Monitoring of the spatiotemporal movement of an industrial robot using a laser tracker

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Abstract
The project introduced here describes the geometric inspection of an innovative robot-based production process for spatially curved extruded profiles. The aim was to prove that the trajectories fulfil a given spatiotemporal tolerance level with respect to repeatability and absolute accuracy using an independent, i.e. geodetic, measurement method. In order to inspect this motion regarding spatiotemporal tolerance, it is necessary to synchronize a laser tracker with the control system of the robot with an order of magnitude of micro seconds. This resolution has been achieved by triggered measurements with a Leica LTD500. Very specific and for the production process, decisive deviations of the robot trajectory have been detected as well as an extraordinarily high kinematic repeatability of the robot.

Keywords
Laser tracker, kinematic measurement, industrial robot, synchronization

1 INTRODUCTION
With the development of new production methods robots play nowadays 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 prove by an independent measuring method how precisely the predefined trajectories are converted and how the given spatial positions are tightened by the robot. The presented project describes the monitoring of an innovative, robot-supported procedure for the production of spatially curved extruded profiles developed by the Institute of Production Science at the University of Karlsruhe. In doing so, the special challenge for the measurement is the synchronization of the involved laser tracker with the robot in the range of microseconds.

2 MOVEMENT OF THE ROBOT
Using the innovative process of rounding during extrusion, spatially curved extruded profiles can be flexibly manufactured. This facilitates the cost-effective production of lightweight structures with curved profiles even for small series. Due to the extrusion process a continuous flow of material is unavoidable. The profiles have to be separated reactionlessly during the extrusion following the complex trajectory of the cut-off point in space. Because of the high accelerations which occur during the spatial motion of the profile the trajectory is separated into the slow motion of an industrial robot guiding the cut-off device and a fast superposed movement generated by a specially designed clamping device with redundant axes. To synchronize the motions according to the real extrusion velocity a server-based central control unit is used [Fleischer et al.].

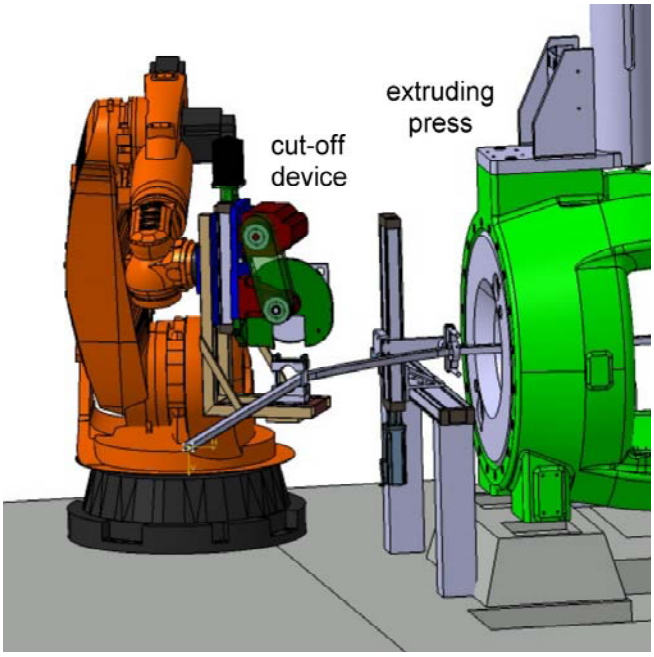

Figure 1: Production system

In the current development phase of the project the focus of the surveying work is 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 remain unconsidered in this phase just as the effect of the very complex temperature field of the environment on the measuring behaviour of the laser tracker. Primarily a comparison of the planned with the actually driven trajectory of the robot is to be made in the current phase, in order to increase the accuracy of the manufactured extruded profile by an inline calibration in a further step.
Since the manufactured profile leaves the extrusion press with a certain speed, it is not only necessary that the actual trajectory of the "flying saw" consists with the geometry of the planned trajectory. Additionally it is necessary that the robot positions the TCP at the right time at the correct place.
In order to prove these trajectories, a synchronisation of manufacturing robot and laser tracker is necessary.

3 SYNCHRONIZED MEASUREMENT

3.1 Measuring method

For the detailed measurement of the trajectory of the TCP a laser tracker Leica LTD500 was used. Laser trackers are highly exact polar measuring systems for the determination of spatial coordinates with a working radius of up to 35 m. The coordinate measuring accuracy of the LTD500 is indicated to ±10 ppm (2σ) for static targets by the manufacturer. This agrees with more extensive investigations for the repetition accuracy of the angular measurement [Juretzko 2007]. For moved targets the accuracy is indicated as ±40 ppm which is confirmed by investigations [Depenthal, Barth 2007].

3.2 Synchronized kinematic measurement

The measured values of the laser tracker must be set into a temporal relationship with the actions of the robot. The synchronisation must guarantee that the assigned times of robot action and measurement on the respective time scales of the two systems are very close together. It must be so close that the blur that is caused by the time difference and the speed of the TCP remains within a tolerable size.
The ideal solution for the synchronization of robot and laser tracker is triggering with the help of a superordinated master clock. A trigger signal (e.g. the sloping flank of a square wave signal) activates a simultaneous action with all process members together. Now the edge steepness and the response

time of the individual process actions determine the quality of the synchronisation, uninfluenced by the drift of the trigger-generating oscillator. This method presupposes that the process components can process external trigger signals and that the correct action is released. The clock frequency of the trigger signal must be selected low enough that within a cycle all participants can terminate their action so far that the start of the next action is possible with the following trigger signal.
The synchronisation with the Leica tracker LTD500 requires the special "LT CONTROLLER plus". This controller permits external triggering. 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 a measurement is interpolated to exactly that point. The timestamp captured with the trigger event will be saved together with the measurement. 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.

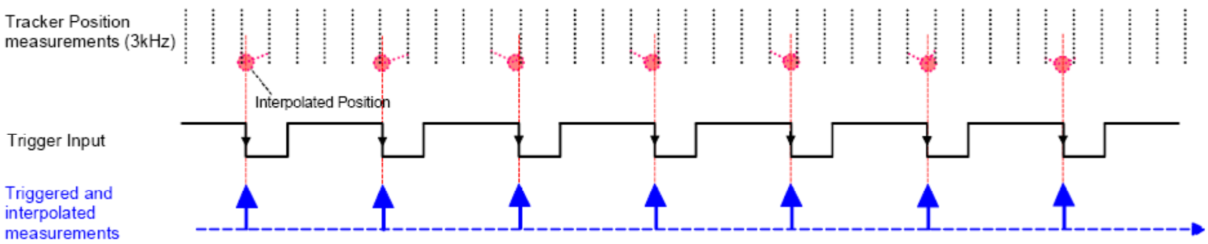

Figure 2: Interpolation of the trigger signal (from: Leica Manual)

The comparison of the clock of the tracker controller with a frequency-stabilized waveform generator showed a constant drift of the tracker clock of +12 µs/s, which lies in the range of the data of the manufacturer [Leica Manual 2005]. Differences in the distances of the individual registered clock pulses did not arise (within the resolution of the tracker clock of 1µs). With the analysis of the trigger signals sent by the control system of the robot (with the clock rate of 250 pulses per second) a drift of the robot clock could be determined in relation to the tracker clock of -55.7 (±0.1) µs/s. The maximum deviation of one trigger time in relation to the allocated time amounted to 78 µs.

4 INSPECTION

4.1 Goal and experiment

The goal of the accomplished monitoring lay primarily on examining how exactly a movement divided into individual cycles is converted by robotic control. From the manufacturer data of ±0.12 mm for the repetition accuracy of an individual position, a requirement was derived for the accuracy of the inspection of better than 0.1 mm (1σ). During the generation of an allegedly simple movement like a straight line all joints are involved by the inspected type of robot. Therefore it is expected that any inadequacies in the joints and/or the controlling of the robot affect the movement in not linear form. The speed of the TCP amounted to 60 mm/s, the length of the trajectory amounted to 2000 mm. The trajectory was put to the control system of the robot in form of a list with 2825 individual values for each space position with a distance of the clock pulses of 12 µs. The positions were interpolated to a distance of the clock pulses of 4 µs. The coordinates referred to the robot coordinate system. The X and Z-coordinates of all points were zero. The position of the laser tracker was 2.5 m away from the point of origin in extension of the straight-line track. The clock pulse for the collection of the measured values was generated by the control system of the robot, the clock rate amounted to 250 cycles per second. For the determination of the reproducibility 10 identically steered runs were accomplished.

4.2 Results

4.2.1 Lateral component

The lateral deviation from the given "straight" trajectory amounted to maximally 0.2 mm. This maximum deviation showed up in a very striking position in the centre of the trajectory (Figure 3). The beginning of the movement shows a transient response with an oscillation period of 0.22 s (54 clocks) and an amplitude of 0.1 mm. In the further process deviations with a period of 0.10 s (25 cycles) and amplitudes up to 0.04 mm are determined again and again. The oscillations at the beginning of the movement are caused partially by the accelerated starting movement, by which the system is exposed to a jerk. The force resulting from it affects the robot structure and causes flexible deformations in the robot structure, that shows up in the initial oscillation. The oscillations in the further, constant process of the movement partly arise as a result of the used transmissions as well as the small rigidity of the overall system. The very small repetition standard uncertainty of the tracks is remarkable: Thus the maximum standard deviation of an individual deviation at a certain position amounted to only 0.03 mm.

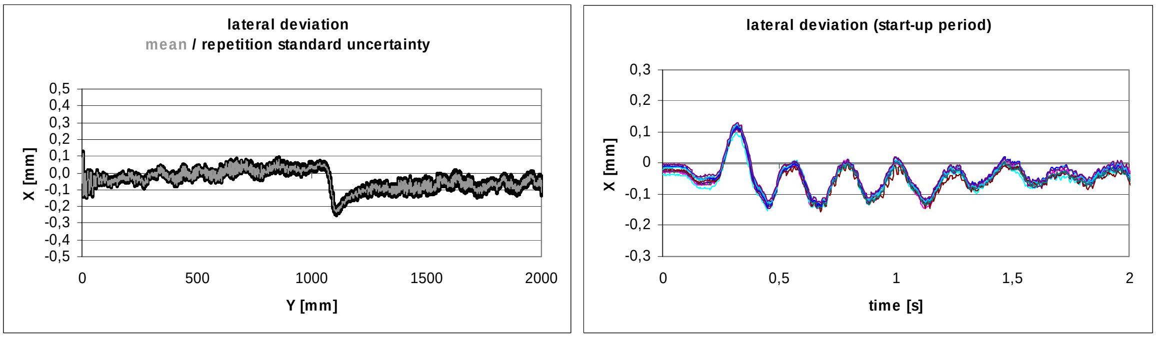

Figure 3: Lateral deviation

4.2.2 Vertical component

The vertical component of the movement exhibits somewhat larger deviations in relation to the nominal trajectory than the lateral component (Figure 4). The maximum deviations amount here to 0.3 mm. More pronouncedly is also the transient response: Vertically first an oscillation of 0.4 mm takes place downward, which changes then into an absorbed oscillation. The oscillation period in the initial phase amounts to 0.18 s (46 cycles). Also here the oscillations can be partly attributed to the small rigidity of the robot structure. In the further process then irregularly ranges with the same frequency are observed with amplitudes up to 0.15 mm. Further it is recognized that for most of the runs different starting elevations were present. Altogether it shows up that the repetition accuracy of an individual position with 0.04 mm is smaller than those of the lateral deviation.

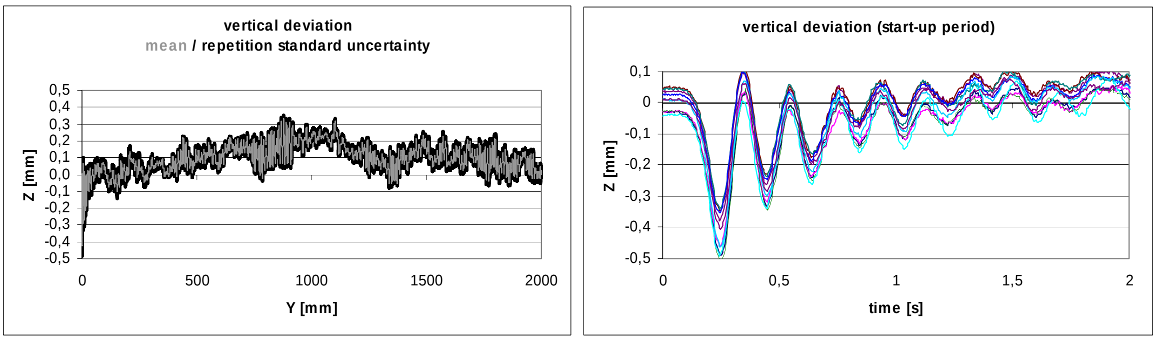

Figure 4: Vertical deviation

4.2.3 Longitudinal component

For the evaluation of the behaviour of the robot in 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. It is recognized clearly that the movement begins due to reaction times and contouring error with a certain delay. When starting the robot from the halt, the nominal velocity is reached after approximately 0.7 seconds (Figure 5). Thus the TCP drags behind nearly 6 mm right from the start. The linear trend in the longitudinal deviation of 290 ppm indicates a scale difference of robot and tracker coordinate system.

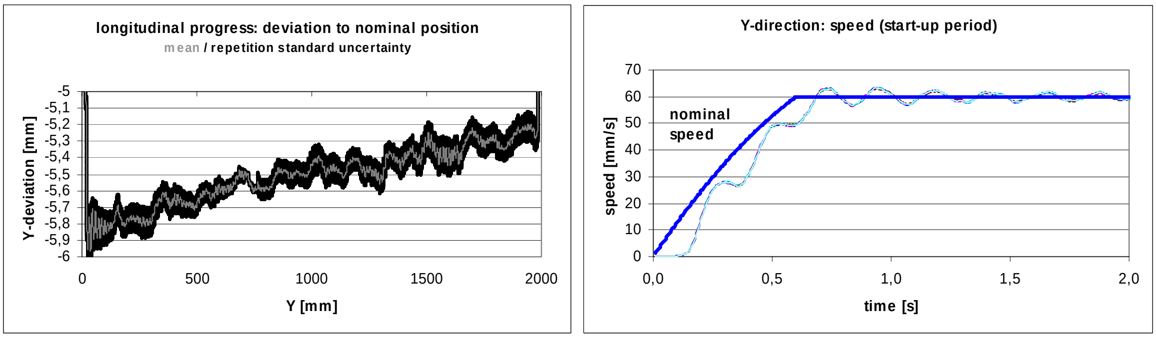

Figure 5: Longitudinal progress and speed

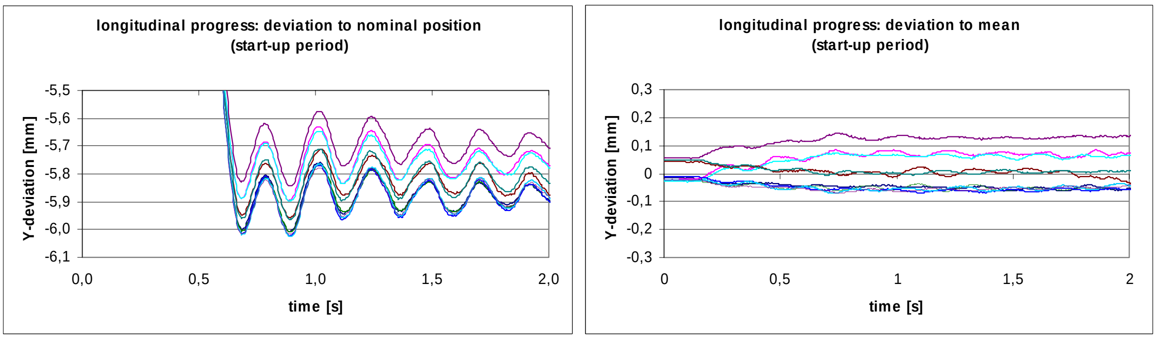

Figure 6: Start of the longitudinal progress

In the initial phase of the movement (Figure 6) oscillations arise with a period of 0.22 s (54 cycles). The amplitude amounts up to 0.1 mm. Even in the further process ranges with a comparable frequency are observed, whereby the amplitudes reach then maximally 0.04 mm. The 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: The diagram of the deviation of the Y-positions from the mean shows that the movements have two different initial positions and that with movement progress a further differentiation of the trajectories takes place. Different levels of progress are reached, which differ around 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.

5 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 deviations in directions must be determined which coincide with the direction of the motion, time referenced measuring systems are indispensable. This succeeds with the necessary accuracy only with the "LT CONTROLLER plus".

The maximum lateral and vertical deviations from the nominal position were less then 0.5 mm. The deviation in direction of the motion amounted due to reaction times and contouring error to nearly 6 mm. In particular in the initial phase 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. This becomes, apart from the calibration of kinematic measuring instruments, in the future a main point of work of the geodetic institute, which owns the necessary hard and software.

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