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Draft

Measuring the motion

Synchronizing a laser tracker for high-accuracy handling tasks

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1 Abstract

The contribution focuses on synchronizing the position of tool center points (TCPs) of assembly robots with a laser tracker. Up to now, the robot's trajectories were surveyed solely in a stop-and-go-mode. Because the actual trajectory of an object is needed, while it is moving, we demonstrate a high-accurate survey method. It enables optimizing a second robot to execute high-precision handling tasks in precision manufacturing. The task shown here is challenging, because the accuracy requirement of mechanical handling is high and, due to the object speed up to 100 mm/s, it requires a synchronization uncertainty down to 50 µs. Therefore, different synchronization methods will be discussed theoretically. As the standard method will not work, the implementation of an appropriate technique will be demonstrated. In the first application gross errors of the robot control system were verified easily, so that the robot's function was improved significantly. In the second step, a very high repeatability of the trajectory was detected. In the third step, the implemented method showed to be suitable for the fine tuning of the robot-bound movements. Furthermore, it is demonstrated, how the measurement set-up can be optimized. Additionally, a preview to a development of a (possibly low-priced) active hub will be given, which will allow for the revertive rotation of the CCR according to the control data of the robot's rotation.

2 Introduction

The development of new production methods let robots play an ever more important role. By the advancements of robot controls in the last years, also sophisticated motions of the robot can be programmed in a relatively simple way. In doing so it is necessary to investigate the quality of the current trajectories by an independent measuring method. The presented project describes the spatio-temporal monitoring of an innovative, robot-supported production method for spatially curved extruded profiles, which is developed by the Institute of Production Science at the University of Karlsruhe, see Fig. 1. The robot steers the cut-off device that must work synchronously to the extruding press. Both are controlled by a server-based control unit (see [Fleischer et al, 2006]). In doing so, the special challenge for the measurement is the synchronization of the involved laser tracker with the robot (including the control-unit) in the range of microseconds.

In the current development phase of the project the surveying focuses on the inspection and optimization of the trajectory of the tool centre point (TCP) of the robot. Effects of the temperature gradient in the extruded profile on the trajectory of the TCP and the effect of the very complex temperature field of the environment on the measuring behavior of the laser tracker are not considered in this phase. In the current phase, primarily the *planned* trajectory has to be compared with the *driven* trajectory of the robot. This should lead to increasing the accuracy of the manufactured extruded profile by an inline calibration in a further step.

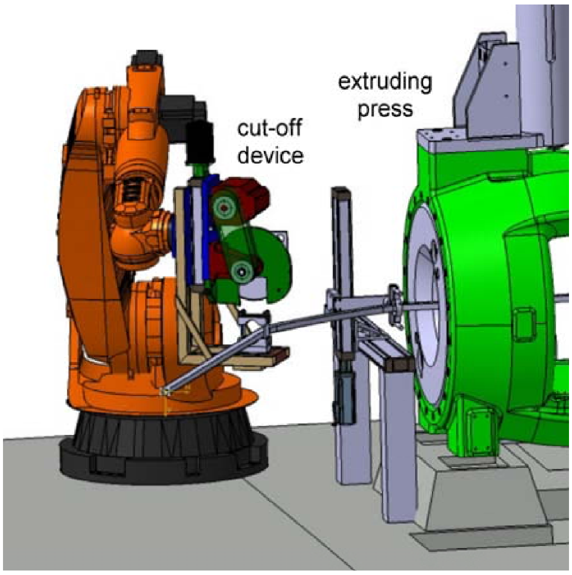

Fig. 1: Production system consisting of extruding press and cut-off device steered by robot

3 The experiment

3.1 Synchronization methods

Synchronization can be achieved by different methods. One is to use time stamps for each action as well as for each measurement, respectively. The other is to use a trigger that initiates the action and the related measurement. The first one is the rougher method, because the clock's drift and the clock's offset must be zero or, for a-posteriori-correction, precisely known. Interpolation between the time-stamps will be inescapable. This increases uncertainty extremely, if the motion is not linear in time and space. The second method performs significantly better. The trigger signal is generated by a superordinated master clock, which could also be identical with a clock of the process members, e.g., the robot. This trigger signal (e.g., the rising edge of a square wave signal) activates strictly simultaneously actions of every process member. The edge steepness and the response time of the individual process-action determine the quality of the synchronization. It is not influenced by the drift of the trigger-generating oscillator. This method requires that all process components can process external trigger signals initiating the correct action. The clock frequency of the trigger signal must be selected sufficiently low to ensure that within a cycle all participants can terminate their action so far that the start of the next action, which is provoked by the following trigger signal, does not disturb the previous action. Nevertheless, one process member should generate time stamp according to the trigger signal to enable convenient data acquisition and processing later on.

Taking the specified repeatability of the investigated robot (0.12 mm) into account and assuming a maximum speed of the TCP 100 mm/s, the temporal resolution should be about 50 µs, taking the specified measurement accuracy for the involved laser tracker into account. Although the time stamp resolution of a Leica laser tracker is 1 µs, the maximum data rate in usual kinematic mode is 1 kHz without information about the age of the data. Therefore, the trigger method has to be applied. The Leica "LT CONTROLLER plus" enables synchronizing the tracker LTD500 by an external trigger signal. The tracker measures angles and distances independently of the trigger events with an internal rate of 3 kHz. The generation of these values takes 1-2 µs [Loser, 2004]. The tracker controller captures the trigger event (point of interest) in its own time system. Then each measurand is interpolated to exactly that point. Although only the number of the trigger event is necessary for the data correlation, also the timestamp captured with the trigger event will be saved together with the measurement (3D coordinates). The maximum rate to display the measured values is 1 kHz. The controller sends these values block-by-block every 1/3 second to the user software.

In the following, some verifications of the temporal uncertainty are given. The clock of the tracker controller drifts with +12 µs/s relating to a frequency-stabilized waveform generator and meets the manufacturer's specifications [Leica Manual 2005]. Individually registered reference clock pulses show to be equally spaced within the resolution of the tracker clock of 1 µs. In relation to the tracker clock the robot clock drift rate amounts to -55.7 (±0.1) µs/s. As the recording time is less then 30 s, this drift uncertainty can be accepted, if the data is analyzed in relationship to the drift-corrected time stamps and not to the more accurate trigger event numbers. So, the robot clock was chosen to produce the trigger signal, delivering 250 Hz and 500 Hz. The maximum deviation of one trigger pulse length in relation to the recorded time amounted to 78 µs, which does not matter as we refer to the trigger event.

Generally, the user has to check for additional delays occurring in the measuring system itself. Normally, it consists of different single sensors, which have to be synchronized in relation to the trigger signal, too. In the case of a laser tracker, the interferometer and the two angle encoders, which are coupled to the PSD-device, must be considered. They deliver data with an internal data rate of 3 kHz. For higher time-resolution, the data will be interpolated internally. Nevertheless, delays cannot fully be excluded when aiming at µs-resolution. Usually, these delay-effects are determined with rotating arm devices (see [Depenthal, 2008] for a time-referenced solution and [Depenthal, Barth, 2007] for first results). However, the repeatability of the checked robot proved to be outstanding, so the measurements with this robot could enable the first steps of self calibration (see chapter 5).

3.2 Measurement set-up

In the experiment, the TCP was steered along a straight line. Therefore it is expected that any inadequacies in the joints and/or the controlling of the robot affect the trajectory non-linearly. A path length of 2000 mm and a speed of 60 mm/s in the first and 100 mm/s in the second experiment were chosen. The trajectory was put to the control system of the robot in form of a list with individual values for each space position referring to a pulse width of 12 ms. As in the first experiment a 250 Hz-trigger and in the second experiment a 500 Hz-trigger was used, these positions were interpolated to a pulse width of 4 ms and 2 ms in the second experiment respectively. For the determination of the repeatability always 10 identically steered runs were completed. The coordinates referred to the robot coordinate system, which y-axis was coaxial to the TCP's path. The coordinate system's orientation and the positions of the laser tracker are shown in Fig. 2. In the first experiment, the approximate distance between station (#2) and the origin of the trajectory amounted to 2.5 m and in the second experiment, 6.5 m and 2 m for station #1 and #2, respectively. The transformation between the observing system of the laser tracker and the robot system (6DOF without scale) based on surveying four (respectively eight) TCP-positions in static mode, which covered more or less the working space. The transformation was checked at the end of each experiment. The RMS-value for each coordinate gives an impression of the achievable uncertainty. For example, in the second experiment, the RMS-value for a single coordinate varies between 14 µm and 62 µm, which is less than could have been respected in respect of specified accuracy. However, increasing the number of measurements to identical points will increase accuracy.

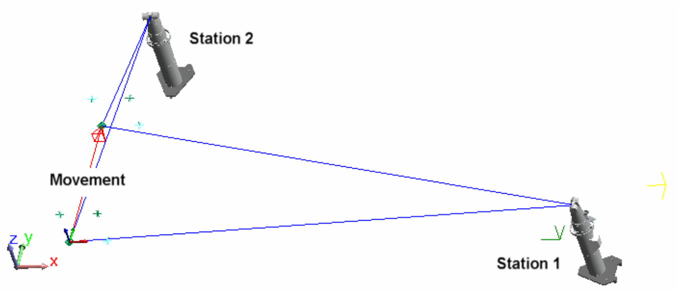

Fig. 2: Measurement set-up

4 Results

4.1 "Systematic" deviations

The first experiment consists of two steps. In the first step, which focused on superposed movements of two devices, gross errors were detected, which could be easily removed by adjusting some steering parameters of the robot. In the second step, the TCP was steered only by one robot along a straight line. The maximum lateral deviation of 0.2 mm showed up approximately midway of the trajectory. The beginning of the movement shows a transient response with an oscillation period of 0.22 s (ref. Fig. 4). In the further process deviations with a period of 0.10 s and amplitudes up to 0.04 mm arise. The oscillations at the beginning of the movement are caused partially by the accelerated starting movement. The force resulting from the abrupt acceleration causes flexible deformations in the robot's structure and produces the initial oscillation. The oscillations in the further, constant process of the movement partly result from imperfections of the transmissions as well as the low rigidity of the whole system.

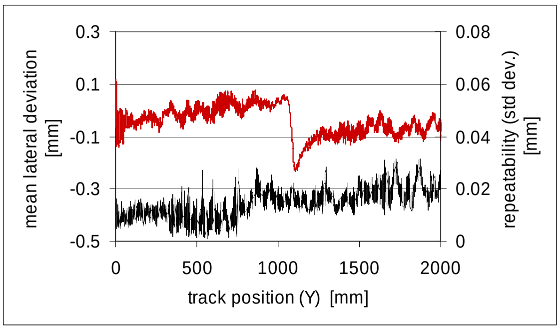

Fig. 3: Red: lateral deviations, first experiment, whole track, average from 10 runs. Black: repeatability, shown on right axis

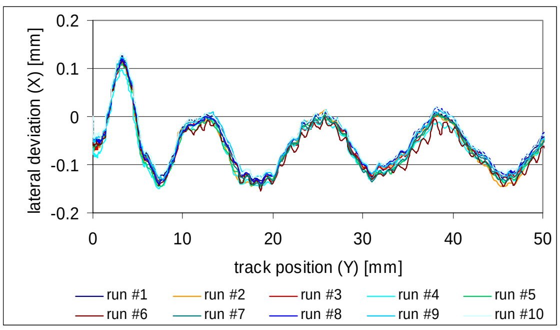

Fig. 4: Lateral deviations, first experiment, initial part of track

The vertical component of the movement exhibits somewhat larger deviations (0.3 mm) in relation to the nominal trajectory than the lateral component. The transient response is even more striking: The first an oscillation starts with 0.4 mm, then decreasing into a damped oscillation with a period of 0.18 s. In the further process, this oscillation shows up irregularly with amplitudes up to 0.15 mm. Furthermore, most of the runs start with different vertical positions (varying by some hundreds of millimeter), partly resulting in (small) phase shifts of the oscillation. Also here the oscillations can be partly attributed to the low rigidity of the robot structure.

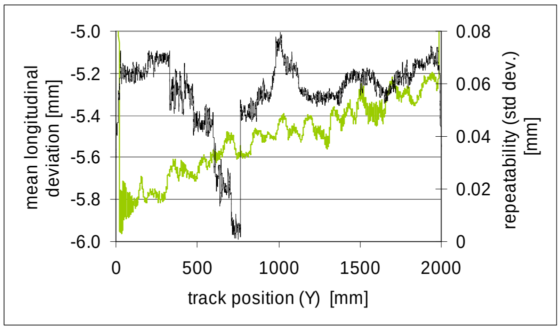

Fig. 5: Green: longitudinal deviations, first experiment, average from 10 runs. Black: repeatability, shown on right axis

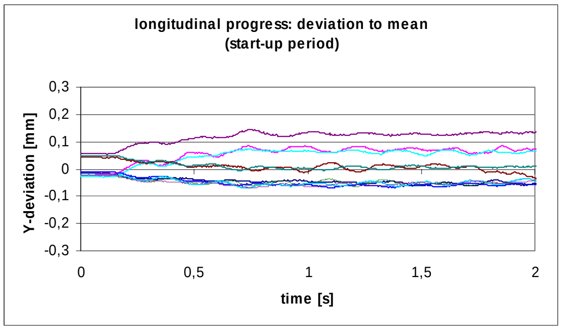

Fig. 6: Longitudinal deviations, first experiment, deviation of 10 runs to the average, thus corrected by delay about 6 mm

For the evaluation of the behavior of the robot in the direction of motion the deviations to the nominal value of the Y-coordinate are analyzed. The nominal positions result from the coordinate list, which was handed over to the numerical control of the robot. A response time and additional systematic delays are clearly detectable (ref. Fig. 5 and Fig. 6). Thus, the TCP drags behind nearly 6 mm right from the start. Additionally, a linear trend in the longitudinal deviation of 0.29 mm/m indicates a scale difference between the robot and tracker coordinate system, which was not eliminated by the 6DOF-transformation. (In this way, robot-axes-related scales can be detected.) Also longitudinal oscillations arise with a period of 0.22 s and amplitudes up to 0.1 mm in the start phase and then occurring irregularly with amplitudes up to 0.04 mm. Additionally, with increasing travel time different offsets are reached, which vary about 0.06 mm in each case. This corresponds to the movement of the TCP in 1/1000 second. Since these offsets increase continuously to their total amount, a rough interpolation error by the laser tracker can be excluded. Furthermore, in the second experiment the position of the laser tracker was changed (ref. Fig. 2) to obtain the deviation mainly by the angular sensors instead of the distance sensor.

Because the measured deviations remain the same in type and magnitude, they are caused by the robot and not by the laser tracker.

4.2 *Repeatability*

The very small repetition standard uncertainty of the tracks is remarkable: Thus, the standard deviation of an individual deviation at a certain position does not exceed 0.03 mm for the lateral component and 0.04 mm for the vertical component. The longitudinal repetition standard uncertainty of an individual position with 0.06 mm is clearly worse than in the case of the lateral and vertical deviation, which is to be explained as follows: Fig. 6 shows that the movements have two different initial positions and that with movement progress a further differentiation of the trajectories takes place. Eliminating this offset, the repeatability will improve significantly to 0.02 mm. However, the repeatability specifications of the robot are met.

4.3 *Results of modifications*

Prior to the second experiment, the robot was modified. This resulted in the improvement of the repeatability uncertainty. Despite of this, the systematic deviations more or less were similar to them shown in the first experiment. The artefact in the lateral deviation remains as well, but changes a little in its shape (ref. Fig. 7). The upper curves in Fig. 7 show the deviations measured from station #1 and station #2. The offset between them is due to the not satisfyingly observed transformation parameters. The type and the range of the oscillations remain also unchanged, but now we observe the phase of the X-component being dependent on the start-offset, instead of the Z-component as seen in experiment before the modifications. The response time increases and produces a delay of about 16 mm in the longitudinal shift, again with slightly different values for each run, but now distinctly apart by 0.2 mm (Fig. 8). This indicates that the modifications of the robot decreased its performance for the motion in Y-direction. Because of the permanent layout studies of the robot, the final solution is still not found. Furthermore, this large delay precludes the determination of the temporal mapping of lateral deviations by the Y-coordinate with appropriate temporal resolution. In this case, the delay reaches 0.2 s.

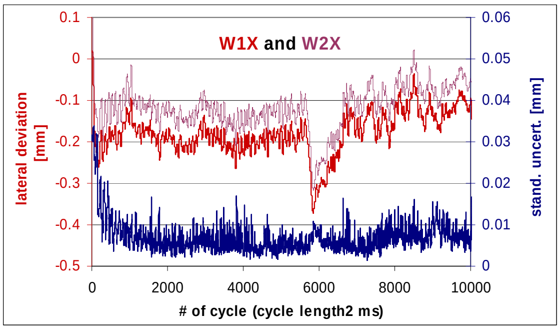

Fig. 7: Lateral deviations (upper curves, uppermost from station 2 and standard uncertainty of station 1), second experiment

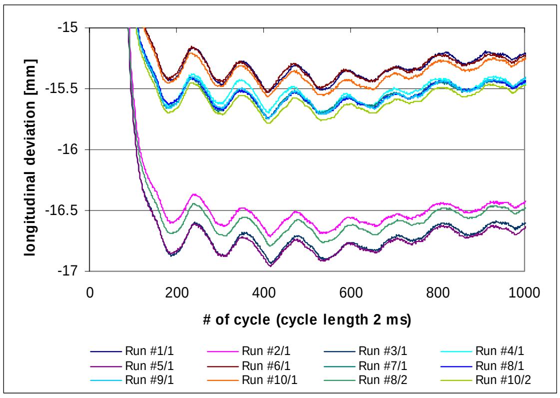

Fig. 8: Longitudinal deviations, initial part of track, second experiment. Results from station 1, example-data from station 2 (green) showing less ripples

5 Optimizing the measurement set-up and self-calibration options

As shown above, with a synchronized laser tracker a powerful tool for testing robot's trajectories is available. Nevertheless, if the robot's repeatability is outstanding, the robot can be used to check a polar measurement system for intrinsic systematic errors – despite of systematic errors of the robot. In doing this, different measuring set-ups are used (ref. Fig. 2). In principal, from each single tracker-position the deviations of the track can be determined. But from specifications and former investigations [e.g. Juretzko, 2007] it is known, that the laser tracker's angle uncertainty exceeds the distance accuracy in the static mode. Therefore, one might assume the same for the kinematic mode. So tracker-position 1 should perform better for determining the x-deviation of the track and tracker-position 2 should perform better for the y-deviation of the track. While using both positions and analyzing the data, specific artefacts of the tracker behavior in kinematic mode could be detected.

If effects, that refer to the horizontal angle measurement, are denoted by ΔH and distance-measurement dependant effects are denoted by ΔD, we can model the actual track deviation in x-direction W_x using the measured deviation W_{1x} from position 1, which shows also different repeatability errors Δx_{1i} in each run i, ref. (1). Additionally, we can use W_{2x}, Δx_{2i}, respectively (ref. (2). The parameter s covers stochastic effects. Of course, all parameters depend on the track position and finally on time, which can be modeled by geometrically based impact factors.

$$W_{1x} = W_x + \Delta x_{1i} \qquad + \Delta D (+ s_{1x}) \tag{1}$$

$$W_{2x} = W_x + \Delta x_{2i} + \Delta H \qquad (+ s_{2x}) \tag{2}$$

Now, the difference between the two tracker positions is independent from the systematic (geometric) track deviation:

$$W_{1x} - W_{2x} = \Delta x_{1i} - \Delta x_{2i} - \Delta H + \Delta D(+s_{1x} - s_{2x}) \qquad (3)$$

So, if the track repeats well in all runs, $\Delta x_{1i} - \Delta x_{2i}$ is small and the extent of the tracker deviations can be estimated. Accordingly, the analysis of the y-component of the track delivers additional information (valid for approximately perpendicular view on track):

$$W_{1y} = W_y + \Delta y_{1i} + \Delta H \qquad (+s_{1y}) \qquad (4)$$

$$W_{2y} = W_y + \Delta y_{2i} \qquad + \Delta D(+s_{2y}) \qquad (5)$$

$$W_{1y} - W_{2y} = \Delta y_{1i} - \Delta y_{2i} + \Delta H - \Delta D(+s_{1x} - s_{2x}) \qquad (6)$$

Furthermore, the sum of (3) and (6) should be zero except for the repeatability errors:

$$W_{1x} - W_{2x} + W_{1y} - W_{2y} \qquad (7)$$
$$= \Delta x_{1i} - \Delta x_{2i} + \Delta y_{1i} - \Delta y_{2i}(+\sum s)$$

Unfortunately, for separating angle- and distance-related effects, a third position might be necessary, which enables measurements with sufficiently different impact factors of these effects on both of the track coordinates. Otherwise, a circle test based on time referenced rotating arm data should be executed.

In the following, some results from the second experiment of the project mentioned above will be shown. These results refer to the specific set of the laser tracker's internal control loop and may depend on production spread. First of all, we find the overall repeatability according (7) not very satisfying for educated guesses (ref. Fig. 9), although on a brief look the results shown above look quite promising in respect to repeatability. Besides some very large offsets relating to the pair of run 2 and 8, we find a strong cyclic component in the data. The large component starts with a peak-to-peak value of more or less 0.1 mm after the acceleration phase and diminishes quickly and totally with time (and traverse path, see Fig. 10). Its period equals to the transient response of the robot (0.2 s or 20 mm). On a closer look on the previous results, we remember a phase shift in the X-component, which seemed to depend on the offset of the start-position (ref. 4.3). Of course, we find now the impact of these phase shifts in oscillating deviations with the same frequency.

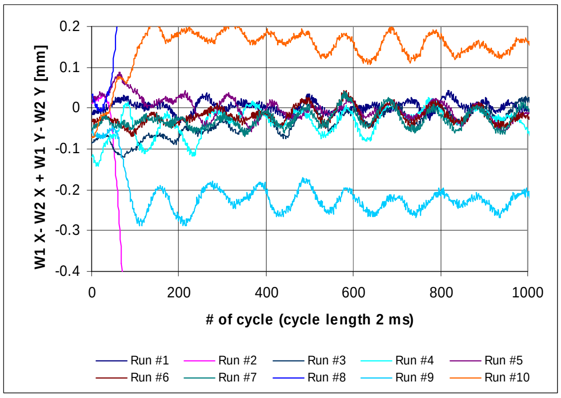

Fig. 9: Overall repeatability in the start-up phase, 10 arbitrarily pairs of runs are shown

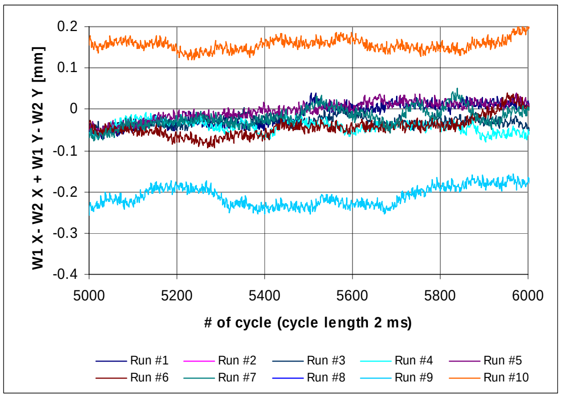

Fig. 10: Overall repeatability in the middle of the run, 8 from 10 arbitrarily pairs of runs are shown due to scale reasons

Additionally, we can detect a very small ripple. Zooming in the original data, we find them mostly belonging to the W_{2x} and W_{1y}. This supports the assumption, that the uncertainty of the angle-related data gathered in kinematic applications also exceeds the uncertainty of distance data. Of course, we cannot exclude cyclic effects in the robot's repeatability. Due to the high data rate of the measuring system on the one hand and the long periods of the demonstrated effects, they theoretically can not be explained by delay effects in the measuring system. Therefore, vibrations and potential resonances should be investigated also. For deeper analysis, wavelet analysis will be a powerful tool (e.g., [Schmidt, Schuh, 2000]). Nevertheless, all artefacts do by far not exceed specifications for kinematic measurements. In fact, the tracker-related deviations seem to behave systematically, so there definitely is potential for calibrating them although they are very small.

6 Active hub

Due to the robot's motion and the limited working range of the reflector we are developing a reflector hub, which will allow for the revertive rotation of the CCR. In a first step, we set up a functional model with one rotation axis as shown in Fig. 11 for 1.5" CCRs or cat-eye-reflectors. This model is improved with respect to accuracy by modifying the bearings and altering the working range from 270° to theoretical endless. The only limitation is given due to the mounting and/or cable routing, but at least 270° could be covered. The resolution amounts to 0.36° and 0.2° respectively, which exceeds the requirement of remaining in the working space of the reflector by far. The bearing is smartly designed, so that the center point of the prism-supporting steel-sphere remains stable within 5 µm lateral and, due to the bearing’s design, less in axis-direction. This value accounts for the bearing tolerance as well as for the roundness of the CCR, but certainly not for the centering of the prism.

For another project (reference-point determination of radio-telescopes [Lösler, Hennes, 2008]) we added a second axis (see Fig. 12). The working range encloses 270° for the first and “nearly endless” (see above) for the second axis respectively. According to this, the device can be used upside-down, but there are geometrical configurations, which provoke a rotation to a force-free position, if the device is powered off. Rotation speed can easily reach 20°/s and rotational acceleration can reach about $10°/s^2$, both not being the bottle-neck of the system. The axes intersect within a tolerance of 0.5 mm and can be adjusted to 0.1 mm. This is not done yet, because the present state is sufficient for the intended large-scale application mentioned above. However, the work-space of an 1-axis-hub combined with a cat-eye reflector is sufficient for most applications.

All versions are driven by a constant current stepper. For steering, we use commercial driver software or own software basing on Labview, which provides fundamental operations. The software either processes a list of given rotations or enables manual steering for stop-and-go mode applications. This list contains all rotations including their temporal allocation. As there are (partly extremely varying) WINDOWS-related delays taken into account, this method does not support precise tracking of apparently very fast rotating CCRs.

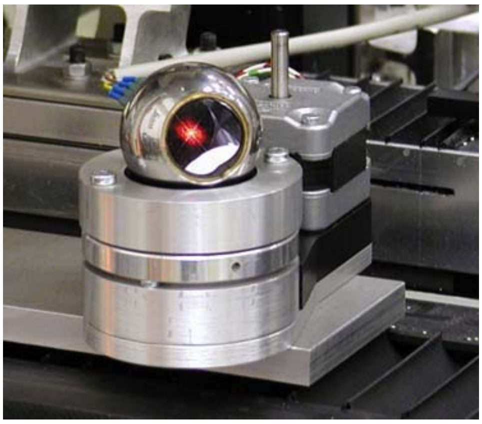

Fig. 11: Functional model of the active hub, 1-axis, high-precision version

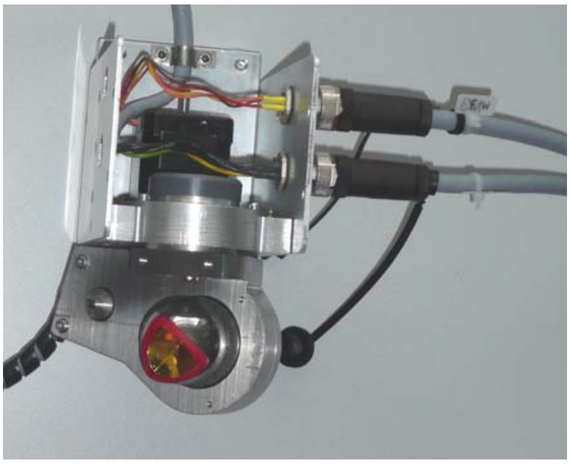

Fig. 12: Functional model of the active hub, bi-rotational version

7 Conclusions

The presented investigations showed that laser trackers are suitable instruments in order to determine deviations of the actual movement of a robot from its nominal movement. As soon as longitudinal deviations exist, time referenced measuring systems are essential: Even if they are not in the focus, delay effects may prevent spatio-temporal correlation. The only measuring system delivering the necessary accuracy is a Leica laser tracker in combination with the "LT CONTROLLER plus"[1], because this system processes trigger signals with the necessary resolution.

With this system, the geometric and temporal deviations of a TCP (tool center point) could be investigated with an uncertainty of 0.05 mm (k=1, low range), mostly limited by the quality of the definition of the robot’s reference system (see 3.2, notes on transformation). In particular, a high repeatability of the robot could be proved. Lateral as well as longitudinal deviations down to the magnitude of some hundredths of a millimeter could be detected and traced back to the robot. Particularly, in the initial part of the movement (first second) a reproducible transient response could be determined.

The repetition accuracy of the inspected robot is extraordinarily high (at least within the investigation period of approx. one hour) with a standard uncertainty of an individual measuring of maximally 0.06 mm. In the future investigations are to be accomplished for the effect of changed parameter sets and the observation of the long-term stability. Apart from the calibration of kinematic measuring instruments, in the future our group will focus on this task.

8 References

[1] Next generation model: AT 901 and AT Controller

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