Research on Mobile Manipulator in the Application of GIS Pipeline Detection

Fa Qing TANG, Rong Hai LIU, Xiao Hong YANG and Zhi Cong DONG

Abstract. In this paper, Based on GIS pipeline internal inspection difficult problem, according to the special structure of GIS pipeline internal proposed using testing equipment such as the mobile manipulator and image acquisition method of GIS pipeline internal components for testing. According to the job requirements of the mobile manipulator inside the pipeline, determine the specific parameters of the mechanical arm, and the mechanical arm was established based on Matlab toolbox robot model, and has carried on the kinematics simulation of mechanical arm. The use of mobile manipulator and vehicle test prototype of mobile manipulator movement characteristics and stability are verified.

Keywords. GIS pipeline inspection, Mobile Mechanical arm, Kinematics simulation.

Introduction
GIS, namely Gas Insulated Full-enclosed Combined Electrical Equipment, including circuit breaker, disconnecting switch, grounding switch, voltage transformer, current transformer, lightning arrester, busbar, cable termination, in and out casing pipe and so on, are organically combined into a whole by optimized design. GIS plays an important role in power transmission, and its safe and reliable operation is the key to ensure the power production[1],[2].

Fa-Qing TANG, Xiao-Hong YANG, Zhi-Cong DONG, School of Energy and Power and Mechanical Engineering, North China Electric Power University, Baoding 071003, China. 1322960631@qq.com, yangxh@ncepu.edu.cn
Rong-Hai LIU, Yunnan Electric Power Research Institute, Kunming 650217, China. lrh19842004@163.com
The GIS is fully enclosed equipment, its structure as shown in Figure 1, and the inner part is provided with a conductive rod and a supporting insulator, so the overhaul process is complicated. GIS maintenance needs to understand the internal conditions of the pipeline, and GIS fault type and fault location can only be judged according to the internal GIS. The internal GIS is relatively narrow, which brings some difficulties to the fault detection.

![FIGURE 1. The GIS pipeline and internal structure.](image)

With the development of robot technology, the application of robot in the inspection of power equipment is more and more mature. Fault detection in GIS pipeline can be realized by using mobile robot and image acquisition technology, and GIS pipeline inspection robot can be used to show the real-time situation of the equipment to the equipment maintenance personnel, so that they can make the maintenance plan[3].

**The kinematics model of the mobile manipulator**

D-H (Denavria-Hartenberg) modelling refers to the use of homogeneous transformation matrix to express the relations between the current coordinate system and the coordinate system of the last bar. The relations between the end of the manipulator and the reference coordinate system can be obtained by the product of all the homogeneous transformation matrices[4]. The movement and rotation of the manipulator is shown in figure 2.

![FIGURE 2. Schematic diagram of the connecting rod parameters of the robot arm.](image)
Because this paper researches the mechanical arm, its joints are rotating, so here only analysis of the rotating joint. Relative to the rotating joint, $\theta_i$ is a variable of the joint, $a_i=0$, and the remaining two are the relevant parameters of the joint, so if you know the values of the four parameters, the D-H matrix of the entire bar is determined[5].

In six degrees of freedom mechanical arm as an example, $i^{-1}T_6$ may represent the relationship between the coordinate system at the end of the robot arm and the link i-1 coordinate system, as shown in Equation 1:

$$i^{-1}T_6 = A_iA_{i+1}\ldots A_6$$ (1)

Can be connected to the general formula as shown in Figure 2:

$$i^{-1}T_i = 
\begin{bmatrix}
    c\theta_i & -s\theta_i & 0 & a_i \\
    s\theta_i c\alpha_{i-1} & c\theta_i c\alpha_{i-1} & -s\alpha_{i-1} & -d_i s\alpha_{i-1} \\
    s\theta_i s\alpha_{i-1} & c\theta_i s\alpha_{i-1} & c\alpha_{i-1} & a_i c\alpha_{i-1} \\
    0 & 0 & 0 & 1
\end{bmatrix}$$ (2)

The expression of the end coordinate system of the manipulator relative to the reference coordinate is shown in Equation 3[6]:

$$T_6 = A_1A_2A_3A_4A_5A_6$$ (3)

Therefore, for a robot with n degrees of freedom, when modeling D-H, in addition to the need to establish the standard orthogonal Cartesian coordinate system ($x_i, y_i, z_i$), where i=1,2,3, 4, 5, 6, also need to establish a reference coordinate system ($x_0, y_0, z_0$) on the base of the manipulator, plus the coordinate system established by each of the previous joint parts, so this robot has a total of n+1 Coordinate system.

($x_i, y_i, z_i$) can move along with the link i, so that the coordinate system at the end of the manipulator is relative to the position of the base coordinate system, and the position of each sub-coordinate system is selected at the end of each rod The transformation between the n and the coordinate system is described[7].

It can be seen from Equation 2 that the kinematic inverse of the manipulator is the process of obtaining the $A_1$, $A_2$, $A_3$, $A_4$, $A_5$, $A_6$ by the known $T_6$ and this process can be expressed by Equation 4[8]:

$$A_i^{-1}T_6 = A_2A_3A_4A_5A_6$$
$$A_i^{-1}A_{i+1}^{-1}T_6 = A_3A_4A_5A_6$$
$$A_i^{-1}A_{i+1}^{-1}A_{i+2}^{-1}T_6 = A_4A_5A_6$$
$$A_i^{-1}A_{i+1}^{-1}A_{i+2}^{-1}A_{i+3}^{-1}T_6 = A_5A_6$$
$$A_i^{-1}A_{i+1}^{-1}A_{i+2}^{-1}A_{i+3}^{-1}A_{i+4}^{-1}T_6 = A_6$$ (4)

Three degrees of freedom mechanical arm model parameters as shown in table 1, figure 3 of mechanical arm D-H coordinate system for calibration;
Where $\alpha_{i-1}$ is the length measured from the direction of $x_{i-1}$ axis from $z_{i-1}$ to $z_i$, that is, the length of the arm $i-1$ rod, the value of $\alpha_{i-1}$ is equal to or greater than 0;

$\alpha_{i-1}$ is the angle obtained by rotating $x_{i-1}$ from $z_{i-1}$ to $z_i$ around it, and the value of $\alpha_{i-1}$ can be negative according to the direction;

d$_i$ is the length obtained from the direction of $x_{i-1}$ to $x_i$ along the $z_i$ axis, that is, the offset of the manipulator joint, the d$_i$ value can be positive and negative;

$\theta_i$ is the angle at which $z_i$ is the rotation axis and the rotation from $x_{i-1}$ to $x_i$ around it, and the value of $\theta_i$ can be negative according to the direction[9].

### Table 1. The D-H coordinate system parameters.

| Connecting rod | a     | $\alpha$ | $\Theta$ | Joint Angle     |
|----------------|-------|----------|----------|-----------------|
| 1              | 0     | 90°      | $\Theta_1$ | -90°~+90°       |
| 2              | L$_1$ | 0°       | $\Theta_2$ | 0°~+90°         |
| 3              | L$_2$ | 0°       | $\Theta_3$ | 0°~+180°        |

**FIGURE 3.** Mechanical arm model and the D-H coordinate system.

The overall structure design of mobile manipulator Design constraints

The system uses the operating arm on the mobile car, to complete the detection of GIS pipes, the overall technical program used as shown in Figure 4.

Wherein the moving carrier is for carrying the robot arm and moving it within the pipe, the operating arm is used to hold the image acquisition device to complete the detection of the pipe.

Power station GIS equipment cylinder center at 500-2400mm, barrel 400-1200mm in diameter, cylinder supporting ground span 800-2200mm, single barrel length is greater than 2000mm; The main structure inside the pipeline is composed of support insulator and the conductive rod. As shown in
figure 4, the mobile manipulator can be moving in the pipe, the end of the mechanical arm testing equipment can be up to the designated place to test the pipeline internal parts.

The design constraints are as follows:
1) flexible operation arm mechanism, can achieve lift, translation and other actions, the image acquisition device or DXR panel detector to the specified location and adjust to the correct attitude;
2) the operating arm has a certain stiffness, in the process of moving the end of the arm vibration should not be too large;
3) mobile body has a certain stability, flexible operation, and has a certain climbing ability

**Main bar size design**
Using the Monte Carlo method, first estimate the range of the joint angles of the manipulator and then constrain the length of the arm according to the working range of the manipulator arm. See Figure 4. And then is optimized by the operability index of the manipulator and the operability of the force as the objective function. The expression is \( Z = \left( U^T \left( J(q) J^T(q) \right)^{-1} U \right)^{-\frac{1}{2}} \), when it gets the maximum value, the pole is long. Using matlab programming calculation, to determine the length of the main arm of the operating arm[10].

The length of the arm of the operating arm is: \( l_1=0, \ l_2=35mm, \ l_3=31mm \).

**Design of main connecting rod structure**
In the traditional industrial robot design, the connecting arm of the operating arm is designed to be straight rod or curved rod with a little curvature. The main function of the mobile arm is the image acquisition equipment or other small detection equipment to the designated detection position, the robot arm with three degrees of freedom joints to meet the work needs[11][12].

**The Matlab simulation movement mechanical arm**
In order to further understand the working characteristic of mobile manipulator, the motion performance of mechanical arm kinematics simulation analysis, the simulation process of mechanical arm was established
based on Matlab toolbox robot 3D model, 3D mechanical arm model is shown in figure 5.

![FIGURE 5. Mechanical arm model.](image)

The model of three degrees of freedom mechanical arm, on both sides of the mechanical arm length is: \( l_1 = 0 \), \( l_2 = 35 \text{ mm} \), \( l_3 = 31 \text{ mm} \), using the method of mechanical arm kinematics inverse solution of mechanical arm motion, as shown in figure 6, figure a starting point for a mechanical arm for information, the coordinates of the starting point of a mechanical arm (0,0,66) figure b for the key position, the coordinates of the end point b (17.5, 0, 21), the whole motion simulation time for 7 s.

![FIGURE 6. The starting point of the mechanical arm and the key position.](image)

Mechanical arm within a specified time reach the designated position, as shown in figure 7 for the robotic arm to finish from the starting point for A track in the end of the movement in the process of mechanical arm B. Figures 8 and 9, respectively, for the mechanical arm in the process of movement of each joint angle and the change of displacement at the end of the mechanical arm, mechanical arm can be clearly seen from the figure in the process of movement posture change of each moment.

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**FIGURE 7.** The trajectory of the end of the manipulator.

![Image](image.png)

**FIGURE 8.** The angle of each joint of the manipulator changes.

**FIGURE 9.** The end of the arm is displaced.

Using Monte Carlo method can solve the manipulator workspace map, in determining the mechanical arm after the d-h coordinate system parameters of
each joint, generates the mechanical arm posture random variable array, after completion of random point set, calculation of mechanical arm under the position coordinates, at the end to complete the mechanical arm work space and sampling area coordinates. As shown in figure 10 and figure 11, the solving of mechanical arm working space sampling distribution points at the end of the three view drawing, the work can be seen from the figure in the minimum radius of 660 mm, satisfies the requirement of basic work.

![Figure 10](image1.png)  
**FIGURE 10.** Manipulator working space side view.

![Figure 11](image2.png)  
**FIGURE 11.** Robot Working Space Top View.

**Mobile manipulator and mobile carrier test prototype**

**Basic structure and function test prototype**

In order to further verify the feasibility of using the mobile manipulator in the GIS pipe inspection, a mobile robot and a moving carrier test prototype were fabricated. As shown in Figure 12, the test prototype consists of a robot arm and a moving carrier and a control table. The overall size of the vehicle body is 621mm ×150mm×80mm. The rear and front of the vehicle body are equipped with image acquisition equipment and lighting. The end of the machine arm is equipped with three axes PTZ and H-D image acquisition equipment. As shown in Figure 13, the mobile robotic console has an image display function, the console has a body movement control handle and a robot arm control keyboard.
The basic motion test of the test prototype

Robot movement test

As shown in figure 14, the mechanical arm to show the process, the whole process of each joint motor work performance is good, from the initial position to the joint arm to stop movement takes 8 s, mechanical arm end image acquisition and display devices work well, the car is also need to carry the weight of the mechanical arm, for mobile vehicle dynamic performance also has certain requirement.

Body movement performance test

The mobile manipulator to walk normally within the GIS pipeline, require mobile carrier has a certain grade ability and stability, the car is also need to carry the weight of the mechanical arm, for mobile vehicle dynamic performance also has certain requirements. As shown in figure 15, car body with four-wheel drive power, wheel with synchronous steering ability.
Mechanical arm in GIS internal work bodywork tilt Angle of 30 degrees, the stability of the car body to satisfy at work, as shown in figure 16 for mechanical arm when going up to the commencement of the body under the condition of the stability of the performance test, car body does not appear when climb 30 degrees slope phenomenon, mechanical arm can work normally.

FIGURE 15. The robot arm carries the body drive wheel and the drive motor.

FIGURE 16. Test prototype climbing ability and stability test.

After the motion test, the mobile robot and the body of the vehicle work normally, the robot is working normally, the stability of the body when moving to meet the needs of GIS pipe inspection work.

Conclusion
In the light of the problems in GIS internal pipeline maintenance difficulties, put forward the use of mobile manipulator and image acquisition equipment to replace artificial detection method of pipeline. Due to the GIS pipeline with internal conductive rod, artificial screen pipe internal fault has so much inconvenience.

In order to adapt to the GIS pipeline internal structure, based on the pipeline internal structure, size and structure parameters for the design of mechanical arm, and according to the parameters of mechanical arm robot movement, Matlab toolbox of mechanical arm kinematics simulation, and the joint rotation Angle of mechanical arm, the end of the mechanical arm displacement parameters such as the collection. Use Monte Carlo method can solve the manipulator workspace map. Mechanical arm according to simulation results, the working performance can meet the needs of basic GIS pipeline detection work.
According to the mobile manipulator experimental prototype of the mechanical arm motion state and the dynamic performance of the mobile carrier for further verification. Judging from the prototype test results, mechanical arm work well each joint motion state, the mobile platform dynamic performance is stable, the module did not appear the phenomenon of interference, experimental prototype meet the demand of basic work.

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