Simulation and compensation of the thermal behaviour of industrial robots

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Abstract

Industrial robot systems offer a flexible, adaptable basis due to their kinematics and their mobility. An influencing variable, which is particularly relevant for processes with long process times \( t_P \), is the thermal heating and the associated thermal drift \( \Delta AP \) of the tool center point. The maximum deviation from the actual nominal position can reach up to \( \Delta AP = 1.5 \) mm. In the investigations, a simulation model for an industrial robot was created and the thermal behaviour was mapped. With this model, the thermal error \( \Delta AP \) within the working area can be determined as a function of the current position \( X \) and temperature \( \theta \). These data can be used for a targeted correction of the robot path. With the correction by the compensation model the amount of drift for real milling processes could be reduced to a value of \( \Delta AP = 0.042 \) mm. The results can help to reduce the influence of thermal heating and the associated thermal drift \( \Delta AP \) of the TCP without using cost-intensive measures with additional hardware and software on external computers for compensating the errors.

Accuracy, Simulation, Robot, Thermal Error

1. Introduction

In the last decade, robotic machining has evolved from a basic research topic to a production technology for industrial use [1]. Various disturbances occur during robot-guided milling. These disturbances have a considerable influence on the accuracy \( AP \). Thermal deformation \( \Delta l \) in continuous operation has the greatest influence on accuracy \( AP \) [2,3]. In this context, drifts from 0.10 mm \( \leq \Delta AP \leq 1.78 \) mm were measured [4, 5].

Currently, there are no established procedures and methods in practice that compensate for the effects of thermal drift \( \Delta AP \) without costly calibration measures with corresponding system downtime \( t_S \). In the field of university and institutional research, there are still a few approaches to compensatory and constructive measures, but there is no development with direct practical relevance [6, 7].

In this contribution a robot model was developed based on the simulation of the thermal behavior of the robot. With this model, the thermal error \( \Delta AP \) within the working area can be determined as a function of the current position \( X \) and temperature \( \theta \). With the correction by the compensation model the amount of drift for real milling processes could be reduced to a value of \( \Delta AP = 0.042 \) mm.

Thereby the knowledge of the thermal behavior of the robot could be extended. The simulation model makes it possible to determine and investigate thermal states within a very short time \( t \). Furthermore, the model allows the compensation of thermal drift \( \Delta AP \) during machining without downtime \( t_S \) and additional expensive equipment.

2. Preliminary investigations

The thermal drift \( \Delta AP \) is time-variant and is constantly changing during the manufacturing process through different processing speeds \( c_P \), operating loads \( m_0 \) and process times \( t_P \) [8]. On the given robot system, the KUKA KR 60 HA from KUKA ROBOTER GmbH, Augsburg, a maximum thermal drift of the tool center point of \( \Delta AP = 1.78 \) mm could be determined. The position of the tool center point is measured with the optical measuring system Leica Absolute Laser Tracker AT960-MR from HEXAGON METROLOGY GMBH, Wetzlar. The measurement accuracy of \( e = 0.04 \) mm is sufficient for the expected drift \( \Delta AP \) of several tenths of a millimeter and a position accuracy of the robot of \( AD = 0.05 \) mm. During a machining process, all axes are rarely in operation simultaneously and the axis speeds \( c \) are much lower. This results in a significantly lower structure heating and thus also in a low drift \( \Delta AP = 0.285 \) mm. The stationary state is reached for sample machining after a time of \( t = 600 \) min and thus after about twice the time \( t \) as for maximum heating.

3. Robot Model

In the simulation environment, the robot system can be simulated in any axis position and with different operating powers \( P \). As a result, the simulation provides both the drift \( \Delta AP \) at the TCP of the robot system and the drift \( \Delta AP \) in all spatial directions of the individual axes. The model only considers the thermally induced change in length \( \Delta l \) of the system. Thermally induced bending is not considered. Thus the change in length \( \Delta l \) of each axis at any time \( t \), in any point of the working area can be determined. To confirm the stability and reliability of the results of the simulation model, comparative measurements are performed at defined points in the working space.

Figure 1 shows as an example the comparison between the calculated drifts \( \Delta AP \) of the simulation environment and the measured drifts \( \Delta AP \) at an operating performance of \( P = 100\% \). For this example, the value of the calculated drift is \( \Delta AP = 1.33 \) mm. In comparison, the measured drift is \( \Delta AP = 1.39 \) mm. This results in an error of \( e_{\text{abs}} = 0.06 \) mm for the absolute value.

For a compensation during the machining process it is necessary that the calculation results are already available. The simulation cannot run simultaneously with the process and...
output the results for the current axis position X in parallel. Therefore the simulation results have to be transferred into a mathematical robot model.

The best results were achieved with a rational polynomial, compare function 1. The coefficients of the formula were determined for all relevant operating powers \( P \). A comparison of the experimentally determined drift \( \Delta AP_i \) and the calculated drift \( \Delta AP_i \) is shown in Figure 2:

\[
f_{p}(t_m) = \frac{\sum_{i=1}^{n+1} p_i t_m^{n+1-i}}{\sum_{i=1}^{n+1} q_i t_m^{n+1-i}}
\]

4. Results

The correction of the drift \( \Delta AP_i \) is done indirectly by an external compensation computer. Figure 3 shows the comparison of the value of the drift \( \Delta AP_i \) with and without correction. The operating power for this test series is \( P = 100 \% \). It can be seen that the compensation leads to a reduction of the thermally induced drift \( \Delta AP_i \). The drift can be reduced by the compensation to a value of \( \Delta AP_i = 0.119 \text{ mm} \). Without the compensation, the drift is \( \Delta AP_i = 1.205 \text{ mm} \). The drift is kept in an almost constant range of \( 0.072 \text{ mm} \leq \Delta AP_i \leq 0.119 \text{ mm} \) over the entire measuring time of \( t = 360 \text{ min} \) by the compensation.

In addition to static measurements, the performance of the model was tested during sample machining after \( t = 240 \text{ min} \) and the spatial error in \( X, Y \) and \( Z \)-direction was considered. The comparison of the processing errors shows that the generated error with the correction is significantly lower than without correction. The component shows lower machining errors in most spatial directions. Due to compensation, the value for the \( Y \)-direction increases slightly but continues to show a very low value. The measurement results are shown in Table 1. With the correction by the robot model, the drift of \( \Delta AP_i = 0.174 \text{ mm} \) can be reduced to a value of \( \Delta AP_i = 0.042 \text{ mm} \).

Table 1. Axis drifts \( \Delta AP_i \) and absolute value during sample machining after \( t = 240 \text{ min} \) with and without compensation

<table>
<thead>
<tr>
<th></th>
<th>( X )</th>
<th>( Y )</th>
<th>( Z )</th>
<th>Absolute Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( \Delta AP_i ) [ mm ][without compensation]</td>
<td>0.115</td>
<td>0.011</td>
<td>-0.131</td>
<td>0.174</td>
</tr>
<tr>
<td>( \Delta AP_i ) [ mm ] with compensation</td>
<td>-0.015</td>
<td>0.022</td>
<td>-0.032</td>
<td>0.042</td>
</tr>
</tbody>
</table>

5. Conclusion

The developed compensation model could prove that a correction during a machining process is possible. The great advantage of this compensation method is that the correction is carried out during the movement and the target point is adjusted exactly during the movement and the target point is adjusted exactly in relation to the thermal drift \( \Delta AP_i \). This is suitable for use in the field of milling, which mainly involves high-precision path operations. With the correction by the compensation model, the amount of drift for real milling processes can be reduced to a value of \( \Delta AP_i = 0.042 \text{ mm} \). This corresponds to a reduction of 75 % compared to the original drift \( \Delta AP_i \). The compensation model does not cause the system to stop for correction by external measuring systems, which is a major advantage of the developed solution.

References