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Accuracy allocation method for five-axis machine tools based on geometric error cost sensitivity prioritizing tool direction deviation

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S1 Geometric error modeling of five-axis machine tools

In WCS, the error matrix E for tool positioning can be calculated as:

$$\boldsymbol{E}={}^{\mathrm{T}}_{\mathrm{W}}\boldsymbol{T}^{\mathrm{r}}-{}^{\mathrm{T}}_{\mathrm{W}}\boldsymbol{T}^{\mathrm{i}}, \tag{S1}$$

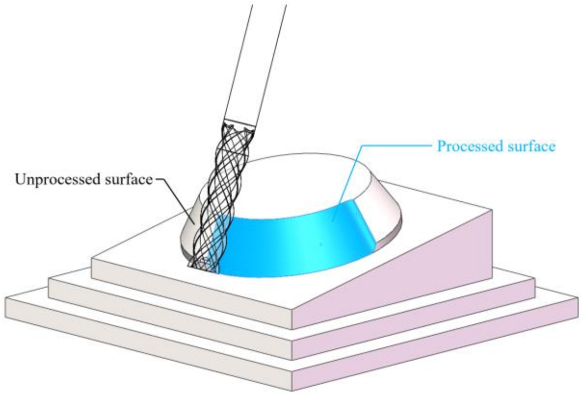
where ${}^{\mathrm{T}}_{\mathrm{W}}T^{\mathrm{r}}$ is the actual transformation matrix from the tool coordinate system to the workpiece coordinate system, and ${}^{\mathrm{T}}_{\mathrm{W}}T^{\mathrm{i}}$ is the ideal transformation matrix from the tool coordinate system to the workpiece coordinate system. Based on the machine tool configuration and coordinate system rules used in this study and the homogeneous transform matrix (HTM) method, ${}^{\mathrm{T}}_{\mathrm{W}}T^{\mathrm{r}}$ can be calculated by as follows:

$$\begin{aligned}
{}^{\mathrm{T}}_{\mathrm{W}}\boldsymbol{T}^{\mathrm{r}}=\Bigg(&\begin{bmatrix}1&0&0&o_{\mathrm{BX}}\\0&1&0&0\\0&0&1&o_{\mathrm{BZ}}-360\\0&0&0&1\end{bmatrix}\begin{bmatrix}1&-S_{\mathrm{BX}}&0&0\\S_{\mathrm{BX}}&1&S_{\mathrm{BZ}}&0\\0&-S_{\mathrm{BZ}}&1&0\\0&0&0&1\end{bmatrix}\begin{bmatrix}\cos B&0&\sin B&0\\0&1&0&0\\-\sin B&0&\cos B&0\\0&0&0&1\end{bmatrix}\\
&\begin{bmatrix}1&-\varepsilon_{\mathrm{ZB}}&\varepsilon_{\mathrm{YB}}&\delta_{\mathrm{XB}}\\\varepsilon_{\mathrm{ZB}}&1&-\varepsilon_{\mathrm{XB}}&\delta_{\mathrm{YB}}\\-\varepsilon_{\mathrm{YB}}&\varepsilon_{\mathrm{XB}}&1&\delta_{\mathrm{ZB}}\\0&0&0&1\end{bmatrix}\begin{bmatrix}1&0&0&o_{\mathrm{CX}}\\0&1&0&o_{\mathrm{CY}}\\0&0&1&-140\\0&0&0&1\end{bmatrix}\begin{bmatrix}1&0&-S_{\mathrm{CX}}&0\\0&1&-S_{\mathrm{CY}}&0\\S_{\mathrm{CX}}&S_{\mathrm{CY}}&1&0\\0&0&0&1\end{bmatrix}\begin{bmatrix}\cos C&-\sin C&0&0\\\sin C&\cos C&0&0\\0&0&1&0\\0&0&0&1\end{bmatrix}\\
&\begin{bmatrix}1&-\varepsilon_{\mathrm{ZC}}&\varepsilon_{\mathrm{YC}}&\delta_{\mathrm{XC}}\\\varepsilon_{\mathrm{ZC}}&1&-\varepsilon_{\mathrm{XC}}&\delta_{\mathrm{YC}}\\-\varepsilon_{\mathrm{YC}}&\varepsilon_{\mathrm{XC}}&1&\delta_{\mathrm{ZC}}\\0&0&0&1\end{bmatrix}\Bigg)^{-1}\begin{bmatrix}1&0&0&X\\0&1&0&0\\0&0&1&0\\0&0&0&1\end{bmatrix}\begin{bmatrix}1&-\varepsilon_{\mathrm{ZX}}&\varepsilon_{\mathrm{YX}}&\delta_{\mathrm{XX}}\\\varepsilon_{\mathrm{ZX}}&1&-\varepsilon_{\mathrm{XX}}&\delta_{\mathrm{YX}}\\-\varepsilon_{\mathrm{YX}}&\varepsilon_{\mathrm{XX}}&1&\delta_{\mathrm{ZX}}\\0&0&0&1\end{bmatrix}\\
&\begin{bmatrix}1&0&0&-Y\times S_{\mathrm{XY}}\\0&1&0&Y\\0&0&1&0\\0&0&0&1\end{bmatrix}\begin{bmatrix}1&-S_{\mathrm{XY}}&0&0\\S_{\mathrm{XY}}&1&0&0\\0&0&1&0\\0&0&0&1\end{bmatrix}\begin{bmatrix}1&-\varepsilon_{\mathrm{ZY}}&\varepsilon_{\mathrm{YY}}&\delta_{\mathrm{XY}}\\\varepsilon_{\mathrm{ZY}}&1&-\varepsilon_{\mathrm{XY}}&\delta_{\mathrm{YY}}\\-\varepsilon_{\mathrm{YY}}&\varepsilon_{\mathrm{XY}}&1&\delta_{\mathrm{ZY}}\\0&0&0&1\end{bmatrix}\\
&\begin{bmatrix}1&0&0&-(Z+360)\times S_{\mathrm{XZ}}\\0&1&0&-(Z+360)\times S_{\mathrm{YZ}}\\0&0&1&Z\\0&0&0&1\end{bmatrix}\begin{bmatrix}1&0&-S_{\mathrm{XZ}}&0\\0&1&-S_{\mathrm{YZ}}&0\\S_{\mathrm{XZ}}&S_{\mathrm{YZ}}&1&0\\0&0&0&1\end{bmatrix}\begin{bmatrix}1&-\varepsilon_{\mathrm{ZZ}}&\varepsilon_{\mathrm{YZ}}&\delta_{\mathrm{XZ}}\\\varepsilon_{\mathrm{ZZ}}&1&-\varepsilon_{\mathrm{XZ}}&\delta_{\mathrm{YZ}}\\-\varepsilon_{\mathrm{YZ}}&\varepsilon_{\mathrm{XZ}}&1&\delta_{\mathrm{ZZ}}\\0&0&0&1\end{bmatrix},
\end{aligned} \tag{S2}$$

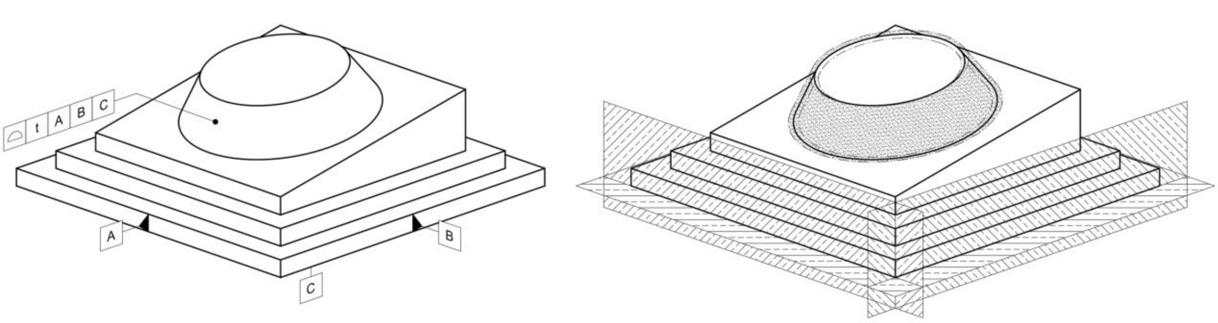
where X, Y, Z, B, and C represent the feed values of the five axes of the machine tool. The ideal transformation matrix ${}^{\mathrm{T}}_{\mathrm{W}}\boldsymbol{T}^{\mathrm{i}}$ can be calculated by setting all 41 error values equal to zero in Eq. (2). By accounting for the coordinates of the tool tip point $\boldsymbol{P}=[0,0,-L,1]^{\mathrm{T}}$ and the tool vector coordinates $V=[0,0,1,0]^{\mathrm{T}}$ in the tool coordinate system, the positional deviation $\boldsymbol{\Delta P}$ and tool direction deviation $\boldsymbol{\Delta V}$ for tool positioning can be calculated by:

$$[\boldsymbol{\Delta P}, \boldsymbol{\Delta V}] = \begin{bmatrix} \Delta P_{\mathrm{x}} & \Delta V_{\mathrm{x}} \\ \Delta P_{\mathrm{y}} & \Delta V_{\mathrm{y}} \\ \Delta P_{\mathrm{z}} & \Delta V_{\mathrm{z}} \\ 0 & 0 \end{bmatrix} = \boldsymbol{E} \cdot \begin{bmatrix} 0 & 0 \\ 0 & 0 \\ -L & 1 \\ 1 & 0 \end{bmatrix}, \tag{S3}$$

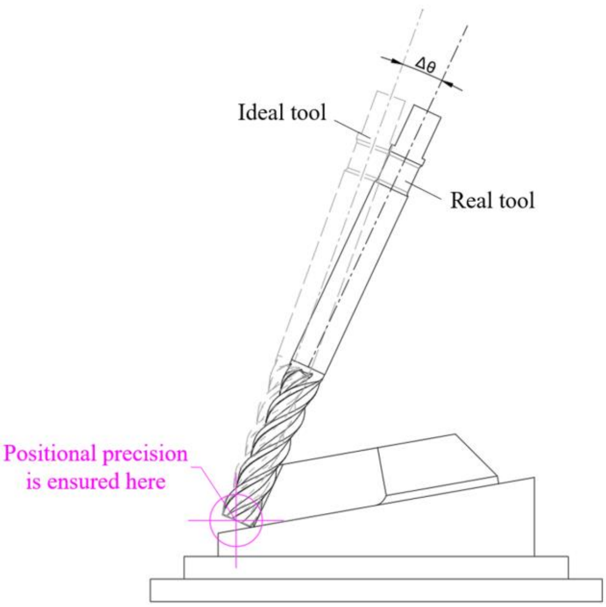
where ΔP_{x}, ΔP_{y}, and ΔP_{z} are the components of the positional deviation in the X, Y, and Z directions, respectively, and ΔV_{x}, ΔV_{y}, and ΔV_{z} are similarly the components of the tool direction deviation in these directions. $\boldsymbol{E}$ is the error matrix obtained from Eq. (1), and L is the length of the tool.



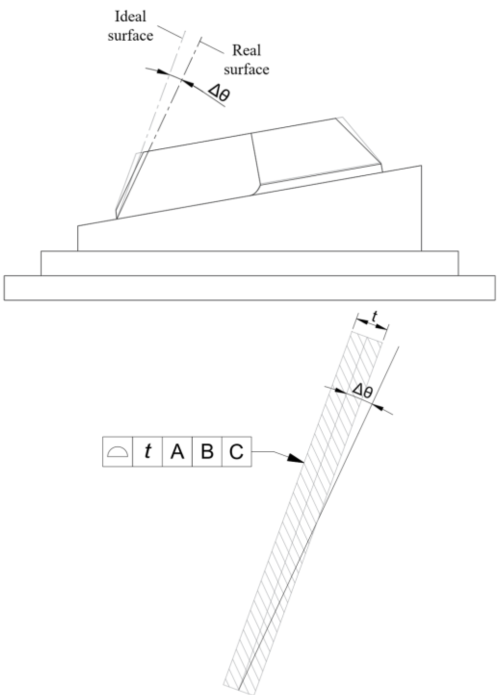
(a) Processing an inclined conical workpiece



(b) Surface profile requirements and tolerance zone indication of the inclined cone



(c) Ideal and real processing conditions



(d) Surface profile that fails to meet the GD&T requirements

Fig. S1 Influence of tool direction precision in five-axis flank milling