Autonomous Positioning and Marking of Flaw Detection Wall-climbing Robot Based on Large Spherical Oil Storage Tanks

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Abstract. The emergence of wall-climbing robots alleviates the limitations of traditional manual flaw detection, and the autonomous positioning and marking system is its core research problem. By installing a three-axis accelerometer and a three-axis gyroscope on the wall-climbing robot, this paper firstly establishes a 3D model of the oil storage tank and stores its data in a database, then realizes the autonomous positioning of the wall-climbing robot on the oil storage tank, and finally marks the unqualified weld seam points.

Introduction

The malfunction of special equipment such as large chemical storage tanks, lifting machinery, and high-pressure vessels may cause catastrophic consequences. To avoid damage to the metal structures of such equipment, extend the service life of the structure and improve the reliability and safety of the structure, the health status of metal structures is determined by appropriate testing methods for early diagnosis, which contributes to the rating of special equipment inspection conclusions and the formulation and implementation of follow-up regulatory measures. It is of great significance for people's life safety assurance and economic benefit protection. Therefore, how to conduct rapid, accurate and reliable comprehensive detection of metal structure damage through certain diagnostic techniques and diagnostic methods is the hot spot of research on special equipment detection technology.

Since the beginning of the 21st century, industrial robots have continuously penetrated from the field of automobile manufacturing to machinery, construction, chemical engineering, aerospace and so on. Intelligent technology is combined with social production and life. For example, the wall-climbing robots studied in this paper are for the detection of special equipment. The application needs to produce an industrial robot that replaces the inspector's work, which can achieve autonomous positioning, weld tracking and marking of unqualified weld seams on large oil storage tanks.

In the research process of the wall-climbing robot, the remote-controlled wall-climbing robot is initially realized, that is, the staff remotely controls the visual operation interface of the console, and the robot goes straight and turns through the keyboard, mouse or handle, as shown in Figure 1.
Therefore, the welding identification technology and the robot autonomous positioning system are added to the remote-controlled wall-climbing robot, which can better realize the intelligence and automation of the robot and save a lot of manpower and material consumption. What is studied in this paper is the robot's autonomous positioning and marking part.

**Establish a 3D Model of the Storage Tank**

To achieve autonomous positioning of the robot, it is first necessary to establish a 3D model of the oil storage tank. The research of 3D spatial modeling method is a hot topic in the field of 3DGIS. Many experts and scholars have made useful explorations in this field. A total of more than 20 spatial modeling methods are proposed, which can be divided into surface-based models and volume-based models. And three models of modeling systems based on hybrid models [1]. Since the oil storage tank is a space entity with regular boundaries and the interior is a hollow entity, the modeling method based on the voxel model is not suitable for constructing a three-dimensional oil storage tank. In this paper, the object-oriented analysis method is used to abstract the basic elements of three-dimensional modeling of oil storage tank into three categories: point, line and surface.

The point class mainly includes the measuring points and characteristic points of the oil storage tank, the line type has characteristic connecting lines, and the surface type mainly includes the basic surface element, the bottom surface of the oil storage tank, the side surface, the top surface, etc. So that the 3D model of the oil storage tank can be constructed by these basic modeling elements through a certain modeling method. Wherein, the feature connecting line is a line segment designated by the user for connecting the feature points. In the 3D modeling process, the generation of the body is mainly composed of the basic surface elements, and the basic surface elements are mainly composed of the characteristic connecting lines. There are usually two types of triangular and quadrilateral elements. In the 3D space surface model expression, the triangular surface element is better than the quadrilateral surface element [2]. The data model that defines the position and shape of an entity by face, line, and point is the boundary representation model, as shown in Figure 2.
The general idea of the 3D model construction of the oil storage tank is to simplify the process, that is, the tank body is first divided, then the parts after the splitting are separately modeled, and finally the models of the splits are integrated. The wall-climbing robot in this paper is mainly applied to the spherical oil storage tank, and its 3D model is shown in Figure 3.

After establishing the 3D model of the tank to be tested, add a unique label to each weld on the tank and set its starting and ending point.

In addition to establishing a 3D model of the oil storage tank, it is necessary to create a database of oil tank wall quality parameters, each of which corresponds to a table in the database including information such as the inspection personnel, the inspection time, the relative position of the inspection points, the quality of the monitoring spot welds, the number of the welds where the monitoring points are located, the inspection pictures, the detection video and the wall thickness.

**Autonomous Positioning of Wall-climbing Robot**

The wall-climbing robot is adsorbed on the surface of the large metal tank by permanent magnet adsorption, and moves on the surface of the tank by wheel movement. It is equipped with high-precision encoders, three-axis accelerometers, three-axis gyroscopes, depth cameras, metal wall flaw detectors, remote communication modules, etc.

The motion module of the wall climbing robot consists of four permanent magnet wheels, two DC motors and two motor drivers. The four permanent magnet wheels are divided into two groups, the left front and rear wheels are a group, and the right front and rear wheels are a group. Each set of magnetic wheels is connected by a transmission mechanism, and each set of transmissions is controlled by a separate set of motor and motor drives. The control module forms a double closed-loop control model. The rotational speed of the magnetic wheels on both sides adopts the
incremental PID control method to precisely control the rotational speed of the magnetic wheels on both sides. The robot realizes free steering by differential mode, as shown in Figure 4.

Figure 4. Double-drive Magnetic Wheel Wall-climbing Robot.

The motion control module of the wall climbing robot also uses a three-axis accelerometer and a three-axis gyroscope sensor. The high-precision encoder can determine whether the robot is slipping by combining the two sensors. When the value of the encoder has been increased and the values of the accelerometer and the gyroscope have not changed greatly, it indicates that the robot is slipping. At this time, the robot will issue a warning and correct the actual movement variable, which makes the speed control more precise [3].

To achieve the autonomous positioning of the wall-climbing robot, that is, to obtain the coordinates of the detection point, it is necessary to use the method of building identification and geometric identification to determine. The first half of the coordinates is determined according to the building identification, that is, the number of welds in the 3D model of the oil storage tank, and the second half of the coordinates is determined according to the geometrical indication, that is, the distance of the detection point from the starting point of the weld. Among them, the distance value is determined by the encoder and the three-axis accelerometer and the three-axis gyroscope. Since the radius of the oil storage tank is large enough, the robot is small enough, so the robot moves almost in the plane as it walks along the weld seam, the direction of the weld is the x-axis, the starting point of the weld is the coordinate origin, and the left hand rule determines y-axis. The movement trajectory of the robot appears as a curve S that fluctuates up and down along x=0 in this coordinate system, and the distance from the point on S on the x-axis to the origin is the distance from the starting point of the solder joint, that is

\[ \text{Distance} = \int f(x, y) \, ds \]

Which \( f(x, y) \) can be obtained by three-axis accelerometer and three-axis gyroscope, \( ds \) can be obtained by encoder.

Unqualified Weld Points Marking

As an important means of fault diagnosis and detection of flaw detection equipment, non-destructive flaw detection technology plays an important role in the aerospace, transportation, energy, electric power, petrochemical, machinery and other industrial sectors. The use of non-destructive testing technology to improve product quality and ensure safe production has achieved significant economic and social benefits. In the petroleum industry, non-destructive testing techniques are increasingly used to ensure the safety and effectiveness of oil production and transportation. Non-destructive testing is a technical means to study the presence or absence of defects in the interior and surface of a product without damage to the material, depending on the internal structure of the product or the presence of defects. At present, flaw detection methods
mainly include: radiographic inspection, ultrasonic flaw detection, eddy current testing and magnetic flux leakage testing.

Compared with other kinds of flaw detection methods, magnetic flux leakage detection has obvious advantages. Magnetic flux leakage detection uses high-sensitivity sensors instead of magnetic powder sprayed on the surface of the workpiece to make the detection more intelligent, to achieve more convenient operation, and the test results are more reliable. The main feature of the magnetic flux leakage testing technology is that the surface of the ferromagnetic material is fast and the detection result is stable and reliable. The probe has the advantages of simple structure, convenient implementation and low cost. Therefore, the method can be applied to the weld inspection of the outer wall of the oil storage tank.

The magnetization curves of different ferromagnetic materials are different. The magnetization curve of common ferromagnetic materials is shown in Figure 5, where point a is the magnetic permeability \( \mu \) maximum point and point b is the magnetic induction intensity \( B \) maximum. As can be seen from the figure, when the magnetic saturation point b is approached, the magnetic field strength increases and the magnetic induction intensity remains substantially unchanged.

![Figure 5. Basic Magnetization Curve of Ferromagnetic Material.](image)

When a piece of internally non-defective and crack-free ferromagnetic material is uniformly magnetized, its magnetic path is theoretically composed of magnetic flux passing through the inside of the ferromagnetic material and a very small amount of leakage flux. If there is a defect, the defect area. The thickness is thinner and the magnetic field density is relatively large, so the magnetic reluctance at the defect is too large. At this time, part of the magnetic path is formed by the magnetic flux inside the material and a part of the leakage flux, that is, the magnetic flux will be significantly distorted at the defect [4].

The wall-climbing robot is equipped with a flaw detector. When the robot walks along the weld, the weld quality and wall thickness of the weld are detected. The detection density is no more than 2 mm from the adjacent sampling point, as shown in Figure 6.

![Figure 6. Flaw Detector.](image)
After the test is finished, the test data is analyzed. If the weld spot is unqualified, the robot will mark it here with the spot nozzle, and the coordinates of the unqualified weld point are obtained by the robot autonomous positioning. The data is stored in the database of the upper computer, which is convenient for the staff to find and record.

Conclusion
This paper introduces the autonomous positioning and marking of the wall-climbing robot based on large oil storage tanks. Firstly, establish a 3D model of the oil storage tank and mark each weld seam, and create a database to record relevant data. Then realize the autonomous positioning of the wall-climbing robot. Finally, the detected unqualified weld points are marked and stored in the database.

In order to improve the detection efficiency of the actual inspection site, modular non-destructive testing equipment that combines several detection methods is a future development trend. Miniaturization is another development trend. With the in-depth development of the market economy and competitive pressures, companies are paying more and more attention to the cost benefits of production. The technical advantages of automated testing are obvious, such as high efficiency, high security and small disturbances. Combined with artificial intelligence, it is an important goal for the intelligent detection system to achieve the behavior of mobile robots through autonomous decision-making under certain circumstances.

References
[1] Scianna A, Ammosvato A. 3DGIS data model using open source software[A].Core Spatial Databases-Updating, Maintenance and Services-from Theory to Practice[C].ISPRS, 2010, 38" 120-125.
[2] Hou E K, Zhang Z H, Deng N D, et al. Comparison of three roadway 3D modeling methods in OpenGL environment[J]. Mining Research and Development, 2009, 29(5): 59-62.
[3] Liu Z, Song L B, Yu T. An IMU-based human-machine cooperation control algorithm of active dancing robot. Computer Engineering & Science, Vol. 40, No. 1, Jan. 2018.
[4] Yao K, Shen K, Wang Z D, et al. Three-dimensional finite element analysis of residual magnetic field for ferromagnets under early damage[J]. Journal of Magnetism & Magnetic Materials, 2014, 354(3):112-118.