular poles in the process of inspection and in the process of climbing.

Adaptability: It can adapt to different diameters and section forms of the tubular poles.

Flexibility: The robot must be able to climb up and do the inspection work in the vertical direction according to the longitudinal weld. If the robot reach the height of the circumferential weld, the whole robot or the part of the robot must be able to change direction and do the inspection work automatically.

Velocity: The vehicle speed is one of main aspects in this project. It might be required to achieve relatively high velocity even in vertical direction or horizontal direction for a sufficient fast navigation between inspection areas or similar points of action..

Based on these requirements, we has to select sensitive inspection method, suitable locomotion and attraction principle. Next sections will introduce these approaches.

3. Robot Design

3.1 Inspection method

The inspection methods that may be suit for the work are as follows: time of flight diffraction (TOFD), ultrasonic phased array (PA), ultrasonic pulse echo method (PE) and electromagnetic-acoustic (EMA). Table 2 lists the advantages and disadvantages of these methods be applied to the steel tubular poles inspection robot.

Table 2. Comparison of different methods

Method	Sensitivity	Weight of the sensor	Movement of the probe	Energy consumptio n	Couplant	Demand of surface condition
TOFD	+	+	+	+	o	-
PA	+	o	+	+	o	-
PE	o	+	-	+	o	-
EMA	-	-	-	-	+	+

Note: "+" means "good", "o" means "normal", "-" means "bad".

According to table 2, couplant is unwanted and it has low demand of surface condition while EMA in using, but it is the disadvantages of weight, power consumption, electric heating and low sensitivity which dictate that EMA is not suitable for the robot. The size (length, height etc.) of the defect in weld is very important to the security assessment. In the aspect of length measurement, TOFD, PA and PE have the similar sensitivity. TOFD has the highest sensitivity in the aspect of height measurement. Since surface processing can't be applied before inspection, the impact of surface conditions must take full consideration. A sensitivity test is carried out in the scene. The result shows that the surface condition of the steel transmission pole has little effect on the inspection sensitivity. So TOFD is applied to the project.

3.2 Locomotion type

As motioned before, climbing robots have been in the focus of research on the last two decades. In general, there are five types of locomotion. They are arms and legs, wheels and chains, sliding frame, wires and tracks, according-like locomotion. Table 3 sums up the locomotion type and rates different aspects related to this project.

Table 3. Comparison of locomotion types to this project

Requirements	Legs	Wheels	Tracks	Frame	Wires
Velocity	-	+	-	o	-
Operability	-	+	-	-	-
Adaptability	+	o	-	o	-
Payload	-	o	+	o	+
Safety	-	o	+	o	+
Simplicity	-	+	+	+	+
Flexibility	+	+	-	+	-

Note: Note: "+" means "good", "o" means "normal", "-" means "bad".

Because tracks and wires type robot demands external guidance and equipment and installation of external device is not permitted and is inconvenience in this project, using tracks and wires type robot is no suitable. The robot for in-service steel tubular poles should accomplish inspection work and bear the weight of inspection device, pipe for pumping couplant (water), power cord, and itself. According to Table 3, the wheels type may be the best choice for this project.

3.3 Adhesion principle

There are many type of adhesion principles be used in the field of climbing robot. Magnetic adhesion, pneumatic adhesion, mechanical adhesion, electrostatic adhesion and chemical adhesion are the most common types of adhesion principles. Similar to the type of locomotion, the adhesion principle has deferent advantages and disadvantages and also has to be chosen depending on the given task. For this project, the robot which will be designed should be used to carry inspection device, climbing to the target weld and accomplish the inspection work. These tasks determine that the robot should have enough payload, good adaptability, excellent steering performance and smooth movement. Because the material of steel tubular poles is made of ferromagnetic material and the outer structure of in-service tubular pole is simple, magnetic adhesion principle can meet the requirements better and make the design work be easier.

Permanent magnets and electromagnets are the two main magnets using in magnetic adhesion design work. In general, electromagnetic needs larger power consumption. If the electromagnetic which will be supplied power by battery, the weight of the battery will be heavier and the capacity of payload will be smaller. If the electromagnetic which will be supplied power by battery AC or DC, there is the risk of fall when the leakage or power-off is occurred. Therefore, the use of electromagnetic adhesion in the project is not a wiser choice. Therefore, magnetic adhesion is the suitable adhesion principle and permanent magnets is the best choice to accomplish the design work.

3.4 Design of the steering function

As mentioned in section 2, there are two types of weld on steel transmission poles, one is vertical weld, and the other is the circumferential weld. The robot should climb in the vertical direction when do the inspection work for the vertical weld. But it should move in the horizontal direction when do the inspection work for the circumferential weld. So the excellent steering performance is the prerequisite and foundation. Generally, most researches were through the complexity of mechanical design to ensure that the robot has good steering performance. If the common method as mentioned above will be putted into use, the main challenge is the curvature of the tubular poles and the force in the vertical direction such as the gravity of itself. For the former, when curvature radius is smaller, some wheels on common robots may be leave the surface of the poles which results a low adhesion capacity and fall failure of the robot. Normally, miniaturization of the robot and a flexible body is the good solution. But in this project, it is impractical to greatly reduce the size of the robot in short time because of amounts of inspection devices carried by the robot. At the same time, when the robot do the inspection work in horizontal direction as described in Figure 3, the sliding friction fs should greater than the gravity of itself and inspection devices. For the target, reducing the weight of the robot and increasing the adhesive force between the robot and the poles are the two effective methods. But both methods are limited, so adopting any other means is the good choice.

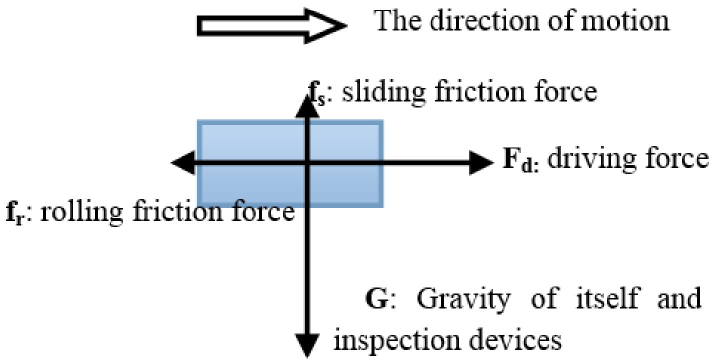


Figure 3. Force analysis of the robot moving in horizontal direction

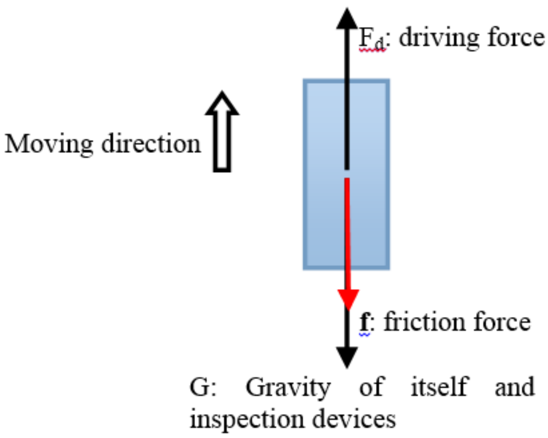


Figure 4 Force analysis of the robot moving in vertical direction

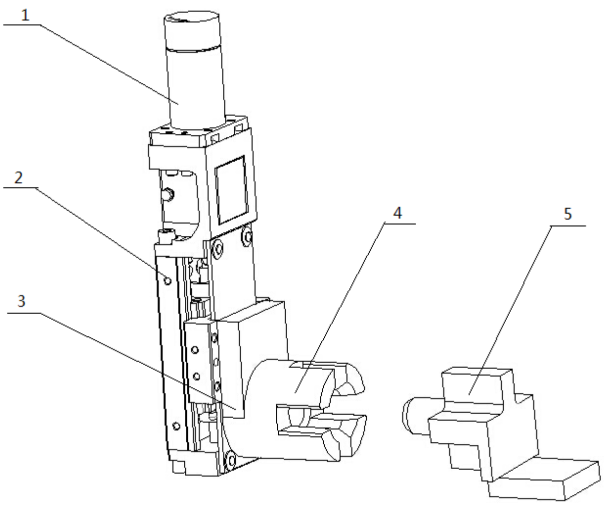
Figure 4 described the force analysis of the robot moving in vertical direction. We can see the difference between Figure 4 and Figure 3. When the robot climbing or holding in vertical direction, equation (1) should be satisfied.

$$Fd \geqslant f+G \tag{1}$$

Where Fd = driving force of the motors; f = friction force between the robot and the pole; and G = gravity of the robot and inspection devices.

Increasing the driving force of the motor (Fd) is very easy-to-realize. Therefore, in this project, the robot was designed into two parts. One is called vertical car and another is called horizontal car. Vertical car only climbs and does inspection work in vertical direction. Horizontal car only moves and do the inspection work in horizontal direction. The former is larger and has large payload. The size of the latter is small and it only carry a small amount of inspection equipment. Every part is the independent and can do the inspection work independently. Two parts are connected together by the device which is called separation and reconnecting device.

Separation and reconnecting device is the key part of the inspection robot. The schematic diagram of the device is showed in Figure 5. Separation and reconnecting device includes servo motor, ball screw, micro camera, female head and male head. The ball screw is installed on vertical car and drove by servo motor. The female head is installed on the nut of the ball screw and the male head is installed on the horizontal car. A wireless micro camera and a limit switch are installed in the hole of female head. In initial state, the male head and the female head are connected together tightly and the vertical car and horizontal car are connected accordingly. When the robot reaches the height of the horizontal weld, the servo motor drives the ball screw to rotate. The joint of the female head and the male head moves down. When the four wheels of horizontal car is adhered tightly to the surface of the transmission pole, the servo motor stop rotating, the locking up device is unloosen and the male head on horizontal car leaves from the female head on vertical car. At this time, horizontal car is an independent device which can do the inspection work along the horizontal weld. When the horizontal car finishes the detection task, backs along the horizontal weld and closes to the vertical car, the wireless micro camera captures the picture of the male head. We can adjust the wheels of horizontal car and slightly change the movement direction of horizontal car through the control unit. At the same time, there is a virtual center in the control screen. When the center of the male head overlap the virtual center, horizontal car moves towards the female head and the male head inserts into the groove of the female head. The limit switch should be launched and horizontal car should be stopped when the male head enters 15mm into the female head. The servo motor and the ball screw start work and horizontal car will be lifted from the surface of the pole until horizontal car is 15-20mm away from the surface. At this time, horizontal car has finished the inspection work.



1：Servo motor 2：Ball screw 3：Micro camera 4：Female head 5：Male head

Figure 5 Schematic diagram of separation and reconnecting device

4. Prototype and Field Test

According to the design in section 3, a prototype was developed which is showed in Figure 6. The body of the robot is made of aluminum alloy. It contains laser automatic weld tracking system, TOFD weld inspection device, magnetic wheels, separation and reconnecting device, driving motors and control unit.

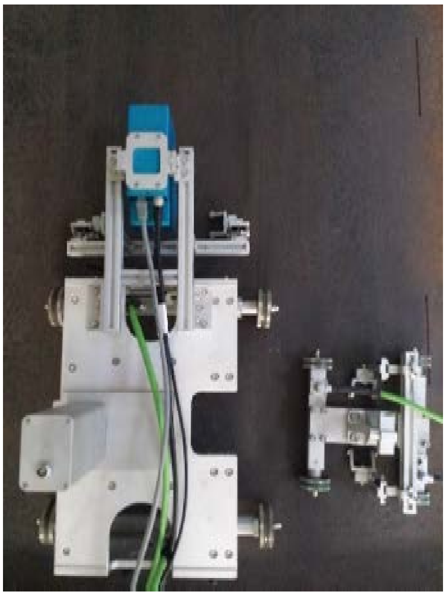


Figure 6 The prototype of the inspection robot

Figure 7 Field test in in an 110kV steel poles

In order to verify the design of the robot, a series of field tests was carried out. The tests involve steel tubes with different diameter, steel plates with different thickness and in-service tubular poles in different voltage grade transmission line (10-220kV). Figure 8 shows the field test at an 110kV transmission line in Nanjing, China.

Through the field tests, we find that the performance of the robot was consistent with those of designed target. It has good applicability to the poles with different diameter and different section shape. It can adhere to the surface of the in-service tubular steel pole firmly and climb along the weld steadily. When it is reaching the height of the horizontal weld, it can hold on the pole steadily, send out the horizontal car to do the inspection work and retrieve the horizontal car at any time. The flaws which may be hidden in the weld of poles can easily be detected by the inspection device carried by the robot.

At the same time, some problems found through the field test are as follows:

There are many accessory devices such as ladder and sign. Restricted to lager size of the robot, some weld near the accessory devices cannot be detected

The pole is conical and made up of several shell sections. Part of the sections are assembled together by flanges and the robot cannot step the flanges. If we need do the inspection for the whole pole, we should move the robot manually to made the robot can step the flange.

There are too many cables between the robot and the control unit which made large payload capacity demand. The demand restricted the design.

5. Conclusion

This paper proposed a prototype robot that can be used for the inspection of in-service steel tubular poles. Based on the design requirement analysis, it presents the design course of the robot in details in the way of inspection method, locomotion type, adhesion principle and steering function. The use of TOFD guaranteed the inspection accuracy. The magnetic wheel and unique separation and reconnecting device made the robot can climb the poles, hold on the poles, do the inspection work in both vertical and horizontal direction. The field tests proved that the robot has good applicability to the poles with different diameter and different section shape, can be used for in-service steel tubular poles inspection. Wireless control, miniaturization, function of stepping the flanges remains as a future work.

References

[1]. Jianming Luo. The Application of Steel Bar in the Transmission Lines of City. Rural Electrification, (2008) No. 6, p. 10-11.

[2]. Shihua wang. Analysis on Breakage Causes of Welded Steel Tube Poles in Transmission Lines, Power Construction, Vol. 24 (2003) No. 7, p. 41-43.

[1]. Schmidt D,Berns K. Climbing Robots for Maintenance and Inspections of Vertical Structures—a Survey of Design Aspects and Technologies. Robotics and Autonomous Systems, Vol.61 (2013) No.12, p. 1288-1305.

[2]. Kikuchi K,Sakaguchi K,Sudo T, et al. A Study on a Wheel-based Stair-climbing Robot with a Hopping Mechanism. Mechanical Systems and Signal Processing. Vol. 22(2008) No.6, p. 1316-1326.

[3]. Tavakoli M,Viegas C. Analysis and Application of Dual-row Omnidirectional Wheels for Climbing Robots. Mechatronics. Vol. 24(2014) No.5, p. 436-448.

[4]. Osswald M,Iida F. Design and Control of a Climbing Robot Based on Hot Melt Adhesion. Robotics and Autonomous Systems. Vol. 61(2013) No.6, p. 616-625.

[5]. Zin MRAM,Sahari KSM,Saad JM, et al. Development of a Low Cost Small Sized In-pipe Robot. Vol. 41(2012), p. 1469-1475.

[6]. Oh J,Jang G,Oh S, et al. Bridge Inspection Robot System with Machine Vision. Automation in Construction. Vol. 18(2009) No.7, p. 929-941.

[7]. Hedenborn P,Bolmsjö G. Robotics in Automated Inspection. International Journal of Production Economics. Vol. 41(1995) No.1, p. 161-166.

[8]. Jang YH,Kim JS. Development of an Amphibious Robot for Visual Inspection of Apr1400 Npp Irwst Strainer Assembly. Nuclear Engineering and Technology. Vol. 46 (2014) No.3, p. 439-446.

[9]. Tavakoli M,Viegas C,Marques L, et al. Omniclimbers: Omni-directional Magnetic Wheeled Climbing Robots for Inspection of Ferromagnetic Structures. Robotics and Autonomous Systems. Vol. 61 (2013) No.9, p. 997-1007.

[10]. Sintov A,Avramovich T,Shapiro A. Design and Motion Planning of an Autonomous Climbing Robot with Claws. Robotics and Autonomous System. Vol. 59 (2011) No.11, p. 1008-1019.

[11]. Müller R,Vette M,Scholer M. Inspector Robot-a New Collaborative Testing System Designed for the Automotive Final Assembly Line. Procedia Cirp. Vol. 23 (2014), p. 59-64.

[12]. Peyvandi A,Soroushian P,Lu J. A New Self-loading Locomotion Mechanism for Wall Climbing Robots Employing Biomimetic Adhesives. Journal of Bionic Engineering. Vol. 10 (2013) No.1, p. 12-18.

[13]. Wang Y,Su J. Automated Defect and Contaminant Inspection of Hvac Duct. Automation in Construction. Vol. 41 (2014), p. 15-24

[14]. Cordes S,Berns K,Eberl M, et al. Autonomous Sewer Inspection with a Wheeled, Multiarticulated Robot. Robotics and Autonomous Systems. Vol. 21 (1997) No.1, p. 123-135.

[15]. Pagala PS,Ferre M,Orona L. Evaluation of Modular Robot System for Maintenance Tasks in Hot Cell. Fusion Engineering and Design. Vol. 89 (2014) No.9, p. 2309-2313