Study of Industrial Robot Numerical Control Program Based on Stationary Tool Control

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Abstract. Six-axis robotic manipulators continue to play a vital role in the development of industrial automation worldwide. Mechanical arms incorporated with computer-aided design and manufacturing systems have gradually received attention in the field of manufacturing. This study adopted the Denavit-Hartenberg notation to construct a kinematic model of the FANUC M-20iA/20M six-axis robot manipulator configuration with stationary point control. Visual C# was employed to develop the transformation interface which converts the tool path files generated from Unigraphics NX software into readable robotic manipulator formats. This study adopted FANUC ROBOGUIDE simulation software for further verification and comparison. The results validate the proposed scheme.

Introduction

Robot manipulators can move fast with high accuracy and reliability, as well as replace humans in high-risk and highly repetitive work, such as in high temperatures and harsh environments. Therefore, they are widely used in various automated production lines. As the development of related technologies matures, the application of robot manipulators to manufacturing, for example, in welding, painting, handing, grinding, and polishing is increasing. A simple robotic manipulator path can be planned using a point-to-point teaching mode. However, if a complex surface machining path is planned using a teaching mode, not only is the efficiency low but the surface precision and quality are relatively reduced. Consequently, robotic manipulator computer-aided design and manufacturing (CAD/CAM) systems have gradually gained attention. Commercial robotic software such as SprutCAM \cite{1}, Robotmaster\textsuperscript{®}\cite{2} can generate a robot numerical control program for complex and irregular curved objects, but they are expensive.

A typical robot manipulator machining mode involves an end-effector holding a tool and teaching the tool center point to machine a workpiece. The manipulator may have an excessive swing range depending on the shape of the workpiece. In addition, if the robot is incorporated with an external linear axis and a rotary axis for processing, the cutting range can be improved and the possibility of excessive swinging of the manipulator can be reduced. However, the cost of the related software and device is high. Conversely, if the workpiece is clamped on the robot’s flange and the tool is fixed to the ground, the robot can process the workpiece with stationary tool control. This can reduce the possibility of excessive tilting posture without requiring an external axis device, making the manipulator more flexible in production and processing.

This study develops a six-axis robotic tool path NC program conversion interface with stationary tool control. The forward kinematics model of the FANUC M-20iA/20M robot \cite{3} is based on the Denavit-Hartenberg (D-H) notation matrix \cite{4}. The cutter location file is generated by a Unigraphics NX system, which includes tool tip position, tool axis vector, and contact point data, and is transformed to the pose of the robot’s flange relative to the base frame and further expressed as Euler
angles. The transformed robot pose data is verified in the FANUC ROBOGUIDE [5] simulation software to validate the proposed algorithm.

**Robot Forward Kinematics**

Robot forward kinematics involves finding the pose (position and orientation) of the end-effector relative to the base and providing the values of the joint variables and the geometric link parameters. The end-effector is any object that attaches to the robot’s flange (wrist), such as grippers, deburring tools, and many other types of tooling. To specify the pose of the robot’s flange, the coordinate system should be established. Figure 1 presents the configuration and coordinate systems of the FANUC M-20iA/20M robot. To fully specify the pose of each link, the D-H notation is introduced. A set of D-H parameters is used to describe the spatial relationships between a joint axis and its two neighbor joint axes. The pose link \(i\) with respect to link \(i-1\) can be defined in terms of the link length \(a_i\), joint distance \(d_i\), link twist angle \(\alpha_i\) and joint angle \(\theta_i\) as

\[
^{i-1}A_i = \text{Rot}(z, \theta_i)\text{Trans}(0,0,d_i)\text{Trans}(a_i,0,0)\text{Rot}(x,\alpha_i)
\]

where \(\text{Rot}\) and \(\text{Trans}\) are the rotation and translation matrix, respectively. The corresponding kinematics parameters of the robot are summarized in Table 1. Because the actual joint angles of FANUC M-20iA/20M illustrated in Figure 1 are \((0, -90°, 0, 0, 0, 0)\), the joint angles of the D-H parameters should be modified as \((\theta_1, \theta_2 - 90°, \theta_3, \theta_4, \theta_5, \theta_6)\).

![Figure 1. Configuration and coordinate systems of the FANUC M-20iA/20M robot.](image)

The pose matrix of the link 6 frame with respect to the base frame, which is known as the robot forward kinematics and denoted by \(^{0}A_6\), can be determined by concatenating the transformations between the fixed frames of the adjacent links:

\[
^{0}A_6 = ^{0}A_1^{1}A_2^{2}A_3^{3}A_4^{4}A_5^{5}A_6
\]

| Link \(i\) | \(a_i\) (mm) | \(d_i\) (mm) | \(\alpha_i\) (°) | \(\theta_i\) (°) |
|-----------|-------------|-------------|----------------|----------------|
| 1         | 150         | 525         | -90            | 0              |
| 2         | 790         | 0           | 180            | -90            |
| 3         | 150         | 0           | 90             | 0              |
| 4         | 0           | 860         | -90            | 0              |
| 5         | 0           | 0           | 90             | 0              |
| 6         | 0           | 100         | 0              | 0              |
Coordinate Transformation for Stationary Tool Control

When deburring tools or arc welding guns are attached to the robot’s flange, the robot can perform the machining process on the workpiece. If the workpiece is clamped on the flange of the sixth of the robot, the control mode is called external tool center point (TCP) control or stationary tool control. The robot can move the workpiece linearly or circularly with respect to the stationary point and perform multi-orientation for workpiece polishing without an additional rotary axis. A robot with a stationary tool is a cost-efficient alternative to 360° milling compared with a robot using an external rotary axis. The relevant coordinate frames for stationary tool control are presented in Figure 2. The coordinate frames are associated with objects and features of interest in this control mode where frames \((XYZ)_{Tcp}\), \((XYZ)_{Base}\), \((XYZ)_{Flange}\), and \((XYZ)_{Prog}\) are attached to the external TCP point, robot base, robot flange, and the program origin of the tool path. In addition, frame \((XYZ)_{Tp}\) is attached to the cutter contact point generated by the CAM system. Most current CAD/CAM systems can produce the cutter location data including cutter tip location and tool axis. To represent the robot pose by frame \((XYZ)_{Tp}\) using the cutter location data, two mutually orthogonal unit vectors should be determined [6]. The goal of the stationary tool control is to determine the transformation relating the flange frame to the base frame and can be expressed as:

\[
A_{Base Flange} = A_{Base Tp} A_{Tcp} A_{Prog} A_{Flange}
\]

Once the transformation matrix \(A_{Base Flange}\) is obtained, the six joint angles \((\theta_1, \theta_2, \theta_3, \theta_4, \theta_5, \theta_6)\) of the robot can be determined using Eq. (2) and Eq. (3), and the inverse kinematics.

Results and Verification

To demonstrate the feasibility of the proposed scheme, a window-based robot program transformation interface was developed. Cutter location data was generated using Unigraphics NX software and
converted to the robot NC program based on stationary tool control. Figure 3 shows a screenshot of the transformation execution dialogue. The user can enter the pose transformation data that relates two frames. For example, the program origin of the tool path \((XYZ)_{\text{prog}}\) frame relative to the external TCP point frame (position and orientation) was \(X: 9.324\) mm, \(Y: -10.235\) mm, \(Z: 96.145\) mm, \(W: -153.435^\circ\), \(P: 24.095^\circ\), and \(R: -29.232^\circ\) where \(W, P\) and \(R\) are the ZYX Euler angles for the FANUC controller. Eq. (4) represents the desired pose matrix \(A_{\text{flange}}\) according to Eq. (3). The corresponding position and orientation values as well as six joint angles calculated by inverse kinematics were \(X: 1122.414\) mm, \(Y: 18.594\) mm, \(Z: 1034.533\) mm, \(W: 125.395^\circ\), \(P: 13.193^\circ\), \(R: 178.207^\circ\); \(J1: -3.231^\circ\), \(J2: 8.193^\circ\), \(J3: -16.027^\circ\), \(J4: -60.208^\circ\), \(J5: -70.536^\circ\), and \(J6: -147.365^\circ\).

\[
A_{\text{flange}} = \begin{bmatrix}
-0.97313 & -0.1678345 & 0.1576376 & 1122.414 \\
0.0304646 & 0.5847512 & 0.8106405 & 18.594 \\
0.2282322 & 0.793661 & 0.5639259 & 1034.533 \\
0 & 0 & 0 & 1
\end{bmatrix}
\]

Figure 3. Execution dialogue of the developed interface.
The pose transformation data were further entered into the ROBOGUIDE software, which is a FANUC simulation software and a system animation tool specifically developed for the production and maintenance of FANUC robot systems. Using ROBOGUIDE, a virtual 3D robot layout environment can be established by importing CAD models of parts, fixtures, machine tools, and work cells. Figure 4(a) illustrates the setup pose transformation data $A_{Tcp}^{Base}$ and $A_{Prog}^{Flange}$ in ROBOGUIDE. Figure 4(b) shows how the workpiece can be correctly machined with stationary tool control using the transformed pose data, demonstrating the feasibility of the proposed scheme.

Conclusions

This paper presented a robot numerical control programming interface with stationary tool control for the FANUC M-20iA/20M robot configuration. The six joint angles of the robot can be determined through forward and inverse kinematics based on D-H notation. A window-based robot interface built using Visual C# language can convert the tool path files generated from Unigraphics NX software into readable robot NC formats. The validity of the generated robot NC program was confirmed through verification using the simulation software ROBOGUIDE.

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