Design of flexible maintenance robot based on Gas Insulated Substation

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Abstract. Gas Insulated Substation (GIS) is a metal enclosed switchgear with SF6 gas as insulating medium, also known as gas insulated substation. Because of its compact structure, high security, easy installation and other characteristics, GIS is widely used in the assembly of all kinds of equipment except the main body of transformer. Due to the unique fully enclosed structure of GIS and the complexity of its own gas chamber, manual maintenance is often adopted at present, which is not only difficult but also dangerous. Based on the author's understanding of flexible robot, a method of intelligent maintenance of GIS cavity with flexible robot is proposed. The flexible robot has a long and narrow structure, and can move flexibly in complex environment. It can also carry sensors and operating equipment into the GIS cavity, and use intelligent control, image recognition, machine learning and other technologies to determine the type and location of GIS faults and deal with them. Through this method, the maintenance of GIS is completed.

Key words: GIS maintenance, flexible robot, intelligent control.

1. Introduction
GIS is a kind of metal enclosed switchgear which uses all or part of gas instead of air at atmospheric pressure as insulating medium. It is composed of circuit breaker, disconnector, bus, grounding switch, current transformer, voltage transformer, bushing, and outgoing line terminal, etc. These equipment are all sealed in the metal grounding cylinder, in which SF6 (sulfur hexafluoride) gas is used as the insulating medium, so it is also called SF6 fully enclosed combined apparatus.

GIS equipment has been widely used all over the world since it was put into practice in 1960s. GIS is widely used not only in the field of high voltage and ultra-high voltage, but also in the field of ultra-high voltage. GIS has many advantages, including compact structure, small volume, high reliability, superior performance, low noise, strong security, strong adaptability to the environment, and small maintenance workload, and the maintenance interval of its main components is not less than 20 years. GIS plays an important role in power transmission and transformation system, and its safe and reliable operation is the key to ensure power production.

GIS equipment adopts fully enclosed structure, and its internal state is not visible. Only barometer, opening and closing state indication and other information can be observed from the external naked eye, and the amount of equipment state information obtained is limited, which is difficult to meet the
requirements of state evaluation and state control. The pipeline of GIS is crisscross, the internal space is narrow, and there are many unknown factors. At present, the manual maintenance method is mostly used. Due to the compact structure and small area of GIS design, once the accident occurs, it will have a great impact on the equipment. Manual disassembly for maintenance is laborious and time-consuming, especially for fault location. At the same time, the ionized fluoride has strong toxicity, which is very dangerous to maintenance personnel and pollutes the environment [1].

Due to the long and narrow structure of GIS cavity, there are many unknown factors, so it is difficult for the general maintenance robot to replace the manual to complete the maintenance work. The flexible robot has the following advantages, so it can complete the maintenance of GIS cavity: (1) the flexible robot device is a kind of high redundancy mobile robot, which has more degrees of freedom than the required to determine the spatial position and posture of the robot, so it can imitate the movement state of biological snake, and move flexibly in the GIS cavity. (2) it can complete dangerous work on behalf of human, and can go deep into the SF6 gas environment I work in the middle of school. (3) Due to the large number of nodes and flexible assembly of the flexible robot, the maintenance equipment can be installed at the appropriate position. Therefore, through the design and improvement, the flexible machine can have the function of GIS maintenance.

2. Review of research level at home and abroad

High speed, precision and lightweight flexible robot system has many advantages, such as small driver, high operation speed, low energy consumption, large load mass ratio and compact component design, etc. [2]. Therefore, developed countries attach great importance to the research and development of flexible robot devices. Since professor i-lirose of Tokyo University of technology developed the first robot in 1972, dozens of prototype flexible robots have been developed. At present, the foreign institutions that systematically and deeply study the flexible robot devices mainly include: hirose Robot Lab of Tokyo University of technology in Japan, mobbie Robotics Laboratory of University of michigan-um in the United States, and Carnegie Mellon University in the United States University-cmu's biorobotics lab, etc., whose prototypes in each phase basically include all the important characteristics of the existing flexible robot devices.

The research of flexible robot started late in China, but it has made rapid progress. Cui Xianshi and Yan Guozheng of Shanghai Jiaotong University developed the first miniature snake like robot prototype in China in March 1999. In November 2001, the University of Defense Science and technology developed their prototype of flexible robot device. There have been many reports in domestic media. The snake body of the robot is composed of 17 segments, 1-2m long, 0.06m in diameter and 1.8kg in weight. It can meander forward, backward, turn and accelerate. Its maximum speed can reach 20m per minute. The lower part of the body is equipped with a driven wheel, and the execution unit is connected in parallel, which can only complete the meandering movement in the plane.

3. Main research contents

This paper focuses on the motion model, hardware structure and equipment of the flexible robot. We plan to design a snake like flexible robot. This flexible robot is equipped with visible light camera, 3D space scanning imaging system, wiping sampler, wiping wipes and other equipment through the mechanical arm. Combined with specific software control, it realizes the functions of GIS visible light recognition, 3D scanning imaging, wiping basin insulator and picking up different objects.

3.1. Motion model of flexible robot

In order to simulate the soft body of snakes, we designed vertical and horizontal orthogonal joints. A unit is composed of two orthogonal joints, each unit is equivalent to a universal joint, with two degrees of freedom in two directions, forming a high degree of redundancy structure. This mechanism design enables the flexible robot to move in any direction and adapt to the complex structure of GIS cavity [3]. The shell mechanism, the installation mode of steering gear and the shell, and the connection mode of two units, that is, vertical → horizontal → vertical, are connected to imitate the joints of biological
snakes. Due to the structural characteristics of the flexible robot, it can be simplified as a spatial link model (Figure 1).

![Figure 1. Space motion model of flexible robot](image)

Serpenoid is the basic curve of planar motion of flexible robot. Based on this idea, the spatial motion of the flexible robot can be regarded as the combination of motion waves in two mutually perpendicular planes:

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\begin{align*}
\theta_i(s) &= -2\alpha_{\theta_0}\sin\left(\frac{k_n\pi}{n_\theta}\right)\sin\left(\frac{2K_n\pi}{L}s + \frac{2K_n\pi}{n_\theta}i\right) + K_1l \\
\varphi_i(s) &= -2\alpha_{\varphi_0}\sin\left(\frac{k_n\pi}{n_\varphi}\right)\sin\left(\frac{2K_n\pi}{L}s + \frac{2K_n\pi}{n_\varphi}i + \delta\varphi\right) + K_1l
\end{align*}
\]

(1)

where \(\alpha_{\theta_0}, \alpha_{\varphi_0}\) is the initial bending angle of two waves, \(n_\theta, n_\varphi\) is the number of modules in each moving plane, and the phase difference of two waves in different planes is \(\delta\varphi\). \(L\) is the length of the body, \(I\) is the length of each module, \(K_n\) is the number of waves propagating in the body, \(i\) is representing the initial bending angle of any joint, \(s\) is the virtual displacement of the tail of a snake like robot along the axis of the snake curve, and \(K_1\) is the curvature deviation. If you change the size of \(K_1\), you can change the direction of motion; if you change the size and sign of \(s\), you can change the speed of motion and the direction of wave propagation.

We propose a 7-joint 6-link peristaltic flexible robot, which is a traveling wave transfer motion. The length of the bar is: \(a\), the mass is: \(m\), and there are 7 joints in the preliminary simulation. When the motor reducer is installed on its axis, the weight of the rod is equivalent to that of the joint, which can be ignored. Therefore, the center of the rotating shaft is the center of mass of the rod, when it creeps on the surface. The first step is to study the gait of the three moving bar. The motion diagram of the simulation is shown in Figure 2.
Figure 2. Gait analysis of snake like three action bar

At first, point P0 advances along the x-axis, and other points Pi (i ≥ 2) are fixed; at the same time, the angle $\alpha$ between member P0P1 and X-axis reaches the given angle $\alpha_0$. In the initial stage, P0P1 and P1P2 move, forming an isosceles triangle between them and the x-axis. At this stage, the foot of the triangle is $\alpha_0$(stage C in Figure 2). Except P1, other points do not move and are still on the x-axis. In the next stage, P0P1, P1P2 and P2P3 are moving rods, and The position of P0 and Pi (i ≥ 3) has not changed. The included angle $\alpha$ changes from $\alpha_0$ to $0^0$, while the included angle $\beta$ between P2P3 and X axis reaches the given angle $\alpha_0$ (stage D in Figure 2). The system is in state E at the end of this stage; P1P2, P2P3 and X axis form an isosceles triangle, and all other points are located on X axis except P2.

Repeat the above process, you will find that when a stage is completed, except for the vertex of the triangle, other points are located on the x-axis. The vertex and triangle will gradually move to the right; the last point P5 will become the vertex of the triangle (as shown in phase f in Figure 2), the angle $\alpha$ will change from $\alpha_0$ to $0^0$, and the whole system will return to the straight line state g (as shown in phase g in Figure 2).

In this motion period, the displacement $l$ of the whole system along the x axis is equal to the displacement of point P0 from state a to state b. Therefore, there are:

$$L = 2a(1 - \cos \alpha_0)$$  \hspace{1cm} (2)

$a$ is the length of the rod.

3.2. Equipment carried by flexible robot

The flexible robot can enter the GIS cavity and move flexibly, but it can not complete the corresponding maintenance work. It must be equipped with corresponding maintenance equipment to realize the maintenance function.

(1) Visible light recognition

Visible light inspection technology is to use the robot equipped with visible light camera, through the sensor data acquisition, software algorithm recognition, through the hardware and function research
and development, make the robot in the closed environment of GIS equipment, realize the optimal imaging in the complex environment. Based on the analysis of digital image preprocessing method, use the color space conversion and image processing. The insulator image is preprocessed by graying, contrast enhancement and image denoising, and then the relatively fuzzy image is analyzed and identified accurately by visual development.

(2) 3D imaging scanning

3D scanning technology integrates optical, mechanical, electrical and computer technology. It is mainly used to scan the spatial shape and structural color of objects to obtain the spatial coordinates of the object surface.[4] The 3D scanning imaging technology of the experimental robot can collect images, encode pixels and reconstruct 3D information in the complex environment of GIS, and finally achieve high-speed and high-resolution 3D scanning imaging, which provides data for mastering the internal situation and faults.

(3) Grab system: Although the reliability of GIS equipment is very high, there are still many accidents in the actual operation process. In the process of manufacturing GIS components, the metal particles and powder left in the cavity may lead to discharge, so it is difficult for maintenance personnel to carry out operation and maintenance. A set of picking system is designed for the flexible robot snake. The robot arms are installed on both sides of the robot, which is convenient for the flexible robot snake to grasp the target in the process of running, and the infrared scanning and 3D imaging devices are installed on the head to get the original image. According to the information of the target point, the grasping trajectory of the robot is planned, the target is tracked, the manipulator is positioned above the target, and finally the workpiece is grasped.

(4) Basin insulator wiping Sampler: basin insulator is the weakest insulation link in GIS. Statistical data show that the faults caused by basin insulator defects account for 37% of the total faults in GIS [5]. Surface flashover of basin insulator is the most common fault of GIS, including metal particles, surface dirt and so on, which is one of the important causes of GIS insulation fault, so the cleaning of insulator is essential. In order to realize the cleaning of basin insulator, the key is to accurately grasp the pollution condition of basin insulator, that is, the salt density value, which directly determines the accuracy and reliability of the cleaning of porcelain insulator.

A wiping sampler is installed at the front arm of the flexible machine, which is mainly composed of an insulating operating rod and a special wiping head. A U-shaped wiping card is installed on the wiping head, a sponge pad is attached on the inner side, and a special wiping wet towel is wound on it. Firstly, the surface of the basin insulator is wiped by the sampler, and the pollution condition of the line is obtained by combining the visible light and 3D imaging images. According to the state cleaning strategy, the cleaning of the basin insulator is guided.

Figure 3. Schematic diagram of robot internal operation
4. Conclusion
This paper puts forward a method of using flexible machine snake to repair GIS. Flexible machine snake can complete the repair in the long and narrow cavity of GIS, so as to replace the manual repair method. In this paper, the motion model and equipment of the flexible robot snake are explored and analyzed, and some parameters of the flexible robot snake motion are obtained. The cooperation of imaging system, grasping system and basin insulator wiping system can make the flexible robot snake have imaging function, grasping foreign matter function and cleaning function, so as to complete the maintenance of GIS. In addition, the flexible machine needs maintenance, including general maintenance and routine maintenance. Robots need the care and operation of professionals, to enhance the professional knowledge and practical operation ability of relevant personnel.

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