A Study on Intelligent GIS Installation System Based on Six-DOF Parallel Multi-axis Motion Control

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Abstract. Aiming at the connection of pipelines during the GIS installation process of power transmission and transformation projects, this subject designs and produces an intelligent GIS installation system based on 6-DOF parallel multi-axis motion control, which is applied to practical applications. The intelligent installation system can realize six independent motions and their combined motions in three-dimensional space. Relying on the multi-dimensional visual positioning system, through the six-degree-of-freedom parallel multi-axis motion control system, the precise docking during the installation of the precision GIS cavity can be realized.

Keywords: GIS, Six Degrees of Freedom, Control

1. Introduction

In domestic substation projects, GIS cylinders have different shapes and high installation accuracy requirements. In addition, it has many overall construction links and complicated processes. Currently, cranes and manual cooperation are used for installation. The cranes are large in size and move and swing. During the process, it is not easy to accurately control the range of up, down, left, and right, and the installation process is easy to bump and cause partial equipment damage. The working environment temperature is high in summer and the working environment temperature is low in winter. The manual operation is labor intensive and frequent ascending and descending also have unsafe factors, which extremely affect work efficiency. In the operation of the substation expansion project, the working space environment is limited, and the parking position of the crane is affected by the surrounding live equipment. It is necessary to expand the scope of power outage and increase the difficulty of construction [1].
With the large-scale construction of projects in various construction industries, smart robotic arms have become an important choice for large-scale projects, precision docking technology, and construction problems in limited space operating environments. At present, the application and development of robotic arms are mostly concentrated in the field of factory intelligent production. In terms of power construction, traditional tools are still used, such as liftable herringbone ladders, hand forklifts, cranes and other hoisting tools.

In this paper, we consider combining a set of parallel six-degree-of-freedom hydraulic platform on the front of the manipulator, and using the advantages of the parallel six-degree-of-freedom hydraulic motion platform which are high rigidity, high precision, high load-bearing and fast response. It can flexibly realize six independent motions in three-dimensional space. Combined motion, relying on the multi-dimensional visual positioning system and through the six-degree-of-freedom parallel multi-axis motion control system, the precise docking during the installation of the precision GIS cavity is realized. What’s more, it solved the problem of operation under limited space construction conditions.

2. Scheme design of intelligent gis installation system

The intelligent GIS installation scheme designed in this paper based on six-degree-of-freedom parallel multi-axis motion control is mainly used for GIS cavity docking and installation. It adopts a modular design and can be split and combined according to different structures, which has good applicability. The scheme is mainly composed of mechanical system, electrical system, control system and multi-dimensional visual positioning system.

3. Six-degree-of-freedom parallel multi-axis motion mechanical structure design

The core of the mechanical system is composed of a six-degree-of-freedom parallel multi-axis motion control mechanism and a mechanical structure. The mechanical system structure mainly includes a hoisting mechanism, a balance mechanism, a slewing mechanism, and a clamping mechanism. The GIS intelligent installation is completed through the coordination of the six-degree-of-freedom parallel multi-axis motion control mechanism and the mechanical structure.

3.1. Six-degree-of-freedom parallel multi-axis motion control system

The six-degree-of-freedom parallel platform is used to adjust the position and posture of large and special-shaped parts. It realize the translation and posture adjustment of the load through the translation of 3 degrees of freedom and the rotation of 3 degrees of freedom. This system is a complex dynamic system with severe nonlinearity, multiple input and output variables, and intricate coupling relationships among various variables.

The pose of the moving platform of the six-degree-of-freedom parallel platform is solved by the forward and inverse kinematics of its mechanism. In order to improve the positioning accuracy of the 6-UPS parallel mechanism, the kinematic parameter identification model of the 6-UPS parallel mechanism based on inverse kinematics is adopted.
The fixed coordinate system is established with the center of the fixed platform as the coordinate origin \( \{B\} \), and the Z axis is perpendicular to the fixed platform. The moving coordinate system is established with the rotation center of the moving platform as the coordinate origin \( \{P_i\} \), \( r_i \) is the position vector of the Hooke hinge center \( A_i \) in the fixed coordinate system \( \{B\} \), \( P_i \) is the position vector of the hinge center \( B_i \) in the dynamic coordinate system \( \{P\} \). The inverse solution of the 6-UPS parallel mechanism, that is, given the pose \( P \) of the moving platform and the geometric parameters \( u \) of the mechanism, solve the length \( l \) of the 6-poles [5].

Differentiate both sides of the equation of the inverse kinematics of the 6-UPS parallel mechanism:

\[
2(\Delta l_i + l_{ai})(\delta \Delta l_i + \delta l_{ai}) = 2( RP_i + X - r_i )^T ( R \delta P_i - \delta r_i )
\]

Simplified:

\[
\delta \Delta l_i = \left[ \begin{array}{c} R ( RP_i + X - r_i )^T - ( RP_i + X - r_i )^T - 1 \end{array} \right] \begin{bmatrix} \delta P_i \\ \delta r_i \\ \delta l_{ai} \end{bmatrix}
\]

So the Jacobian matrix of the single-stroke parameter identification model is:

\[
J_{ij} = \nabla f(u_i) = \left[ R ( RP_i + X - r_i )^T - ( RP_i + X - r_i )^T - 1 \right] \begin{bmatrix} \delta P_i \\ \delta r_i \\ \delta l_{ai} \end{bmatrix}
\]

\( i = 1, 2, 3 \ldots 6 \); \( j = 1, 2, 3 \ldots m \); \( m \) is the measured number of poses.

The Jacobian matrix of the overall parameter identification model of the 6-UPS parallel mechanism can be obtained from the Jacobian matrix of the single parameter identification model:

\[
\nabla F(u) = \left[ J_1, J_2, \ldots, J_i, \ldots, J_m \right]^T_{6m \times 42}
\]

\[
J_j = \begin{bmatrix} J_{1j} & 0 & \ldots & 6 \\ 0 & J_{1j} & \ldots & 6 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \ldots & J_{6j} \end{bmatrix}_{6 \times 42}
\]

The current six-degree-of-freedom motion platform is increasingly widely used, and its structural model is shown in Figure 4. The platform is matched on different bases, and the platform can move freely in six directions by six hydraulic mechanisms. The load capacity, moving range, and moving accuracy all meet the requirements of the equipment site installation process. It is mainly composed of 6 driving units distributed in a circle and identical in structure. The motion platform is adjusted to the position to be loaded, equipment or parts are loaded, and then the motion platform is driven to perform spatial three-degree-of-freedom translation and spatial three-degree-of-freedom deflection movement.
to adjust the docking posture. And finally it can achieve linear close to the assembled parts for assembly [6].

3.2. Mechanical structure system

3.2.1. Hoisting mechanism. The crane interface installation mechanism is mainly to connect and fix the docking equipment with the front of the crane, and realize the long-distance transportation and movement of the GIS cavity by connecting with the bearing mechanical structure. This interface can meet the connection of cranes, self-propelled cranes and other equipment, and realizes the functions of simple assembly and disassembly of the mechanical arm and the carrying platform.

The crane is selected as the bearing platform to realize the application of automatic precision docking technology in new projects or projects with small environmental constraints. The crane has a wide range of activities, large carrying capacity, low requirements on the ground and site environment, flexible movement, and strong ability to overcome obstacles. But it has high requirements for space and has strong crane operations. It is suitable for outdoor new construction or installation with a large space [7].

The forklift type structure is selected, and the forklift is easy to operate and easy to install and debug. It is suitable for indoor or outdoor open areas directly in front. It does not require high space height, but the disadvantage is that the ability to cross obstacles is poor and the path needs to be flat.

3.2.2. Balancing mechanism. The horizontal mechanism is mainly composed of a balance cylinder and a load-bearing rack. It is used to adjust the inclination angle formed by the front end of the boom and the docking mechanism when the crane boom lifts up heavy objects. The upper end of the load-bearing frame is movably connected with the crane connecting frame. And the entire docking mechanical system is adjusted to maintain vertical downwards through the balance cylinder [8].

3.2.3. Slewing mechanism. The slewing mechanism is mainly composed of a slewing bearing, a planetary reducer and a servo motor. Its function is to adjust the position of the front-end clamping mechanism when clamping the pipe. So the clamping mechanism and the placed pipe are parallel, which can easily and quickly clamp the ground. So it can be used to improve work efficiency.

3.2.4. Docking organization. The docking mechanism is mainly composed of six parts: upper platform, lower platform, upper double inclined block, lower double inclined block, spherical hinge and cylinder. The function is to realize the docking of six degrees of freedom in space. The control system receives feedback from the visual positioning system. After the data is obtained, the movement of the six oil cylinders controlling the docking mechanism is solved to realize the control docking function.

3.2.5. Clamping mechanism. The clamping mechanism is composed of the most important components such as fixed clamps, movable clamps, and clamping cylinders. The function is to smoothly clamp the pipeline from the ground to ensure that the pipeline and the docking mechanism remain relatively static during the working process of the crane, without rotation or displacement.

4. Control system design based on multi-dimensional visual position technology
The control system is used to control the entire structure. Through the effective combination of the positioning system and the actuator, it can get the cooperation of software and hardware. And the actual installation movement logic is programmed to meet the actual needs of on-site installation and one-button automatic docking.

(1) Receive recognition and positioning system data, and prompt the operator to perform precise docking operations after the relative displacement meets the activity space of the six-free motion platform;

(2) The use of wired and wireless remote control methods to control the docking system and clamping mechanism, and the use of handwheels or joysticks for manual operation of the remote six-degree-of-freedom motion platform, which is easy to learn;

(3) It has functions such as fault alarm, emergency stop, and one-key automatic docking.

The control system is mainly composed of handwheel, visual positioning system and EPEC controller. The docking process is a combination of manual docking mode and automatic docking mode.

4.1. Multi-dimensional visual positioning technology

Multi-dimensional visual inspection function and the ability to perceive relay perception. For the precise docking of GIS, the automation level of the robotic arm needs to be further improved, and the assembly system needs to have high positioning accuracy. In addition, it need multi-dimensional visual detection functions and docking force perception capabilities, which requires multiple types of sensors, such as wireless cameras, infrared ranging, etc. The control of multi-directional distances in complex environments must be precise and evasive, which requires the cooperation of software and hardware to make the robotic arm have simple artificial intelligence and can judge actions in specific scenarios.

The visual positioning system includes a 3D camera, main control computer, communication cable and power supply, as shown in Figure 1. Fix the 3D camera on a bolt hole of the clamping pipe. Through the tooling installation, the position and distance of the camera relative to the axis of the clamping pipe can be known. Then, by collecting the visual information of the fixed pipe, the neural network model is used to train the bolt hole. Detect and extract the target characteristic small holes, as shown in Figure 1, and then calculate the depth of field between the flange surface of the target butt pipe and the camera to obtain the deflection angle and translation distance of the target pipe relative to the butt pipe.
Figure 1. GIS cavity bolt hole identification

Recognize roll angle, pitch angle and rotation angle of flange hole attitude rotation:

By measuring the distance between two points in the horizontal direction of the pipe B section relative to the camera, a triangle is obtained, and the triangle is solved to obtain the roll angle of the pipe.

(2) In the same way, by measuring the distance between two points in the vertical direction of the pipe B section relative to the camera, a triangle is obtained, and the triangle is solved to obtain the pitch angle of the pipe. The angle of rotation of the pipeline in the Z axis direction is calculated by the arc distance of the depth camera to the candidate mark positioning hole to be aligned from the center position in the camera field of view.
Since the installation of the camera is determined by the tooling, the center position of the camera relative to the pipe A has been determined. The center point of the position of the B pipe in the camera can be identified. By measuring the offset of the B pipe center point in the camera field of view, the relative displacement of the B pipe and the A pipe on the three axes can be obtained.

4.2. Docking system

The docking process is as follows:

(1) Swing the crane boom, clamp the pipe by the clamping mechanism, and send a signal to the EPEC controller through the handwheel to control the rotation of the slewing mechanism and the clamping cylinder for telescopic action, adjust the clamping mechanism to quickly clamp and take. Then install and fix the camera on the flange hole at the front end of the clamping pipe;

(2) Swing the crane boom and rotate the butt pipe to a position 300mm away from the target butt pipe;

(3) Feedback the inclination angle of the front gripping mechanism and the horizontal ground through the inclination sensor, and control the balance and leveling docking mechanism through the EPEC control system to make it receive the vertical downward force and keep it still;

(4) Switch the docking mode to manual docking, Adjust the axes of the two pipes to roughly coincide with each other through the handwheel (the difference between the outer circles of the two mating flanges does not exceed ±20mm);

(5) Switch the docking mode to the automatic docking mode. The visual positioning system is responsible for obtaining and calculating the spatial attitude and position of the target pipeline and the docking pipeline (including rotation and translation in three axes), and sending the target value to the docking system EPEC Controller, remove the camera. The controller calculates and obtains the target displacement value of the oil cylinder, controls the movement of the oil cylinder to connect the docking pipeline to a position 20mm away from the target pipeline, and then the construction personnel screw on the bolts;

(6) Finally switch to manual docking mode, control the axis direction to move slowly forward, and tighten the bolts at the same time, loosen the clamping mechanism after tightening the four diagonal bolts, and proceed to the next docking task.

4.3. Control system

The EHA actuator is selected, driven by a DC brushless motor, and controlled by the controller in real time. It can complete the rotation around the X, Y, and Z axes and the translation along the three axes, which can meet the calibration movement requirements of the GIS installation.

The inclination angle of the front end of the docking mechanism is monitored and fed back by the inclination sensor, and the control system controls the balance cylinder to adjust the docking mechanism vertically downward. The handwheel and vision send control instructions to the EPEC control system, and then the EPEC control system controls the actions of each mechanism. Adjust the rotation mechanism, clamping mechanism and change the docking mode (automatic docking and
manual docking) through the handwheel. In manual docking mode, the single-axis movement of the docking mechanism is controlled by the handwheel.

In the automatic docking mode, the multi-dimensional vision positioning system collects the relative spatial pose of the target pipeline and the docking pipeline, feeds it back to the control system, and calculates it through the control system, and then controls the docking system to complete the posture transformation to realize the docking function of the docking pipeline and the target pipeline.

5. Application of manipulator based on six-degree-of-freedom parallel multi-axis motion control

The use of robotic arms to participate in precision docking operations has relatively mature technology abroad. It benefits from its mature operation mode, sufficient applicable mold accessories, and years of accumulated construction experience. However, domestic robotic arms are less used, and more in electric power construction. It is a rare application, which leads to a large gap between the current domestic application level and the international level. Through several project simulation practices and the existing robotic arm test in Xiaoshan Robot Town, the research can improve the robotic arm to meet the requirements of electrical installation and construction. It fills up the blank in domestic robotic construction technology and has accumulated valuable experience. In addition, it is useful for improving the mechanized construction level of electrical installation of the State Grid Corporation. And it can solve the difficult environmental construction problems such as limited space non-stop installation and precise docking encountered in the electrical construction process.

6. Conclusion

For a long time, the installation of GIS equipment generally has problems such as high labor intensity of manual operation, frequent climbing and climbing, and unsafe factors and low work efficiency. This paper has completed a set of intelligent GIS installation system research based on six-degree-of-freedom parallel multi-axis motion control. The system has the advantages of large rigidity, high precision, high load-bearing and fast response, and can flexibly realize six independent motions in three-dimensional space. In GIS installation, it can bear the weight of multiple GIS, lift or grab GIS cavities of different sizes, relying on the multi-dimensional visual positioning system. Through the six-degree-of-freedom parallel multi-axis motion control system, the precision GIS cavity installation process. It solves the operation problems under the limited space construction conditions. And it can effectively shorten the electrical installation period and reduce the manpower and material resources.

Acknowledgments

Fund projects: In this paper, the State Grid Zhejiang Electric Power Co., LTD. "Intelligent manipulator in substation engineering research and application" (5211JJ18000K) subsidizes.

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