Constructive compensation of the thermal behaviour for 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, is the thermal heating and the associated thermal drift of the tool center point. The maximum deviation from the actual nominal position can reach up to ΔAPt = 1.5 mm. Currently, there are no procedures and methods established in practice which compensate the effects of thermal drift without expensive calibration measures and system downtime. In these investigations a system was developed which allows the reduction of thermally induced displacement by using controlled heating elements. The aim is to keep the entire robot system at a permanent, balanced temperature level. The heating elements are adapted to the geometry of the respective axis and heat the material to a temperature ϑ close to the steady state. A comparison of the drift through the heating system with the error occurring in normal operation shows that the drift of the heating system is comparable with the drift of normal heating. With the heating mats, a thermally induced error of ΔAPt = 0.234 mm can be generated within t = 20 min. While normal heating requires up to t = 600 min. The achieved error deviation of the drift of the self-heating to the heated variants is with ΔAP = 0.04 mm only minimal. The results can help to reduce the influence of thermal heating and the associated thermal drift of the TCP without using cost-intensive measures with additional hardware and software on external computers for compensating the errors.

1. Introduction

In the last decade, robotic processing has evolved from a basic research topic to a production technology for industrial use [1]. The main reasons are technological progress and ongoing research [2], which have led to an increase in accuracy AP. Robot-guided machining is an innovative production technology that combines the advantages of a highly accurate machine tool with the flexibility of a 6-axis jointed arm robot. Due to their relatively low investment costs KI compared to machine tools, milling robot systems represent a cost-effective alternative.

Continuous improvement of the industrial robots with regard to stiffness s and path accuracy AT results permanently in new industrial applications [3]. Another advantage of inexpensive industrial robots is the relatively large, usable work space AR. Currently, the use of robot-guided machining systems in industrial serial production is mainly limited to the deburring and fettling of components with relatively rough accuracy requirements [4].
Current research concentrates, for example, on the thermally induced influence on the processing accuracy [3] or tries to increase the accuracy by compensating the deviation of the TCP with an improved robot control [5]. The thermally induced machining drift, the so-called thermal drift $\Delta A P_t$, is a significant obstacle to the development of new applications for machining robots in series production.

2. Motivation
Various disturbances occur during robot-guided machining. These disturbances have a considerable influence on the machining accuracy. In order to implement industrial robots in production, it is of great importance to increase the machining accuracy. Thermal deformation $\Delta l$ in continuous operation has the greatest influence on accuracy, see Figure 1 [6]. In addition, this influence is relevant for handling and assembly without dynamic loads as well as for high-precision machining processes such as milling or grinding, regardless of the type of use. Various studies have shown that the thermal influence has a great impact on the accuracy of six-axis industrial robots. In this context, drift from $\Delta A P_t = 0.10 \text{ mm}$ to $\Delta A P_t = 1.78 \text{ mm}$ was measured [7, 8, 9].

![Figure 1. Factors influencing the machining deviation $\Delta A P$ [6]](image)

The majority of robotic systems continue to be used in handling and processes with low accuracy requirements. Due to the current low number of robot systems in manufacturing, robot manufacturers have no need for retrofit solutions to compensate for thermal drift $\Delta A P_t$. Currently, there are no established procedures and methods in practice that compensate for the effects of thermal drift $\Delta A P_t$ 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 approach with direct practical relevance [5, 10, 11].

3. Measures to reduce thermal influences

3.1. Preliminary investigations
The thermal drift $\Delta A P_t$ is time-variant and is constantly changing during the manufacturing process through different starting and processing speeds $c_P$, operating loads $m_O$ and process times $t_P$ [3]. This is particularly relevant in continuous operation, however, also in the production of individual parts, since a large part of the temperature-induced deviation already occurs in the first 30 minutes of heating. Due to the knowledge of the robot system and the process sequence, the thermally induced deviations can only be assessed to a limited extent or not at all.

All investigations for the experimental system analysis as well as the technological investigations are carried out on a six-axis vertical articulated robot of the type KR 60 HA from the company KUKA ROBOTER GMBH, Augsburg. A high-frequency spindle of the type ES350 from HSD SPA, Pesaro, Italy, is mounted on the end effector of the robot. The drive power is $P = 8 \text{ kW}$. The maximum speed is specified as $n_s = 36.000 \text{ 1/min}$. Tools can be accommodated with the standardized form HSK-E
The position of the tool center point is recorded with the optical measuring system Leica Absolute Laser Tracker AT960-MR from HEXAGON METROLOGY GMBH, Wetzlar. The reflector required for the laser tracker can be mounted directly in the holder of the milling spindle and thus in the tool axis via an adapter.

On the given robot system, the KUKA KR 60 HA, a maximum thermal drift of the tool center point of \(\Delta AP_t = 1.78\) mm could be determined. It must be taken into account that all axes reach a quasi-stationary state after \(t = 300\) min and do not continue to heat up, i.e. the displacement does not increase any further. Compared to the robot-specific repeatability of \(RP = 0.05\) mm, the deviation is significant and has a detectable effect on the accuracy achievable with a processing robot system.

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 \(\Delta AP_t\). Figure 2 shows the comparison of the directions of thermal drift \(\Delta AP_t\) of the sample machining with the maximum heating of the system. Due to the reduced range of motion and the low axis speeds \(c\) during sample machining, there is less heating of the servo motors and gears and thus less heat input \(Q\) into the robot structure. The result can be explained by the sample machining and the related axis movement. Machining is carried out within a small working space on the machining table. The manual axes, i.e. axes 3, 4 and 5, are mainly used for machining. These axes mainly cause heating of the arm and consequently a thermally induced drift \(\Delta AP_t\) in the X-direction in world coordinates. The difference in the Z-direction can be explained by the stronger heating and the associated expansion of the swingarm. Due to the expansion, the TCP lifts in the Z-direction and leads to a positive drift \(\Delta AP_t\). For sample machining, the heating of the swingarm is low. This results in a significantly lower thermal drift \(\Delta AP_t\). 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.

![Figure 2](image-url)

**Figure 2.** Comparison influence of direction on drift \(\Delta AP_t\) on TCP between sample machining and maximum power P in world coordinates

The IPK and the WINKLER AG, Heidelberg have developed a system that allows the reduction of thermal caused displacement \(\Delta AP\) or different temperature gradients \(\Delta \vartheta\) by controlled heating elements. From thermographic photographs of an industrial robot it can be seen that temperatures of \(40^\circ C \leq \vartheta \leq 90^\circ C\) are present at gear and motor components, whereas the axes are in a temperature range of \(30^\circ C \leq \vartheta \leq 50^\circ C\).

According to the current state of knowledge on thermal drift \(\Delta AP_t\), the heating of affected axles is preferable to cooling [8, 11, 12]. The aim is to keep the entire robot system at a permanent, balanced...
temperature level, the steady state. In this case, no additional heating and thus no additional increase in thermal drift $\Delta A_P$ is to be expected.

### 3.2. Heating system

The heating elements are adapted to the geometry of the axis and keep the material at a temperature $\vartheta$ close to the highest expected heat level $\vartheta_{\text{max}}$. The heating elements are switched off when the temperature $\vartheta$ on the axes of the industrial robot no longer changes or the heat input of the motors and gears automatically keeps the system at a constant level. The robot system must then be calibrated once.

High-performance surface heating systems are used, which have a new type of material and heating wire base, resistant cover materials suitable for use in a production environment and a geometry adapted to six-axis industrial robots.

With a total weight of $m = 680 \, \text{kg}$ of a KUKA KR 60 HA, heating up the entire mass in the time $t = 30 \, \text{min}$ resulted in a heating power of approximately $P_H = 10 \, \text{kW}$. For this approximate calculation, a temperature of $\vartheta = 50 \, ^\circ\text{C}$ is assumed as steady-state temperature. Not the entire surface of the robot system is available for the heating mats. For usable surface area $A_H$, the maximum heating power for the robot system is $P_H = 2.6 \, \text{kW}$. The total heating surface of the robot results to $A_H = 1.05 \, \text{m}^2$ and the surface capacities of the individual heating elements are between $P_A = 0.16 \, \text{W/m}^2$ and $P_A = 0.30 \, \text{W/m}^2$. The heating surface is divided into 14 individual mats and the mats are operated with a voltage of $12 \, \text{V} \leq U \leq 60 \, \text{V}$. Figures 3 and 4 show the heating mats attached to axes 1, 2 and 3.

**Figure 3.** Heating mats attached to axes 1 and 2.

**Figure 4.** Heating mats attached to axes 2 and 3.

In addition, a solution for the measurement and control of the new surface heating mat systems was implemented. The systems have integrated regulators to control the heating power $P_H$ and individual settings of the individual heating mats. These can be parameterized by an infrared interface. The controllers use a Fast-Adaptive-Tuning-Algorithm (FAT), which automatically and continuously adapts the control behaviour to the controlled system. Heating elements of the company WINKLER AG, Heidelberg, are used for targeted heating. The required heating systems are individually manufactured and adapted for this investigation.

### 4. Results

For a real consideration of the heating and the associated drift $\Delta A_P$, a simplified milling process is considered. The working area is limited to an area near the working table. The machining was performed in a continuous loop and the heating behaviour and the resulting drift $\Delta A_P$ was recorded. The loop simulates a series production of a milling component and the realistic temperature-related error development associated with it. The temporal error development is shown in **Figure 5**.
Figure 5. Experimentally determined drift $\Delta A P_t$ as a function of time $t$ for sample machining using the
of measuring position 1 of the KUKA KR 60 HA

The maximum drift for sample machining is $\Delta A P_{t,\text{max}} = 0.28$ mm. The value is reached after a time
of $t = 600$ min. This results in a significantly lower drift $\Delta A P_t$ for real machining, but a longer heating
phase until the material is stationary.

For a real machining process, the heating system can be used to reach the stationary state and the
maximum drift after a time of $t = 20$ min. For this purpose, the heating mats on the robot system were
used in addition to the movement loop of the processing. The result is shown in Figure 6. In comparison
to the results of Figure 5, the time to reach the steady state can be reduced from $t = 600$ min to $t = 20$ min.
The heating system was used for only $t = 11$ min and then switched off. Subsequently, overshooting
occurred due to the residual heat in the system. After a short cooling down period, the system is now in
a stationary state. For real processes and motion sequences, a thermally stable state can be achieved with
the help of the heating system after less than $t = 30$ min.

Figure 6. Experimentally determined drift $\Delta A P_t$ for sample processing including heating mats
In a first series of tests a machining process without heating system is simulated. Obomodulan® is chosen as the material for the test components. These are sheets or blocks of polyurethane foam. The material was chosen because it is cost-effective and very easy to machine. Compared to metallic materials, considerably lower cutting forces $F_S$ and thus a reduced displacement $\Delta A_P$ can be expected.

In the present investigations, Garant milling tools from the company HOFFMANN SE, Munich, are used. With its rake angle, the milling cutter is particularly suitable for soft materials such as aluminum or plastic. Furthermore, the milling cutter with its face cutting geometry enables plunging, which is necessary for the drilling operation in the sample component. The robot system processes a first component in a cold state and then heats up in the programmed loop for a time of $t = 600 \text{ min}$. In the stationary state a further component is machined. Afterwards the two components are measured and the drift $\Delta A_P$ is observed. The visual evaluation of the scanned components shows how the thermal drift $\Delta A_P$ affects the milling process. The geometric shapes and the hole in Figure 7 show that the robot shifts the entire milling image in the drift direction as the heat is generated. A distortion of the shapes cannot be detected or measured. It can therefore be concluded that the mutual influence of the individual axis drifts $\Delta A_P$ and also the overall drift $\Delta A_P$ in the area of the component remain almost constant.

**Figure 7.** Thermally induced error during milling on selected geometries at time $t = 0 \text{ min}$ (grey) and $t = 600 \text{ min}$ (green); a) circle; b) square; c) hole

To assess the performance of the implemented heating system, the described test series is carried out again. At the time $t = 0 \text{ min}$ a component is manufactured by the robot system as reference. Then the heating systems are started, the robot system is heated for $t = 11 \text{ min}$, the system is switched off and the stationary state is reached after $t = 20 \text{ min}$. After reaching the stationary state another component is manufactured. The manufactured components are measured and the drift $\Delta A_P$ is determined. A comparison of the drift $\Delta A_P$ through the heating system with the error occurring during normal operation is shown in Figure 8.
It shows that the drift $\Delta A P_t$ of the heating system is comparable with the drift $\Delta A P_t$ of normal heating, see Figure 8. The component shows comparable drifts in all spatial directions. With the heating mats, a thermally induced error of $\Delta A P_t = 0.234$ mm can be generated within $t = 20$ min. For normal heating by the process, the system reaches this error value only after $t = 600$ min. For normal processing, a thermally stable robotic system can be generated after less than $t = 30$ min with the help of the solution. The achieved error deviation of the drift of the self-heating to the heated variants is with a value of $\Delta A P = 0.04$ mm only minimal.

5. Summary
Within the scope of the investigations, it was shown that a targeted heating of the robot structure enables faster and more economical precise manufacturing with a robot. The developed system can bring the robot within shortest time into a thermally stationary state and thus prevent thermal drift $\Delta A P_t$. The drift $\Delta A P_t$ only needs to be corrected at the beginning of the process, no further corrections are necessary afterwards.

Especially for small and medium-sized companies, the developed system is a great opportunity to integrate robot systems into precise and flexible production. Whereas expensive systems such as laser trackers with a cost of $K > 100,000$ € were previously necessary to compensate for thermal influences, the developed system with costs of up to $K = 5,000$ € is much cheaper and also easier to operate.

For normal machining, the solution can be used to create a thermally stable robot system after less than $t = 30$ min. With a voltage of $U = 48$ V and temperatures at $\theta_H = 90$ °C, the system poses only a low risk to users and robots. Furthermore, the achieved error deviation from the drift of the self-heating to the heated variants with a value of $\Delta A P = 0.04$ mm is only minimal.

It was shown that the system is slowed down by the low heating capacity $P_H$. Current systems do not allow for larger heating capacities $P_H$ for this area of application. Flexible heating systems are reduced to small line cross-sections $d_L$ and thus limited in heating power $P_H$. Development work would therefore be needed in the area of heating systems and the achievable heating power $P_H$ at low line cross-sections $d_L$. 

Figure 8. Comparison of drift $\Delta A P_t$ on sample component with and without heating system

- No heating mats $t = 600$ min
- Heating mats $t = 20$ min

Object of measurement:
Test sample

Measurement:
Romer Absolute Arm
Typ 7325 Si

Process parameters:
$v_f = 0.025$ m/s

|                | X-Direction | Y-Direction | Z-Direction |
|----------------|-------------|-------------|-------------|
| Drift $\Delta A P_t$ | 0.20        | 0.00        | 0.20        |
| mm             | -0.20       | 0.00        | -0.20       |
| 0.60           | 0.00        | 0.20        | -0.20       |
| 0.00           | -0.20       | 0.00        | -0.20       |
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