Solution to Prehension Movements of Explosive Ordnance Disposal Robot based on Pro/E and ADAMS

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Abstract

After analyzing mechanical arm joint structure, this paper obtained an inverse kinematics equation for positions of arm joints of explosive ordnance disposal (EOD) robots using the vector relationship between different joint positions fixed in an established frame of reference. Pro/E modeling software was used in combination with ADAMS (virtual prototyping software) to simulate the kinematics of a three-dimensional arm model, where the forward solutions to mechanical arm kinematics were acquired. We compared the movement trajectories in forward and inverse simulation. The overlapped trajectories verify the correctness and reliability of the proposed method in the paper. With simple solution steps and intuitive kinematic properties, this method provides meaningful reference for prototype debugging and design in real life.

Key words: mechanical arm, Pro/E software, ADAMS software, movement solution

1. INTRODUCTION

Explosive ordnance disposal (EOD) robots mainly serve in departments of public security, armed police, fire, and military. As professional apparatus in bomb search and disposal operations, they provide support to EOD technicians in terms of searching, grasping, moving, and disposing suspicious explosives under perilous environment (Lee et al., 2016; Bartnickiet al., 2016; Thanakodiet al., 2016). However, through independent control of robot joints, the general operation mode for in-service EOD robots across the globe is so inefficient and difficult that it usually costs long time of training and practice for operators to smoothly manipulate EOD robots to complete various tasks like reach-to-grasp movement (Fracchia et al., 2015; Rowreet al., 2014; Hintonet al., 2013; Fuet al., 2013; Rodriguezet al., 2012). The EOD robot arms can operate easier if we predesign several prehension trajectories. When detecting explosives in expected positions, a sensor controls the mechanical arm to grasp explosives along preset movement trajectories with one button. Reach-to-grasp movement requires at least three joints. The calculation load will be too heavy if mathematical approaches are used to design trajectory and obtain solutions to kinematics equation of joints. In contrast, we can achieve twice the result with half the effort by use of virtual prototyping, which operates towards the dynamic response of mechanical arm joints according to demands on reach-to-grasp movements (Fuet al., 2013; Schooret al., 2012; Zeng et al., 2007). In this paper, after analyzing solutions to arm joint movements, we obtained an inverse kinematics equation for positions of EOD robot arm joints. Pro/E modeling software was used in combination with ADAMS (virtual prototyping software) to simulate the kinematics of a three-dimensional arm model, where the forward solutions to mechanical arm kinematics were acquired. With a case study, we conducted simulation test on movement trajectory solutions, and the result validates the feasibility of the proposed method in this paper.
2. ANALYSIS OF ARM JOINT STRUCTURE

2.1 Structure analysis

Figure 1 shows the sketch map of the arm joint structure. The mechanical structure is composed of the base and a mechanical arm with 2 rotating joints and 1 sliding joint. Long arm BC connects to base AB by a rotating pair centered at B, which constitutes joint 1. Short arm CD and long arm BC are linked by another rotating pair whose center is C, thus becoming joint 2. Joint 3 comprises short arm CD, a pincer, and the sliding pair that connects them. Joint 1 and joint 2 are driven to rotate by servo motor. Joint 3 operates under the force of a push rod driven by servo motor. By controlling the rotating angle of joint 1 and joint 2 as well as the sliding distance of joint 3, we are capable of manipulating the pincer to move along different trajectories.

![Figure 1. The sketch map of the arm joint structure](image)

2.2 Movement solution and analysis

We established a reference frame O-zy, whose origin lies at the center of the base bottom, and a kinematic coordinate system P-z’y’, whose origin is the geometric center of the pincer (Qi et al., 2008; Bozek et al., 2016). The coordinate axis y and AB are collinear. The origin O is located at point A. The coordinate axis z’ is parallel with CD.

By finding the solution of structure movement, we determine drives before defining the movement parameters of output components such as displacement, velocity and acceleration. The key is to decide on the position of output components, because it provides the basis for determination of velocity and acceleration (Cretescu et al., 2016; Krid et al., 2016). Position solution is divided into forward position solution, which comprises the location and posture of the pincer on the premise of known parameters of positions of the three joints, and inverse position solution, which includes the positions of the three joints on the premise of determined location and posture of the pincer.

3. SOLUTION TO ARM JOINT STRUCTURE MOVEMENT

3.1 Inverse position solution

To find the inverse solution of joint positions, we rendered a fixed coordinate for P position, with which the rotating angle $\theta_1$ of joint 1, the rotating angle $\theta_2$ of joint 2, and the sliding distance $L_4$ of joint 3 could be obtained. The position vectors of all rotating joints’ centers and the point D in the kinetic coordinate system were expressed as
\[ D' = (-L_4, 0)^T, \quad C' = (-L_4 - L_3, 0)^T, \quad B' = C' + L_2 \begin{bmatrix} \cos(\theta_2 - \pi/2) \\ \sin(\theta_2 - \pi/2) \end{bmatrix} \]

The position vectors of them in the reference frame were given as

\[ A = (0, 0)^T, \quad B = (0, L_1)^T, \quad C = B + L_2 \begin{bmatrix} \cos(\theta_1 - \pi/2) \\ \sin(\theta_1 - \pi/2) \end{bmatrix} \]

Then, equation (1.1)-(1.3) were used to convert coordinates in the kinetic coordinate system into those in the frame of reference:

\[
B_r = \begin{bmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{bmatrix} B' + \begin{bmatrix} z \\ y \end{bmatrix} \tag{1.1}
\]

\[
C_r = \begin{bmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{bmatrix} C' + \begin{bmatrix} z \\ y \end{bmatrix} \tag{1.2}
\]

\[
D_r = \begin{bmatrix} \cos \theta & -\sin \theta \\ \sin \theta & \cos \theta \end{bmatrix} D' + \begin{bmatrix} z \\ y \end{bmatrix} \tag{1.3}
\]

Where \( \theta \) is the angle between the kinetic coordinate system and the reference frame in plane \( zy \), and the initial position is 0.

Based on the geometric condition that the length of the push rod is fixed, we established the constraint equation of mechanical arm structure (Blasik et al., 2016; Guo et al., 2016; Vishal et al., 2016), and found its solution

\[
f_{1_1} = (C_r - B)^T (C_r - B) - L_2^2 = 0 \tag{2.1}
\]

\[
f_{1_2} = (D_r - C)^T (D_r - C) - L_3^2 = 0 \tag{2.2}
\]

\[
f_{1_3} = (B_r - A)^T (B_r - A) - L_4^2 = 0 \tag{2.3}
\]

We substituted the coordinates and equation (1.1)-(1.3), and acquired

\[
(-L_4 - L_3 + z_p)^2 + (y_p - L_1)^2 - L_2^2 = 0 \tag{3.1}
\]

\[
(-L_4 + z_p - L_2 \cos(\theta_1 - \pi/2))^2 + (y_p - L_1 - L_2 \sin(\theta_1 - \pi/2))^2 - L_3^2 = 0 \tag{3.2}
\]

\[
(-L_4 - L_3 + L_2 \cos(\theta_2 - \pi/2) + z_p)^2 + (y_p + L_2 \sin(\theta_2 - \pi/2))^2 - L_4^2 = 0 \tag{3.3}
\]

Among which each equation is independent. As \( z_p, y_p \) has been given in advance, we calculated the equation (3.1), and obtained

\[
L_4 = z_p - L_3 - \sqrt{(L_2^2 - (y_p - L_1)^2)} \tag{4}
\]
We let \(-L_4+z_p=u;\ y_p-L_1=v;\ -L_4-L_3+z_p=w.\) Then, equation (3.2) and equation (3.3) were converted into
\[
\begin{align*}
(u - L_2 \cos(\theta_1 - \pi/2))^2 + (v - L_2 \sin(\theta_1 - \pi/2))^2 - L_3^2 &= 0 \ (5.1) \\
(w + L_2 \cos(\theta_2 - \pi/2))^2 + (y_p + L_2 \sin(\theta_2 - \pi/2))^2 - L_1^2 &= 0 \ (5.2)
\end{align*}
\]
We extended equation (5.1) and equation (5.2), and obtained
\[
\begin{align*}
2uL_2 \cos(\theta_1 - \pi/2) + 2vL_2 \sin(\theta_1 - \pi/2) + L_3^2 - v^2 - u^2 - L_2^2 &= 0 \ (6.1) \\
2wL_2 \cos(\theta_2 - \pi/2) + 2y_p L_2 \sin(\theta_2 - \pi/2) + w^2 + y_p^2 + L_2^2 - L_1^2 &= 0 \ (6.2)
\end{align*}
\]
Therefore equation (6.1) and equation (6.2) could be simplified as a triangular transcendental equation:
\[
a_i \sin \phi_i + b_i \cos \phi_i + c_i = 0 \]
where\(i=1,2.\)

In equation (6.1) the corresponding coefficient values \(a_i=2vL_2,\ b_i=2uL_2,\ c_i=-L_3^2-v^2-u^2-L_2^2.\) In equation (6.2) the corresponding coefficient values \(a_i=2y_p L_2,\ b_i=2wL_2,\ c_i=w^2+y_p^2+L_2^2-L_1^2.\) They were the known expressions of \(z_p, y_p\) and structure parameters. Therefore,
\[
\theta_i = 2\arctan \left( \frac{a_i \pm \sqrt{a_i^2 + b_i^2 - c_i^2}}{b_i - c_i} \right) + \pi/2 \quad (7)
\]
Thus, when the coordinates of pincer trajectories were predetermined, we could use equation (4) and equation (7) to calculate the rotating angle \(\theta_i\) of joint 1, the rotating angle \(\theta_2\) of joint 2, and the sliding distance \(L_3\) of joint 3.

3.2 Forward position solution

To find the forward solution to joint positions, we calculated the coordinate of pincer center in the center of base bottom in the reference frame when the rotating angles of joint 1 and joint 2 as well as the displacement of joint 3 were given in advance. Corresponding methods such as local polynomial interpolation, mathematical solution to nonlinear equations, and the least square method are sophisticated. A relatively simple technique is the ADAMS-based method, which is expounded below (Blasik et al., 2016; Zhu et al., 2016).

After a three-dimensional mechanical model was built up, we added constraints of edition definitions to the mechanism in ADAMS. The geometric pincer center was chosen as the key point to bear motion force, where a three-dimensional point motion was added. By simulation, the objective measurement function of ADAMS/view was used to measure the rotating angles of joint 1 and joint 2 as well as the sliding distance of joint 3. The obtained measurement curve was plotted into spline, so that acquiring its discrete data point. By applying the AKISPL function to the processed curve in ADAMS, we could select the driving functions for time-varying joint angles and displacements, and further obtained the movement trajectories of the pincer. These trajectories would be edited towards spline functions, and the forward position solution was found accordingly.
3.2.1 Establishment of the mechanical arm model

In Pro/E, we constructed three-dimensional models for the pincer, short arms, the long arm, and the base, respectively. We also assembled them into an integral model, as shown in Figure 2. Table 1 is size parameters.

![Figure 2. The mechanical arm model](image)

<table>
<thead>
<tr>
<th>Parameter</th>
<th>L1</th>
<th>L2</th>
<th>L3</th>
<th>L4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Size</td>
<td>50</td>
<td>300</td>
<td>400</td>
<td>200–500</td>
</tr>
</tbody>
</table>

3.2.2 ADAMS simulation solution

The Pro/E assembly model was imported to ADAMS. The attributes (name, position, material, color, etc.) of and constrains on the pincer, short arms, the long arm, and the base were re-defined. Figure 3 is the renewed model.

![Figure 3. The renewed model in ADAMS](image)

A three-dimensional point motion was added to the pincer center. The relationship equation between the position of the point motion and time was

\[ z = 577 \cos \left( \frac{\pi}{6} - \frac{\pi}{36} t \right) \text{ (mm)} \]

\[ y = 577 \sin \left( \frac{\pi}{6} - \frac{\pi}{36} t \right) \text{ (mm)} \]
A 10s, 2000-step simulation was conducted on the mechanical model. The plot showed that P moved along the preset trajectory, as shown in Figure 4. The objective measurement function of ADAMS/view was used to measure the rotating angles of joint 1 and joint 2 as well as the sliding distance of joint 3, and the result was demonstrated in Figure 5.

![Figure 4. Kinematic simulation](image)

**Figure 4.** Kinematic simulation

![Figure 5. The simulation curves of rotating angles and the sliding distance](image)

**Figure 5.** The simulation curves of rotating angles and the sliding distance

We generated another motion on three joints after invalidating the former motion. With a second 10s, 2000-step simulation, we obtained the new movement trajectory of pincer center. The positions of the pincer center were acquired, whose horizontal and vertical coordinates were respective time and displacement. The corresponding movement trajectories along axis z and axis y were shown in Figure 6. These curves were transformed into spline functions, and the data was the forward position solution.
This simulation result of the same P trajectory as the one in Figure 4 shows that it is correct and feasible to find the forward solutions to mechanical arm movement using the proposed method in the paper.

3.3 Solution to pincer velocity

We calculated the first-order derivative of the displacement curves in Figure 6, and accordingly obtained the corresponding velocity curves, as shown in Figure 7. These curves were transformed into spline functions, and the data was the forward position solution (Madhusoodanan et al., 2012; Ouddhaj et al., 2006; Qureshi et al., 2007).

4. CONCLUSION

After analyzing mechanical arm joint structure, this paper obtained an inverse kinematics equation for positions of EOD robot arm joints. Pro/E modeling software was imported into ADAMS, from which it gained related attributes and constraints defined before simulating the kinematics of a three-dimensional arm model. Under a given motion on pincer
movement trajectory, we plotted the curves of joint angles and sliding displacement. These curve maps were processed into driving functions of the three joints that allowed the pincer to move again. Accordingly, the forward position solution in terms of movement trajectory and velocity was found. Both of the overlapped trajectories verify the correctness and reliability of the proposed method in the paper, from which the movement property of mechanical arms is animated directly. This method provides meaningful reference for prototype debugging and design in real life. It saves time for scientists and researchers, and reduces the cost of research and development of EOD robots.

5. REFERENCES


