Non-destructive Testing Assisted by Six-Axis Manipulator Based on POE Formula

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Abstract. At present, aluminum plates are widely used in aerospace, machinery, and other fields because of their light weight, good manufacturability, and strong corrosion resistance. However, during long-term use, defects that will affect the structural strength such as cracks are easy to appear. Therefore, it is necessary to conduct automatic non-destructive testing of large metal plates to determine the location, size, and structural damage to their defects. Compared with manual detection, automated detection has many advantages such as high detection efficiency, high repeatability, strong flexibility, and low labor intensity. Based on the spinor theory, this paper uses the product of exponentials (POE) to model the kinematics of the Aubo-i5 manipulator and obtain the positive kinematics equations, which are compiled by analytic geometry and algebraic methods combined with Paden-Kahan subproblems and matrix theory. The inverse kinematics algorithm of the 6R manipulator is based on this model. An automated non-destructive testing system including a robotic arm and ultrasonic phased array testing equipment was built. At the same time, a robotic arm simulation platform was built based on ROS, and the inverse kinematics algorithm was used to control the robotic arm through the MoveIt!. The angle error can be controlled within 2.5°.

1. Introduction
Metal plates such as aluminum and steel are widely used in various fields because of their various good properties. In the process of manufacturing large metal plates, due to the influence of many factors, there are inevitably inclusions and cracks in the plates, and defects such as corrosion and scratches may appear on the surface of the plates in the process of re-service. When the accumulation of these defects expands to a certain scale, its service life will be greatly shortened, and may even cause serious safety accidents. To detect possible defects in large metal plates in time, and then determine the location, size, and structural damage of the defects, it is very necessary to conduct online non-destructive testing. At present, the ultrasonic guided wave detection technology is widely used in the non-destructive testing technology of aluminum plate and the effect is good [1], and in the traditional ultrasonic testing method, the imaging algorithm is used to obtain the contour image of the defect in the aluminum plate by the ultrasonic signal [2-3]. Ultrasound imaging needs to use a large amount of data for analysis in aluminum plate detection, so multiple excitations and receiving points are needed to obtain a large amount of information about aluminum plates[4]. For multiple excitations and detection points, manual area division and placement of transducers are not only inefficient but also have accuracy errors. It is easy to cause inaccurate guided wave information and cause certain problems in defect contour images.
With the rapid development of industrial automation, robotic arms are increasingly used in inspection, assembly, and other fields, and the use of robotic arms for automated inspection has become an inevitable trend. Compared with manual detection, automated detection has many advantages such as high detection efficiency, high repeatability, strong flexibility, and low labor intensity. The inverse kinematics algorithm is needed in the process of using the robotic arm to assist the nondestructive testing. The inverse kinematics of the manipulator is to determine the angle of each joint through the target position. Currently, the commonly used methods are the D-H (Denavit-Hartenberg Matrix) method and the POE (the product of exponentials) method. Among them, the D-H method is more mature and widely used [5-6]. However, the D-H modeling method needs to establish a coordinate system for each joint, and the posture of each coordinate system is different. When changing the configuration of the robot, the model needs to be rebuilt. Therefore, the D-H method has problems such as the complex calculation process, low calculation efficiency, and unclear geometric meaning. Because of the various defects of the D-H method, a new method, namely the product of the exponentials method, has emerged to solve the above-mentioned shortcomings of the D-H method. The POE method only needs to establish the base coordinate system and the tool coordinate system, and then calculate the motion transformation matrix of each joint. The modeling process is simple and there is no singularity. The exponential product model was first proposed by Brockett [7]. In 2015, the University of New South Wales Yang et al. [8-9] developed a robot calibration method that only requires position coordinates without posture based on exponential product, thus solving the limitations of the traditional POE method. Similarly, some other scholars proposed other methods to avoid the singularities of different robot systems [10-14].

After the kinematics calculation of the robot, it is necessary to plan its trajectory so that the robot arm can reach the designated position faster and more accurately. To reduce the wear or collision damage of the actual mechanical arm, it is necessary to perform simulation analysis on computer software. Among various simulation platforms, ROS (Robot Operating System) is an open-source operating system mainly used in robot development. Due to its multiple programming language compatibility, free and open-source, cross-platform advantages, it is gradually being applied to various robots. Design and research in progress. In 2015, Cao et al. [15] designed a method to build a model in ROS, including external 3D model import and URDF file compilation. In 2016, Gao et al. [16] mentioned that ROS also provides a series of toolkits and libraries that integrate a variety of computer vision algorithms, planning algorithms, and navigation-driven algorithms. MoveIt!, as the ROS integration for the robotic arm function package, provides an easy-to-use platform for developing advanced robot programs, evaluating new robot designs, and building integrated robot products for industry, commerce, R&D, and other fields.

The remainder of the letter is organized as follows. Section II introduces the kinematics of AUBO-i5 manipulator based on the screw theory and the Paden-Kahan sub-problem. Section III mainly talks about the principle of transducer excitation and reception of ultrasound and describes the system integration scheme, while Section IV elaborates the establishment of a robotic arm simulation platform based on ROS, using the inverse kinematics algorithm written in C++ to control the robotic arm through MoveIt! to carry out the feasibility experiment of transducer placement. Finally, Section V provides a conclusion and some directions for future work.

2. Kinematics of 6-DOF manipulator

The 6-DOF robotic arm selected in this article is the AUBO-i5 type robotic arm, which consists of 6 revolving joints, including waist, shoulder, elbow, and wrist joints with 3 degrees of freedom. The base can be used to determine the installation position of the robot, and the wrist 3 can be used to connect tools to meet requirements. The first three joints mainly control the position of the end of the robot, and the last three joints mainly control the posture of the end of the robot. Through the coordinated movement between the various joints, the robot can move arbitrarily within its working range.
2.1. Kinematics of AUBO-i5 manipulator

Based on the screw theory, the structure coordinates are established as shown in Figure 2. Take the manipulator pose as the initial pose:

\[ g_{st}(0) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & -l_1 + l_4 + l_5 - l_6 \\ 0 & 0 & 1 & l_6 + l_2 + l_3 + l_5 \\ 0 & 0 & 0 & 1 \end{bmatrix} \] (1)

According to the configuration and size of the robotic arm in the initial state, the unit direction vector of each joint axis can be determined as:

\[ \omega_1 = \omega_6 = \begin{bmatrix} 0 \\ 0 \\ -1 \end{bmatrix}, \quad \omega_2 = \omega_4 = \omega_5 = \begin{bmatrix} 0 \\ 1 \\ 0 \end{bmatrix}. \]

We can choose axis points:

\[ q_1 = \begin{bmatrix} 0 \\ l_0 \end{bmatrix}, \quad q_2 = \begin{bmatrix} 0 \\ l_0 \end{bmatrix}, \quad q_3 = \begin{bmatrix} -l_1 \\ l_0 + l_2 \end{bmatrix}, \quad q_4 = \begin{bmatrix} -l_1 + l_4 \\ l_0 + l_2 + l_5 \end{bmatrix}, \quad q_5 = \begin{bmatrix} -l_1 + l_4 + l_5 \\ l_6 + l_2 + l_3 \end{bmatrix}, \quad q_6 = \begin{bmatrix} -l_1 + l_4 + l_5 \\ l_6 + l_2 + l_3 + l_5 \end{bmatrix}. \]

The full forward kinematics map of the manipulator has the form:

\[ g_{st}(\theta) = \exp(\hat{\xi}_1 \theta_1) \cdots \exp(\hat{\xi}_6 \theta_6) \cdot g_{st}(0) = R(\theta) \cdot p(\theta) \] (2)

The individual exponentials are given by:

\[ \exp(\hat{\xi}_1 \theta_1) = \begin{bmatrix} \cos \theta_1 & -\sin \theta_1 & 0 & 0 \\ \sin \theta_1 & \cos \theta_1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad \exp(\hat{\xi}_2 \theta_2) = \begin{bmatrix} \cos \theta_2 & 0 & -\sin \theta_2 & l_6 \sin \theta_2 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \cos \theta_2 & \sin \theta_2 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad \exp(\hat{\xi}_3 \theta_3) = \begin{bmatrix} \cos \theta_3 & 0 & \sin \theta_3 & 0 \\ -\sin \theta_3 & \cos \theta_3 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad \exp(\hat{\xi}_4 \theta_4) = \begin{bmatrix} \cos \theta_4 & -\sin \theta_4 & 0 & (l_6 + l_2 + l_3) \sin \theta_4 \\ \sin \theta_4 & \cos \theta_4 & 0 & (l_6 + l_2 + l_3) (1 - \cos \theta_4) \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad \exp(\hat{\xi}_5 \theta_5) = \begin{bmatrix} \cos \theta_5 & 0 & \sin \theta_5 & -l_1 - l_4 + l_5 \sin \theta_5 \\ -\sin \theta_5 & \cos \theta_5 & 0 & (l_6 + l_2 + l_3) (1 - \cos \theta_4) \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}, \quad \exp(\hat{\xi}_6 \theta_6) = \begin{bmatrix} \cos \theta_6 & 0 & \sin \theta_6 & 0 \\ -\sin \theta_6 & \cos \theta_6 & 0 & (l_6 + l_2 + l_3) \sin \theta_6 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \]

2.2. Inverse Kinematics of AUBO-i5 manipulator

Consider the six-degree of freedom AUBO-i5 manipulator shown in Figure 1. From the forward kinematics devised before, the tool configuration has the form:

\[ g_{st}(\theta) = \exp(\hat{\xi}_1 \theta_1) \exp(\hat{\xi}_2 \theta_2) \exp(\hat{\xi}_3 \theta_3) \exp(\hat{\xi}_4 \theta_4) \exp(\hat{\xi}_5 \theta_5) \exp(\hat{\xi}_6 \theta_6) g_{st}(0) = : g_d \] (3)
where is the desired configuration of the tool frame. Post-multiplying this equation by \( g^{-1}(0) \) isolates the exponential maps:

\[
\exp(\xi_1 \theta_1) \exp(\xi_2 \theta_2) \exp(\xi_3 \theta_3) \exp(\xi_4 \theta_4) \exp(\xi_5 \theta_5) \exp(\xi_6 \theta_6) g_{st}(0) = g_d g_{st}^{-1}(0) = \theta_1 \quad (4)
\]

Assume that the axes of the fifth and sixth joints intersect at point \( P_{56} \). Right-multiplying equation (4) by \( P_{56} \), and according to the principle of position invariance, we can get

\[
g_1 P_{56} = \exp(\xi_1 \theta_1) \exp(\xi_2 \theta_2) \exp(\xi_3 \theta_3) \exp(\xi_4 \theta_4) P_{56} = \theta_1 = [P_x \quad P_y \quad P_z \quad 1]^T \quad (5)
\]

![Figure 3 The screw motion of the first four joints.](image)

The equation (5) represents the screw motion of point \( P_{56} \) in the first four joints and corresponds.

According to the geometrical relation in Figure 3, we have

\[
\left\{ \begin{align*}
(P_2 - P_{56}) \cdot \omega_2 &= 0 \\
(P_2 - O_1) \cdot \omega_1 &= 0 \\
\|P_2 - O_1\| &= \|P_1 - O_1\|
\end{align*} \right. \quad (6)
\]

where \( \omega_1 \) and \( \omega_2 \) are given in 2.1. \( O_1 = [0 \quad 0 \quad p_z]^T \), \( P_{56} = [0 \quad -L_1 + L_4 - L_5 \quad L_0 + L_2 + L_3]^T \). Then we can get

\[
P_2 = \frac{\pm P_x + P_y - (-l_1 + l_4 - l_5)^2}{-l_1 + l_4 - l_5} \quad (7)
\]

Applying Subproblem 1 with \( \theta_1 \), we can get \( \theta_1 = a \tan 2 \left( -b \cdot P_x + a \cdot P_y, a \cdot P_x + b \cdot P_y \right) \), where

\[
a = \pm \sqrt{P_x + P_y - (-l_1 + l_4 - l_5)^2}, \quad b = \pm \sqrt{P_x + P_y - (-l_1 + l_4 - l_5)^2}.
\]

Since \( \theta_1 \) is known, equation (4) becomes

\[
\exp^{-1}(\xi_1 \theta_1) g_1 = \exp(\xi_2 \theta_2) \exp(\xi_3 \theta_3) \exp(\xi_4 \theta_4) \exp(\xi_5 \theta_5) \exp(\xi_6 \theta_6) = \theta_2 \quad (8)
\]

In equation (2), let \( g_{st}(\theta) = \begin{bmatrix} M_1 & N_1 & G_1 & H_1 \\ M_2 & N_2 & G_2 & H_2 \\ M_3 & N_3 & G_3 & H_3 \\ 0 & 0 & 0 & 1 \end{bmatrix} \) and \( g_4 = g_{st}(\theta) g_{st}^{-1}(0) \)

According to the corresponding matrix elements of each side in equation (8), the equation set can be obtained

\[
\left\{ \begin{align*}
cos \theta_5 &= \cos \theta_1 \ N_2 - \sin \theta_1 \ N_1 =: s_1 \\
\sin \theta_5 \cos \theta_6 &= M_2 \cos \theta_1 - M_1 \sin \theta_1 =: s_2 \\
- \sin \theta_5 \sin \theta_6 &= G_2 \cos \theta_1 - G_1 \sin \theta_1 =: s_3 \\
\sin \theta_5 \sin(\theta_4 - \theta_3 - \theta_2) &= -N_3 =: s_4 \\
\sin \theta_5 \cos(\theta_4 - \theta_3 - \theta_2) &= -\cos \theta_1 \ G_1 - \sin \theta_1 \ G_2 =: s_5
\end{align*} \right. \quad (10)
\]

The \( \theta_5, \theta_6 \) and \( (\theta_4 - \theta_3 - \theta_2) \) can be determined by utilizing equation (10)

\[
\theta_5 = a \tan 2 \left( \pm \sqrt{1 - s_5^2}, s_5 \right) \quad (11)
\]

\[
\theta_6 = a \tan 2 (-s_3, s_2), \quad \sin \theta_5 \neq 0 \quad (12)
\]

\[
(\theta_4 - \theta_3 - \theta_2) = a \tan 2 (s_4, s_5), \quad \sin \theta_5 \neq 0 \quad (13)
\]
The remaining kinematics can be written as

\[ \exp(\xi_2 \theta_2) \exp(\xi_3 \theta_3) \exp(\xi_4 \theta_4) = g_2 \exp^{-1}(\xi_5 \theta_5) \exp^{-1}(\xi_6 \theta_6) = g_3 \]  

(14)

From equations (14) and \( g_3 = \begin{pmatrix} m_1 & n_1 & g_1 & t_1 \\ m_2 & n_2 & g_2 & t_2 \\ m_3 & n_3 & g_3 & t_3 \\ 0 & 0 & 0 & 1 \end{pmatrix} \), we can obtain

\[
\begin{cases}
-l_2 \sin \theta_2 + l_3 \sin(\theta_3 - \theta_2) = t_1 - \sin(\theta_4 - \theta_3 - \theta_2) (l_0 + l_2 + l_3) =: t_7 \\
l_2 \cos \theta_2 + l_3 \cos(\theta_3 - \theta_2) = t_3 + \cos(\theta_4 - \theta_3 - \theta_2) (l_0 + l_2 + l_3) - l_0 =: t_8
\end{cases}
\]

(15)

The \( \theta_2 \) and \( (\theta_3 - \theta_2) \) can be given according to equation (15).

\[
\begin{align*}
\theta_2 &= a \tan 2(B,A) + a \tan 2(C, \pm \sqrt{A^2 + B^2 - C^2}) \\
\theta_3 - \theta_2 &= a \tan 2(t_1 + l_2 \sin \theta_2, t_3 - l_2 \cos \theta_2)
\end{align*}
\]

(16)

(17)

where \( A = 2l_2 t_7, \quad B = 2l_2 t_8, \quad C = l_3^2 - l_2^2 - t_7^2 - t_8^2 \).

We can determine \( \theta_3 \) and \( \theta_4 \) by

\[
\begin{align*}
\theta_3 &= (\theta_3 - \theta_2) + \theta_2 \\
\theta_4 &= (\theta_3 - \theta_2 - \theta_4) - (\theta_3 - \theta_2)
\end{align*}
\]

(18)

(19)

At the end of this procedure, \( \theta_1 \) through \( \theta_6 \) are determined. There are a maximum of eight possible solutions, due to multiple solutions for equations (7) (10) and (15).

3. Non-destructive testing

3.1. Principles of Nondestructive Testing

There are two sets of transducers, one is the receiving transducer and the other is the excitation transducer. As shown below:

![Figure 4 Transducer](image)

The left side of Figure 4 is the excitation transducer. By applying an excitation signal to the circuit in the PCB board, an eddy current is generated in the board. Under the action of the bias magnetic field of the permanent magnet, the eddy current is subjected to the Lorentz force, which then acts on the metal. The crystalline lattice makes the crystal vibrate to excite the ultrasonic wave in the plate, and the receiving transducer on the right receives the ultrasonic signal in the plate by the same principle.

3.2. Non-destructive testing system integration scheme

The non-destructive testing system includes the Aubo-i5 robotic arm and ultrasonic phased array testing equipment. The Aubo-i5 robotic arm is installed on the base. The currently used ultrasonic non-destructive testing imaging data is to divide the aluminum plate into one area and place it on the edge of this area. The transducer is tested. This ultrasonic phased array uses a circular array, so when dividing the area on the aluminum plate, first manually draw a circle to determine the coordinates of each position. Since the SH0 mode ultrasonic guided wave has the characteristic that the speed hardly changes with the frequency, the SH0 mode is used for detection. However, this mode is directional. When it is fixed on the board and placed in different positions, in addition to adjusting the centripetal position, it is also necessary to ensure that the transducer is always aligned with the center of the circle, so that the conditions are consistent, and there will be no excitation of the transducer. The relative angle of the receiving transducer causes imaging errors.
4. Simulation and experiment

4.1. Implementation of inverse kinematics algorithm
According to the algorithm in section 2 of this article, the corresponding program was written in C++, and the header file kinematic.h and source file kinematic.cpp in the aubo function package were modified accordingly. Then use the modified file as Kinematic Solver in MoveIt! Setup Assistant.

After everything is set up, we can use the POE-based forward and inverse kinematics algorithm to control the robot arm by inputting instructions in the terminal and turning on RVIZ. The number of movement posture changes and movement time can be read from the interface of MoveIt! Setup Assistant.

4.2. Feasibility test of transducer placement
An experimental platform is built with existing experimental instruments, and a mechanical arm is used to test the placement accuracy and speed of the transducer. The robotic arm control platform uses a ROS-based environment for control. The data and speed of the robotic arm are viewed using rviz and the corresponding rostopic. Currently, the coordinates of each placement position are determined by artificially drawing points. Since the center position of the PCB of the transducer cannot be determined, the center position is calibrated by dividing the tangent line and the centripetal line at the placement position, and the angle error between the line on the transducer PCB and the calibration line of the center position is compared to analyze and compare inverse kinematics The accuracy of the algorithm.

Accuracy test experiment is carried out by placing the transducer. The experiment steps: input the coordinate position on the board into the robot arm pose calculation program in advance, calculate the pose through the forward and inverse kinematics method designed above, and then obtain the motion trajectory through the trajectory planning algorithm. Use the input trajectory to first clamp the excitation transducer and place the excitation transducer to a predetermined position; then clamp the receiving transducer and place it to the predetermined signal receiving position, and then perform a nondestructive testing experiment.

The schematic diagram of the experiment placement is shown in Figure 5. It can be seen from Figure 6 that the pose calculated by POE can be placed in a predetermined position, and the error along the radius direction is measured by the line drawn by the transducer PCB board and manually, and then measured along the tangent direction. The error records are shown in Figure 7-9.
From the Figure 7 and 8, the error is controlled within 2.5°. And From Figure 9, we can conclude that the centers of the circles are almost aligned from the two curves basically coincide. However, while rotating along the circumference, the angle of the transducer needs to be improved to make it align with the center of the circle. For the motion of the robotic arm, there is no singularity in the robotic arm grasping, and the grasping can be performed within the range of the aluminum plate.

5. Conclusion
This study is optimized for the automatic placement of ultrasonic probes for non-destructive testing of aluminum plates. The design uses the Aubo-i5 robotic arm to clamp the ultrasonic probes and place them at the predetermined excitation and reception positions. By using the POE algorithm to calculate the pose of the robotic arm, and verify its feasibility through experiments with the gripping and placement of the ultrasound probe. From the experimental data, the error is controlled within 2.5°, and the center of the circle can almost be aligned, but while rotating along the circumference, the angle of the transducer needs to be improved to make it align with the center of the circle. For the motion of the robotic arm, there is no singularity in the robotic arm grasping, and the grasping can be performed within the range of the aluminum plate. It takes an average of 0.053s for the mechanical arm to grab the transducer and place it to the designated position, which is more efficient and accurate than manual placement.

Since the research in this article is a preliminary exploration, the next step can be to visually capture the position of the aluminum plate of the transducer and plan the detection area inside the computer to improve the accuracy and reduce the angle error.
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