Inverse Kinematics-Based Trajectory Generation For Robot-Assisted 3D Surface Machining

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Abstract

Machining and tracking of 3D surfaces using industrial robot is not a new method, but the new in this paper is the use of simple trigonometric relations in the calculations of robots joints variables by using the inverse kinematics approach rather than the previous conventional methods like forward kinematics, decoupling, and sensor based machining. Calculations of the joints variables are mainly based on knowing the robot reference point (origin point) and the coordinates of the tip of the end effectors which is the cutter contact point (CC-P) at the surface. The coordinate of the cutter location point (CL-P) is the coordinate of the normal vector that passing through the intended cutter contact point. The joints variables are calculated based on simple trigonometric relationships. The results of the proposed method are verified based on hand-made simulation programs organized for this purpose. The simulation results explore the high accuracy and efficiency of the proposed method and its high speed in prediction of joints variables.

Keywords 3D surface machining, Inverse Kinematics, Surface tracking, CL-Points, CC-Points, NURBS surface, Tool Path Generation.

1. Introduction

Using industrial robot in tracking a 3D contours is a widely used method in recent industry [1-4]. The machining of 3D surfaces is usually done on 3-axes or 5-axes
CNC milling machines [5]. The main objective of using robot instead of CNC machines in machining or finishing of 3D surfaces is to increase the machining flexibility thought increasing the degree of freedom DOF. The previous works related to the use of robots in 3D contour tracking which utilizes the inverse kinematics method were based on converting the transformation matrices to a system of explicit equations or based on decoupling methods [6,7]. These methods are iterative and hence they are unstable from the numerical point of view and they are not easy to be solved especially for 3 or more than 3 DOF. Fortunately, the machining of 3D surfaces with the aid of robots not -in general- requires a force or moment sensors to In this paper a new method for using a 6 degree of freedom (6-DOF) articulated robot is used for the machining of 3D surfaces. The method is based on position control alone utilizing the cutter contact data CC-data of the surface to be machined and cutter location data CL-data of the end-effector. The proposed method uses the trigonometric relations to extract the joints variables. Therefore, a unique solution can be obtained for each CL-data rather than many solutions obtained by previous iterative methods.

2. The Proposed Setup and Machining Strategy
The proposed articulated machining robot is the same as the well known industrial articulated robots which is also known as anthropomorphic arm as it is closely resembles the human arm [10]. The proposed setup of the machining robot is shown in Fig.2. In this setup a toroidal cutter is attached to the end effector enabling it tracking the required contour and rotating though a suitable cutting speed. The robot reference point (RRP) is coincide with the origin of the global coordinate system (0,0,0) , while the work piece reference point (WRP) is located so that the end effector can reach any point in the designed surface. The zigzag motion is the trajectory fashion nominated in this paper due to its simplicity and widely used compared with the other tool motion strategies as shown in Fig.3. The machining tool firstly sinks at the WRP and directed to move along the forward motion (red paths) towards point P₂ (see Fig.2). The tool is then reverses its motion towards the point P₃ to follow the cross motion and so on till the cutting tool finishes its motion at point P₂₂.

3. The Proposed Inverse Kinematics Method
The proposed inverse kinematics method is purely based on trigonometric relationships of the given reference frame (robots arms). Therefore the geometrical approach is used for solving the positioning problem rather than inverse matrices transformations method which entails iterative search method which leads to multiple solutions. The proposed geometrical method has a closed form solution; hence, it gives a unique solution for a given CL-data. Therefore, the closed form solution is preferable in 3D curve/surface tracking [11]. In our inverse

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kinematics method the knowing variables are (see Fig.4):

\[ \mathbf{R}_k = [ \mathbf{a} \; \mathbf{b} \; \mathbf{c} \; \mathbf{d} \; \mathbf{P}_o \; \mathbf{CC-P} ] \] ...(1)

Where: \( a, b, \) and \( c \) are the lengths of the robots arms, \( d \) is the length of the end effector (containing the unclamped tool length), \( \mathbf{P}_o \) and \( \mathbf{CC-P} \) is the position vector of the robot reference point RRP and the given cutter contact point (CC-P) on the required surface.

The required four unknown variables are:

\[ \mathbf{\bar{R}}_u = ( \alpha \; \beta \; \gamma \; \mathbf{P}_2 ) \] ...(2)

Where: \( \alpha, \beta, \gamma \) are the shoulder, elbow and wrist angles joint respectively.

The following steps are followed to find the unknown variables of the final configuration.

3.1 Surface Generation and Cutter Location Data CL-Data Extraction

The NURBS surface is used for the generation of the required 3D parametric surface due to its widely used in CAGD. The required 3D NURBS surface is constructed using MATLAB programming environment according to the following mathematical format [12]:

\[
S(u,v) = \sum_{i=0}^{p} \sum_{j=0}^{q} B_{i+m}(u) B_{j+n}(v) \mathbf{P}_{i,j} w_{i,j} \\
\sum_{i=0}^{p} \sum_{j=0}^{q} B_{i+m}(u) B_{j+n}(v) w_{i,j} 
\] .......(3)

Where \( p,q \) are the number of control points (4 in this study), \( \mathbf{P}_{i,j} \) is the control points, \( w_{i,j} \) the weight being associated with them, and \( B_{i,n} \) is the basis function defined by:

\[
B_{i,0}(t) = \begin{cases} 1 & \text{if } t_{i-1} \leq t < t_{i} \\ 0 & \text{else} \end{cases}
\]

\[
\forall k > 0, B_{i,k}(t) = \frac{t-t_{i}}{t_{i+k}-t_{i}} B_{i,k-1}(t) + \frac{t_{i+k+1}-t}{t_{i+k+1}-t_{i+1}} B_{i+1,k-1}(t)
\]

The cutter contact data CC-Data are generated based on isoperimetric decartelization approach [13]. The decartelization isoparametric increment are \( \Delta u = \Delta v = 0.05 \), accordingly the whole surface is descretized to 441 CC-point, 21 forward paths and 20 traverse paths as shown in Fig.5. To generate the cutter location data (CL-Data), the normal vector at each cutter contact point CC-point must be determined. The CC-Data is then translated along the unit normal vector at a distance equal to the length of the end effector (d) as follows (see Fig.4):

\[
\mathbf{CLP} = \mathbf{S}(u,v) + d.\mathbf{N} 
\] .......(4)

\[
\mathbf{N} = \frac{\partial \mathbf{S}}{\partial u} \times \frac{\partial \mathbf{S}}{\partial v} = \left| \begin{array}{c} \frac{\partial S}{\partial u} \\ \frac{\partial S}{\partial v} \\ \frac{\partial S}{\partial v} \end{array} \right| 
\] .......(5)

Where \( \mathbf{S}(u,v) \) is the instantaneous cutter contact point, \( \mathbf{N} \) is the unit normal vector and \( \frac{\partial \mathbf{S}}{\partial u}, \frac{\partial \mathbf{S}}{\partial v} \) is first partial derivative of the NURBS
surface with respect to the parameter \( u \) and \( v \) respectively. It is worth pointing that translating the CC-point along with the normal vector guarantee the perpendicularly of the tool over the surface.

### 3.2 Calculation of the Robot’s Arms Orientations

The joints variables \( \mathcal{R}_u = [a \; \beta \; \gamma \; \rho] \) of the general situation of the robot’s arms (see Fig.6) can be calculated according the following trigonometric formulation (see Fig.6):

\[
\alpha = 90 + \phi + \Omega \quad \cdots (6)
\]

\[
\beta = 180 - \eta \quad \cdots (7)
\]

\[
\gamma = \text{arc} \cos \left( \frac{V_x V'_2}{\|V_1\| \|V_2\|} \right) \quad \cdots (8)
\]

Now we are about finding \( \phi, \Omega, \eta \) to find the required joints variables \( \mathcal{R}_u \). Applying Cosine’s law to the triangle \( P_1P_2CL-P \) gives:

\[
L^2 = b^2 + c^2 - 2bc \cos(\beta) \quad \cdots (9.a)
\]

or

\[
L^2 = b^2 + c^2 + 2bc \cos(\eta) \quad \cdots (9.b)
\]

\[
\therefore \eta = \text{arc} \cos \left( \frac{L^2 - b^2 - c^2}{2bc} \right) \quad \cdots (9.c)
\]

Substituting Eq.9.c in Eq.7 yields:

\[
\beta = 180 - \text{arc} \cos \left( \frac{L^2 - b^2 - c^2}{2bc} \right) \quad \cdots (10)
\]

Applying the Sine law to the same triangle gives:

\[
\frac{\sin(\Omega)}{c} = \frac{\sin(\beta)}{L} \quad \cdots (11.a)
\]

\[
\therefore \Omega = \text{arc} \sin \left( \frac{c \sin(\beta)}{L} \right) \quad \cdots (11.b)
\]

Substituting Eq.10 in Eq.11.b yields:

\[
\Omega = \text{arc} \sin \left( \frac{c \sin(180 - \text{arc} \cos \left( \frac{L^2 - b^2 - c^2}{2bc} \right))}{L} \right) \quad \cdots (11.c)
\]

\[
\phi = \arctan \left( \frac{L_1}{L_2} \right) \quad \cdots (11.d)
\]

\[
L_1 = \left| Z_{CLP} - Z_R \right| \quad \cdots (11.e)
\]

\[
L_2 = \left| X_{CLP} - X_R \right| \quad \cdots (11.f)
\]

Substituting Eq.11.f and Eq.11.e in Eq.11.d gives:

\[
\alpha = 90 + \arctan \left( \frac{Z_{CLP} - Z_R}{X_{CLP} - X_R} \right) + \arcsin \left( \frac{c \sin(180 - \text{arc} \cos \left( \frac{L^2 - b^2 - c^2}{2bc} \right))}{L} \right) \quad \cdots (12)
\]

To find the elbow joint variable \( \gamma \) it is necessary to find the coordinates of the elbow joint as follows:

\[
X_R = b \cos(\phi + \Omega) \quad \cdots (13.a)
\]
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\[ Y_{\text{p}} = b \cdot \sin(\phi + \Omega) \quad \ldots (13.\text{b}) \]
\[ \dot{V}_1 = \text{CLP} - \dot{P}_2 \quad \ldots (13.\text{c}) \]
\[ \dot{V}_2 = \dot{P}_1 - \dot{P}_2 \quad \ldots (13.\text{d}) \]

Equation 13.c and 13.d can be used with the aid of Eq.8 to find the elbow orientation (\( \gamma \)). It is worth pointing out that our mathematical formulation is a function of two variables namely: the cutter location points CL-P and the length between the shoulder joint and wrist joint (L) (see Fig.6). Accordingly the experimental runs show that the joint variables \( \lambda \) can be updated very fast within 0.187 second which is a very important task in contour tracking using robot.

3.3 Singularity

It is worth noting that from previous mathematical formulation and some other equations that the following deliverance condition should be satisfied to avoid singularity:

\[ \frac{L^2 - b^2 - c^2}{2bc} \geq 1 \quad \ldots (14.\text{a}) \]
\[ \therefore 2bc \geq L^2 - b^2 - c^2 \quad \ldots (14.\text{b}) \]
\[ \text{let } b = \lambda_1 L; c = \lambda_2 L \quad \ldots (14.\text{c}) \]
\[ \therefore 2bc = 2\lambda_1\lambda_2 L^2; \quad \& \]
\[ L^2 - b^2 - c^2 = L^2 - \lambda_1^2 L^2 - \lambda_2^2 L^2 
\]
\[ …(14.\text{d}) \]
Substituting Eq.14.d in Eq.14.b gives:

\[ 2\lambda_1\lambda_2 \geq 1 - \lambda_1^2 - \lambda_2^2 \quad \ldots (14.\text{e}) \]

Let \( \lambda_1 = \lambda_2 = \lambda \) so that \( a=b \), this will lead to:

\[ \lambda \geq 0.5 \Rightarrow b = c = 0.5L \]
\[ \ldots \ldots (14.\text{f}) \]

Since that L is variable and depend upon the joints variables (see Eq.9) and to ensure machining the whole surface, the length of the arms a and b should be related to the longest L. Therefore the arm's length is selected to be 725 mm as the maximum length (\( L=1400 \) mm) according to our 3D surface.

4. Implementation and Results

In order to explore and test the validity and efficiency of the proposed inverse kinematics method an experimental example has been presented as follows:

4.1 Surface and Tool Path Generation

The proposed inverse kinematics approach is tested and applied to a 3D NURBS surface shown in Fig.5. The required surface is generated using MATLAB programming software while the required zigzag tool path using linear interpolation is generated using the well known professional CAD/CAM software UGS NX 5.0. The selected scallop height is 0.254 mm to attain 0.05 mm chordal deviation.

Table 1 shows the technical parameter of the robot used to machine the intended surface (for the simulation purposes). The cutting tool diameter (\( D=10 \) mm) is selected to avoid gauging so that its diameter is smaller than the
minimum Gaussian radius of curvature over the whole surface.

4.2 Results Verification
In order to verify the results of our inverse kinematics method, the forward kinematics method is used. To insure that the tip of the end effector (milling cutter) touch the surface at each given CC-P for a given joint variable, the well known forward kinematics procedure is used. The results of the joints variables of the designed surface based on the aforementioned discretization approach (section 2.1) are listed in Table 2. There is no error measured between the calculated position of the end effector and the verified position.

4.3 Performance Simulation
The purpose of the robot simulation is to evaluate how the robot will react to the calculated joints variables. The proposed simulation method is realized utilizing MATALB software. The cutter contact file, cutter location file, and the joints variables are processed and the Figure 7 shows the output of the UG software and the selected machining parameter. The coordinates of the five positions shown above in the previous Fig.6 are shown in previous Table 2. This table also includes the joint variables calculated through applying the proposed inverse kinematics approach (Eqs.6-13). In order to verify these results, the system of verification equations (see Appendix A) is used and the coordinates are listed in the same table. The verification results reflect the robustness of our inverse kinematics approach in the extraction of joints variables from the given robot’s tip position.

5. Conclusions
An inverse kinematics approach was proposed in this paper in order for machining of 3D surfaces rather than the use of CNC milling machine. From the experimental runs it could be concluded that very small time is needed for the calculations of the joints variable (0.187s). The gathered results show the accuracy of the proposed method where the error between the required and verified CC-P is zero for all the end effector positions. The use of industrial robot in the machining of 3D surfaces facilitates the machining process compared with the ordinary CNC milling machine. The verification results exhibit the high precision in the calculations of the joints variable from the given CL-data. The proposed method establishes for the concept of portable milling machine which very important task for many industries such as marine applications.

Appendix A
The forward kinematics equations used to verify the results of the proposed inverse kinematics method.
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\[X_{CCP} = [b.\cos(\phi + \Omega) + c.\cos(\phi + \Omega + \eta) + d.\cos(180 + \phi + \Omega + \eta - \gamma)].\cos(\zeta)\]
\[Y_{CCP} = [b.\cos(\phi + \Omega) + c.\cos(\phi + \Omega + \eta) + d.\cos(180 + \phi + \Omega + \eta - \gamma)].\sin(\zeta)\]
\[Z_{CCP} = [b.\sin(\phi + \Omega) + c.\sin(\phi + \Omega + \eta) + d.\sin(180 + \phi + \Omega + \eta - \gamma)]\]

References
Table (1) The Experimental Technical Parameters of the Proposed Robot.

<table>
<thead>
<tr>
<th>a (mm)</th>
<th>b (mm)</th>
<th>c (mm)</th>
<th>d (mm)</th>
<th>D (mm)</th>
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<td>700</td>
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Table (2) The Results and Verifications of the Joints Variables of the Five Positions Shown in Fig.6.

<table>
<thead>
<tr>
<th>#</th>
<th>X</th>
<th>Y</th>
<th>Z</th>
<th>φ + Ω</th>
<th>η</th>
<th>γ</th>
<th>ζ</th>
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<th>Y</th>
<th>Z</th>
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</table>
Figure (1) Deburring of 3D surfaces.

Figure (2) The Proposed Setup of the Machining Robot, (a) Front View, (b) Top View.
Figure (3) The Proposed Zig-Zag Tool Path Method.

Figure (4) Schematic Representation of the Proposed Robot Showing the Known and
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Figure (5) The Descretization method of the 3D Surface Showing the CL-Points and Surface Normal.

Figure (6) The Joint’s Variables in General Situation and their Notations
Figure (7) Simulation the Results of the Robot's Arms Positions at Different Locations.

Figure (8) The tool path and the machining parameter using UG system