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POSITION CONTROL OF AN INDUSTRIAL ROBOT USING AN OPTICAL MEASUREMENT SYSTEM FOR MACHINING PURPOSES

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ABSTRACT

A series of mechanical properties and disturbances limit the accuracy achievable in robotic applications. External control of the end effector position is commonly known as being an appropriate mean to increase accuracy. This paper presents an approach for position control of industrial robots using the pass-through between an industrial CNC and servomotors. A CNC-controlled robot is used together with an external optical measurement system to close the feedback loop of robot end effector and robot controller in order to improve robot accuracy. For short cycle times and implementation reasons a PLC is used for signal processing and control implementation. The relevance of the approach is outlined in experiments. The robot behaviour in free space motion and in machining application is analysed with the optical measurement system and a CMM.

Keywords: Robot position control, robot end effector tracking, robot machining.

1 INTRODUCTION

Limited stiffness and limited position accuracy reduce the impact of industrial robots in machining applications. In order to achieve better surface quality different approaches have been presented. Kinematic calibration (Dietz *et al.* 2012) as well as deflection compensation have been investigated in the past (Abele *et al.* 2011). However, the consideration of kinematic effects and dynamic effects could further improve the performance. Dynamic effects are in particular such as backlash, compliance and friction as well as temperature effects and disturbances from the environment. Schmitt, Norman and Mosqueira use an iGPS system to compensate for those effects in an handling operation (Schmitt *et al.* 2010, Norman *et al.* 2012, Mosqueira *et al.* 2012). Schuetze and Ziegler use photogrammetric measurement systems in order to improve positioning accuracy (Schuetze *et al.* 2009, Ziegler *et al.* 2011). Another method for end effector tracking is proposed by Drust *et al.* 2011. This approach measures the variation of projections to control the robot. Wang analyses the end effector tracking of robots with iGPS and lasertracker and compares them (Wang *et al.* 2011). The presented results are promising, However, they do not show the relevance of the approach in high-frequent applications like machining. In machining process disturbances influence the positioning of the robot and require a fast and dynamic compensation. This topic will be addressed within this paper.

Within the European FP7-project COMET different compensation approaches are addressed in order to reduce surface tolerances to 50 µm (COMET 2012). Kinematic and dynamic robot models are used to predict deviations and to compensate for them. Further online compensation is used to compensate and push precision beyond 100 µm.

This paper is organised as follows. Section 1 introduces the topic. Section 2 describes the experimental setup and the implementation of interfaces and controllers and is followed by Section 3 explaining the experimental validation of the performance with free space robot movement and robot machining experiments. Finally conclusions are reached affirming improvement for the robot's positioning accuracy with the implemented control.

2 SETUP AND IMPLEMENTATION

In order to show the real potential of end effector control a robotic machining cell is set up and all required components are integrated. A KR125 industrial robot from KUKA together with a K600 measurement system from Nikon Metrology and a Chopper 3300 spindle from Jaeger are combined on a 14 t machine bed (see Figure 1). The K600 measurement system fulfills all key requirements needed for a robotic machining process: Short cycle time, robust measurements, precision. The sensing of a series of LEDs with three cameras in an appropriate workspace allows to measure several frames with an accuracy of ±90 µm in a cycle time up to 1 kHz. The possibility to attach redundant LEDs is essential in order to provide a constant measurement signal while shadowing LEDs by robot movements or disturbances from the machining process such as chips or lubrication.

Figure 1: Robotic machining cell with K600 measurement system, Chopper 3300 spindle and KR125 robot.

In order to optimize path generation and to provide proper interfaces the KR125 hardware is driven by TwinCAT CNC control from Beckhoff. The extended look-ahead as well as the adjustable trajectory planning of the CNC kernel allow to optimize the robot path for the machining requirements. The trajectory planning task is interfaced to the PLC where signal processing, computation of corrections and signal routing is performed. The corrected signals are then fed to the servo-drives (see Figure 2).

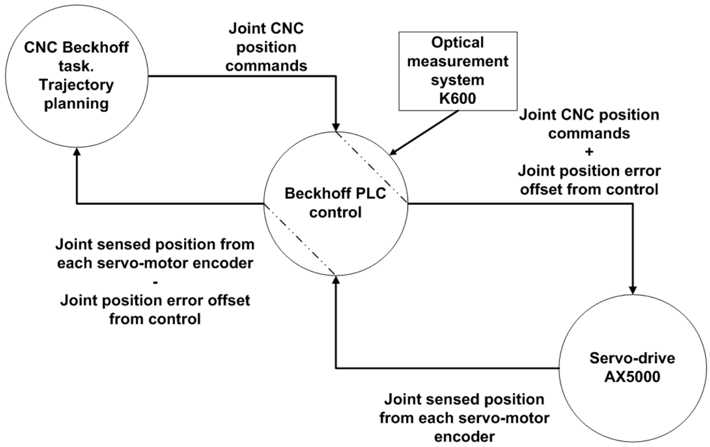

Figure 2: Combination of CNC-kernel, PLC, K600 and drives to a closed loop control system

Via a TCP connection the PLC receives the measurements of the K600 measurement system containing the 6D pose of the robot's end effector. Figure 3 shows the cycle time analysis of the K600 communication. A state machine is used to organize the communication. In state 2 the TCP stack is read lasting 1.7 ms. The PLC task is set to a cycle time of 10 kHz in order to minimize calculation time between stack readings. The sum of stack reading and communication routing results in a maximal polling frequency of 500 Hz. Considering the bandwidth of industrial robots of < 30 Hz (Schneider *et al.* 2013) 500 Hz is considered to be sufficient for end effector control of industrial robots.

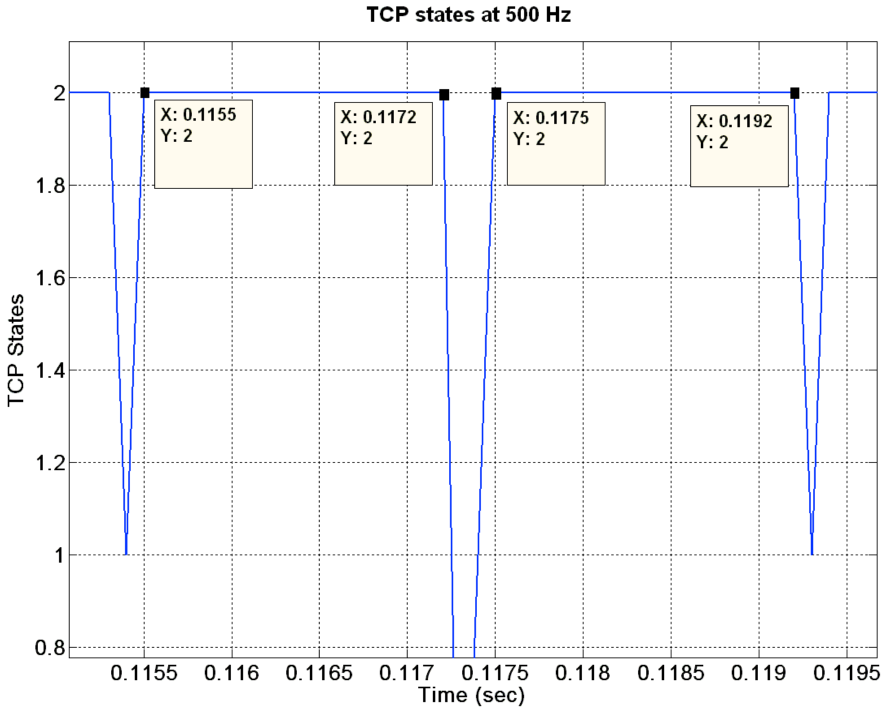

Figure 3: TCP communication between PLC and K600: Stack reading lasts 1.7 ms

As the transformation between joint and Cartesian space is performed within the CNC-kernel control adjustments need to be performed on joint level. As measurements are only available in Cartesian space a mapping to joint space needs be performed. The error between Cartesian reference and measurement is transformed to joint space using the inverse Jacobian (see Equation 1).

$$\delta Q = J^{-1}\delta X \tag{1}$$

As the correction offsets are expected to be small the linearization of the Jacobian is valid and Cartesian offsets will be transformed to joint offsets until the errors are compensated for. Depending on the operational mode of the CNC kernel the Cartesian pose is not always available. In order to be independent from the operational mode, a forward kinematics implementation is used to compute the Cartesian pose. The description of Denavit-Hartenberg is used to deduce the 6D pose. The analytical expressions of forward kinematics and Jacobian are implemented in the PLC. Mathematical simplifications of the analytical terms to reduce computation time and functionalities to detect singularities are applied. A general scheme for the implemented position control is depicted in Figure 4.

6 digital PID controllers are implemented on joint level. Manual tuning of controller gains k_p, k_v and k_i (see Equation 2) with the input q and the output τ leads to the results depicted in Section 3.

$$\tau = k_P\, q + k_v\, \dot{q} + k_i \int_0^t q(\sigma)d\sigma \tag{2}$$

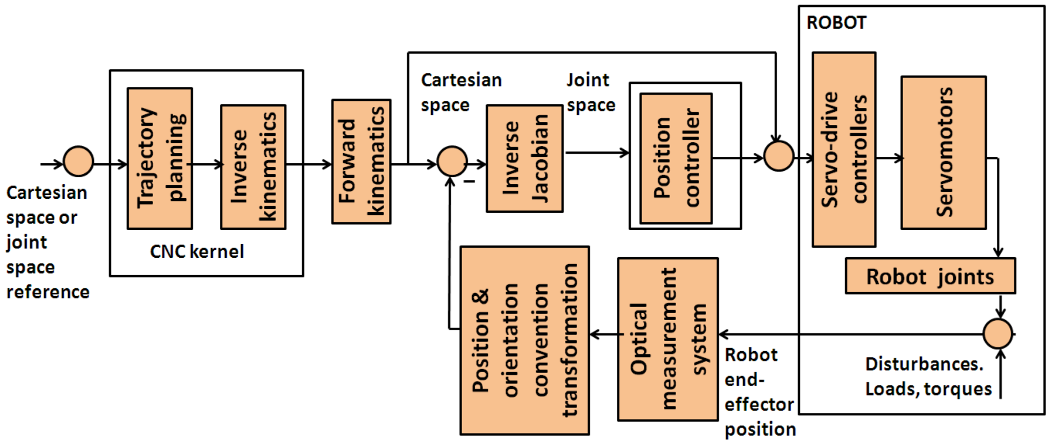

Figure 4: General scheme for the implemented position control.

3 EXPERIMENTAL VALIDATION

In order to analyse the performance and improvement of the system experiments have been conducted. First the performance of this implementation is evaluated by measuring the trajectory accuracy of a circular path as defined in the ISO 9283 standard. Finally, machining experiments are performed and measured on a Coordinate Measurement Machine (CMM) in order to depict the control performance.

3.1 Validation in Free Space Motion

ISO 9283 describes the standard for determination of robot accuracy (ISO). The movement is designed as a circular trajectory of 210 mm of radius inclined 45 degrees. The movement is performed in a designed work space close to the spindle in order to point out the relevance for the machining application. The feed rate was set to 1000 m/min as it is typically used in machining. Table 1 depicts the calculated trajectory accuracy for both the uncontrolled robot and the robot controlled by the feedback loop with the external tracking system. Figure 5 depicts the XY plane of the circular movement pointing out the improvements. A similar result can be observed in XZ and YZ planes.

Table 1 points out the trajectory accuracy calculated according to the standard. Accuracy could be increased by 33.76% by means of feedback control.

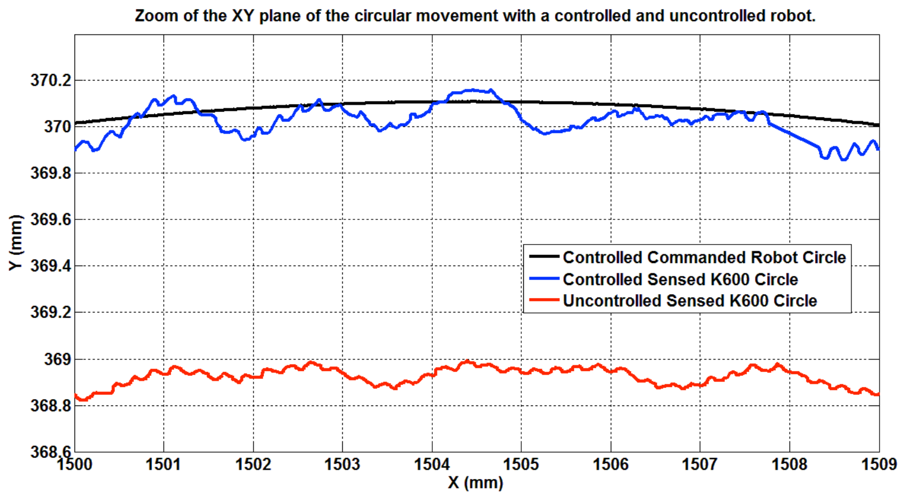

Figure 5: Comparison of circular movements with a controlled and uncontrolled robot.

Table 1: Trajectory accuracy according to ISO 9283 for the free space movement experiment.

Trajectory Accuracy (mm)	
Robot without control	1.7133 mm
Robot with control (Final PI tuning)	1.1348 mm

3.2 **Validation in Machining Experiments**

A circle with a diameter of 70 mm is machined in steel to show the relevance of the approach in machining operation. The circle is placed in the YZ plane of the robot. With a stepdown of 0.5 mm and a feedrate of 300 m/min an 8 mm solid-carbide tool "HPC TiSi" from HOLEX is chosen to operate in full width cut. No lubrication or cooling is used. The machining result is analysed with a "Videocheck HA400" coordinate measuring machine (CMM) from Werth. By raster scanning point clouds of the inner and the outer circle can be captured and then subsequently be compared to ideal circles. Figure 6 depicts the circles captured by the CMM and the nominal circles.

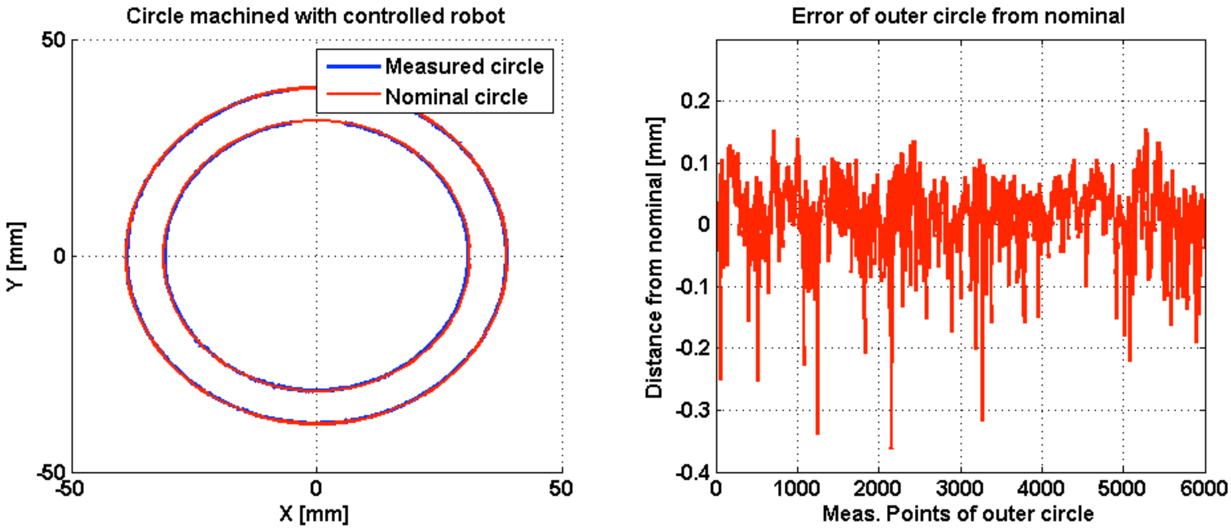

Figure 6: (Left) Contours for the machining with a controlled robot. (Right) Errors of the measured points from the nominal circle

The results are evaluated using the Mean Absolute Error (MAE) (see Equation 3).

$$MAE = \sum_{t=1}^{T} \frac{|X_i - X_f|}{T} \tag{3}$$

"Where X_i = observed value of data at time t, X_t = forecasted value, and T = total number of observations at time t." (Hyndman *et al*. 2006). The comparison of the two experiments is listed in Table 2.

Table 2: Mean Absolute Error for the machining with uncontrolled and controlled robot.

	MAE Inner Circle (IC)	MAE Outer Circle (OC)	(IC + OC)/2
Robot uncontrolled	252 µm	255 µm	253 µm
Robot PI controlled	80 µm	47 µm	63 µm

As expected the result with the controlled robot is better than the result with the uncontrolled robot. The improvement for the conducted test can be quantified by 75%. It should be noted, that the improvement in machining operation is even higher than in free space motion. This can be explained by disturbances due to the machining process which deflect the robot in uncontrolled configuration whereas the deflection can be compensated when machining in controlled configuration. Further, it should be noticed that the combination of redundancy of LEDs and intelligent signal routing enables an optical measurement system to provide robust control behavior in machining environment where disturbances such as chips and dust are available.

4 CONCLUSION AND FUTURE WORKS

This paper describes a novel approach of implementation and evaluation of a position control using an external optical measurement system for machining purposes. A CNC controlled robot is interconnected with a K600 system and a closed loop control is set up. Under consideration of sample times and delays the system has been optimized for fast, robust and precise robot positioning. The performance of the approach is evaluated in free space motion as well as in machining operation in steel. Results are examined on a CMM and applicability of the approach has been proven. Improvements of 46.88% could be experimentally demonstrated.

More advanced control approaches could be considered in future works. Using models describing the dynamics of the system, model-based control systems could be set up and performance of the system could be increased.

REFERENCES

Abele, E., J. Bauer, C. Bertsch, R. Laurischkat, H. Meier, S. Reese, M. Stelzer, O. von Stryk. 2011. Comparison of Implementations of a Flexible Joint Multibody Dynamics System Model for an Industrial Robot. In *Proceedings of the 6th CIRP International Conference on Intelligent Computation in Manufacturing Engineering*

COMET, EU/FP7-project. 2012. Plug- and produce Components and METhods for adaptive control of industrial robots enabling cost effective, high precision manufacturing in factories of the future. URL: http://www.cometproject.eu

Dietz, T., U. Schneider, M. Barho, S. Oberer-Treitz, M. Drust, R. Hollmann, M. Haegele. 2012. Programming System for Efficient Use of Robots for Deburring in SME Environments. In *Robotik 2012 - 7th German Conference on Robotics*

Drust, M., A. Verl. 2011. Conceptual design and analysis of an on-line opto-mechatronic measuring system based on pattern projection. In *IEEE/ASME International Conference on Advanced Intelligent Mechatronics (AIM)* 844–849

Hyndman, R. J., A. B. Koehler. 2006. Another look at measures of forecast accuracy. In *International Journal of Forecasting*, 22, 4, 679-688

ISO International Organization for Standardization. 1998. ISO 9283:1998(E). *Manipulating industrial robots - Performance criteria and related test methods.* Geneva, Switzerland

Mosqueira, G., J. Apetz, K. M. Santos, E. Villani, R. Suterio, L. G. Trabasso. 2012. Analysis of the indoor GPS system as feedback for the robotic alignment of fuselages using laser radar measurements as comparison. Robotics and Computer-Integrated Manufacturing. 28:6:700–709

Norman, A. R., A. Schoenberg, I. A. Gorlach, R. Schmitt. 2012. Validation of iGPS as an external measurement system for cooperative robot positioning. In: *International Journal of Advanced Manufacturing Technology* 1–20

Schmitt, R., S. Nisch, A. Schoenberg, S. Renders. 2010. Performance Evaluation of iGPS for Industrial Applications. In *Proceedings of International Conference on Indoor Positioning and Indoor Navigation (IPIN)* 1–8

Schneider, U., M. Ansaloni, M. Drust, F. Leali, A. Verl. 2013. Experimental Investigation of Sources of Error Robot Machining. In *International Conference on Flexible Automation and Intelligent Manufacturing.* Reviewed and submitted.

Schuetze, R., C. Raab, F. Boochs, H. Wirth, J. Meier. 2009. Optopose – a Multi-Camera System for Fast and Precise Determination of Position and Orientation for Moving Effector. In *9th Conference on Optical measurements* 115–124

Wang, Z., L. Mastrogiacomo, F. Franceschini, P. Maropoulos. 2011. Experimental comparison of dynamic tracking performance of iGPS and laser tracker. In *International Journal of Advanced Manufacturing Technology*, 56, 205–213

Ziegler, C., J. Franke. 2011. A cost-effective stereo camera system for online pose control of patient handling robots. In *Proceedings of 5th International Conference on Automation, Robotics and Applications (ICARA),* 459–464