Thermal Effects and the Consequences for Repeatability of an Industrial Robot

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1. INTRODUCTION

Repeatability is an issue when designing applications that use the robot equipped with an appropriate sensor head as a measurement tool to capture the geometry of parts. Future robotic applications therefore include measurement tasks (geometry measurement of parts too complicated for standard systems), flexible measurement and duplication (machining) as well as rapid prototyping systems or high-precision manipulating systems. In all the above mentioned tasks the repeatability and accuracy of the robot is of major importance for the overall performance of the system. By simply comparing the specifications of different commercially available and custom sensor heads for geometry measurement to the specifications provided by the manufacturers of industrial robots the necessity for a closer look becomes evident. The robots at our institute (KUKA KR-15/2 and Kawasaki Js-10) have a specified repeatability of ±0.1 mm. The absolute accuracy is not stated in the robot data sheet, but figures provided by the manufacturer estimate it to be in the region of 10 mm for an off-the-shelf robot and 1 mm for an absolutely calibrated robot. Commercial light-sectioning heads suitable for robotic applications have a typical height/lateral range of 4 to 200 mm (depending on sensor type) and a resolution of 0.006 to 0.3 mm respectively with better performance where sub-pixeling can be implemented. For sensors with a small field of view therefore the system uncertainty is mainly contributed to by the robot itself.

Even if one decides not to rely on the absolute accuracy of robots and instead just uses the accuracy of relative motion in restricted areas of the workspace the repeatability presents the final limit. In practice industrial robot manufacturers give vague quantification of repeatability while virtually ignoring accuracy alltogether. The given specifications for repeatability are not defined with respect to other operating parameters such as temperature, joint rates and payload. Even though a detailed ISO standard for definition and evaluation of robot performance criteria exists (see [2] and [3]) it was decided to test the robot type to be used for a measurement system at this institute.

2. SETUP

The repeatability of a KUKA KR-15/2, a wrist-partitioned industrial robot with six actuated revolute axes (6 degrees of freedom (DOF)) is investigated. The repeatability is measured by a cyclic robot task with determination of the end effector pose in 4 positions, A to D (determination of 2 DOF in each position). The temperature distribution along the robot (links, joints and motors) is also measured using an infrared camera. A Laser is mounted on the end-effector of the robot and is pointed directly onto the CCD-chip of a standard CCIR-camera (Pulnix TM-6CN, no optics used). The cameras are mounted in suitable positions so that the pose of the end-effector can be determined in 2 DOF. Before capturing the vibrations of the end-effector are allowed to settle. By means of a refined 2-dimensional COG-algorithm (Center of Gravity algorithm, see [4]) we calculate the center of the spot. The pixel size of the cameras used (8.6 x 8.3 μm) and the sub-pixel accuracy reached with the algorithm yield a resolution of the Laser spot center of at least 1 μm. The mounting positions of the cameras are chosen to get an estimation of the repeatability in the major axes of the world coordinate frame of the robot, $\{W\}$ (camera A and B). By moving the end effector from camera B to C by a relative motion of just axis 4, and from camera C to D by a relative motion of axis 5, the Laser spot positions include information about the contributions of these axes to the overall repeatability. See Figure 1 for schematic arrangement of the camera coordinate systems related to the robot world coordinate system and for an image of the actual setup.

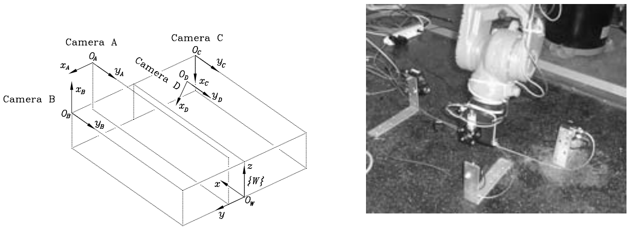

Figure 1. Camera placement; CCD-cameras and head mounted to robot.

The temperature of the robot frame is recorded with a FLIR SC500 Thermovision uncooled infrared camera. This camera captures images with 320 x 240 pixels with a sensitivity of 0.1 °C (at 30 °C) and an absolute accuracy of ± 2 °C.

3. EXPERIMENTAL RESULTS

We conducted 3 series of cyclic tasks with 30%, 75% and 10% of maximum speed (run 1, 2 and 3). At run 1 and 2 the robot frame has ambient temperature at the start, run 3 is started directly after the end of run 2, the robot is not allowed to cool down. Here we describe the results of run 1 in more detail. At the beginning the results are dominated by thermal effects. The heat generated by the operation of the robot causes its links to elongate (can be described by an exponential function), due to the asymmetrical setup of the robot one expects also a twisting of the robot structure while heating up. These effects can be seen from the position of the center of the Laser spot over time of the measurement (see Fig 2). To quantify the time constant for comparison to the results of the thermal camera the data sets are approximated by single-exponential decay-curves (where appropriate). In the datasets for some x-axes a single-exponential fit seems not to be sufficient. The fitting results are inserted into the figure 2.

It can be seen that the dominant portion of the positional change is associated with the temperature in-

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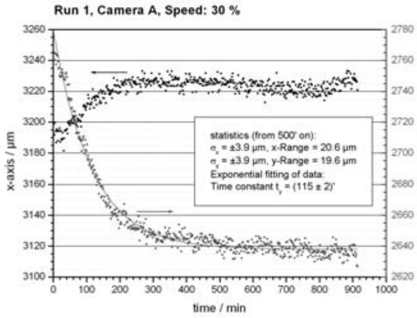

Figure 2. center of laser spot on camera A over measurement time (arrows indicate, to which axis each dataset belongs).

duced elongation of the robot links (corresponding to the y-axis of camera A) and that a temperature induced twist of the frame must be significantly smaller (should appear in the x-axis of camera A) as well as a change in the height of the end effector (corresponding to x-axis of camera B). The time constants of the single-exponential function are between 115 and 122 minutes. After 500 minutes the positioning variation range is reduced to approximately 0.02mm.

Measurement of robot temperature

These results are compared directly with the temperatures measured by the infrared camera. A thermal image is shown in Figure 3 for the end of run 1.

On the spots marked by rectangles the average temperature is plotted and evaluated by first order exponential fitting.

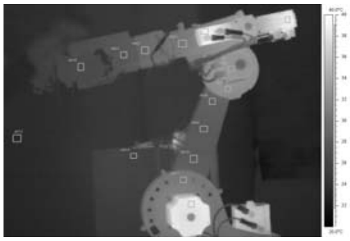

Figure 3. Temperature of robot at end of measurements (Note, the hot spot visible on the nearly vertical arm of the robot (link 2) is the Laser power supply.

The time constants of the average temperature of the spots on link 2 agree with those resulting from the position repeatability data (2). Those of the spots on the motors exhibit significantly lower time constants (42 and 45 minutes), while those on link 3 and 4 and on link 1 lie in between.

4. THEORETICAL ANALYSIS

The measured positional changes are compared with calculated changes using the measured thermal data and based on the material and dimensions of the robot frame. The start temperature of 23.5 °C is extracted from the infrared image in Fig. 3. By averaging the temperature in the rectangles on the robot links the end temperature is 34.1 °C, thus giving a ΔK of 11.1 K. The coefficient of expansion for the frame is $\alpha_{aluminum} = 23.8 \cdot 10^{-6}/K$ based on manufacturer's information (frame consists of different aluminum alloys). Using these values together with the projections of the lengths of link 2 and 3 of 972.3 mm onto the x- and y-axis one gets the elongations

$$\Delta l = l \cdot \alpha \cdot \Delta K$$

$$\Delta l_x = 956.4mm \cdot 23.8 \cdot 10^{-6}/K \cdot 11.1K = 0.253mm$$

$$\Delta l_y = 174.9mm \cdot 23.8 \cdot 10^{-6}/K \cdot 11.1K = 0.046mm$$

These results are transformed to the coordinate frame of camera A (see also 1):

$$\Delta l_{xA} = \Delta l_y = 0.046mm$$

$$\Delta l_{yA} = -\Delta l_x = -0.253mm$$

and compared to the experimental results:

Table I
Camera A: calculated and experimental elongation.

Calculated	Experimental	Difference
Δx_A = 0.046 mm	Δx_A = 0.053 mm	-13.2%
Δy_A = -0.253 mm	Δy_A = -0.141 mm	79.4%

While the results agree quite well in x they differ significantly in y. One has to use some precaution due to the simple temperature averaging and to the fact that the robot is constructed of different aluminum alloys that may differ in their thermal expansion coefficients. Minor parts of the frame are also constructed of steel.

5. CONCLUSIONS

From these results it can be concluded that once the robot has warmed-up, the positioning repeatability is nearly one order of magnitude better than the manufacturers stated repeatability of ± 0.1 mm. On the other side, if one neglects these heat-up effects, the actual positional shift is closer to ± 0.2 mm, nearly twice the specified value. The measurement series gives valuable information for setting up robotic measurement systems by estimating positional errors introduced by the robot. If the task to be done allows, a first order calibration by presenting the robot head to a camera or measuring a calibration object with the head itself could significantly reduce deviations caused by thermal effects.

6. FUTURE WORK

Our future work will concentrate on evaluating angular and linear relative accuracy and on setting up a measurement system together with a calibration routine based on relative robot motion. An interesting task will also be the measurement of effects caused by strong external heat radiation, since the measurement system should be applied in a hot-forging environment.

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