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Dynamic Accuracy Optimization for NC controlled Industrial Robots

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***Abstract*— In the last years the usage of industrial robotic manipulators is being extended to new applications, like laser or machining-based manufacturing. These applications require new user interface functionalities coming from common NC control systems, as well as increased demands in path tracking, dynamics, and accuracy. In this paper, a Dynamic Accuracy Optimization strategy is applied on a NC controlled industrial manipulator to minimize robot Tool Center Point errors during path execution. A state-of-the-art laser tracker system is used for online characterization of the TCP position which is fed to the compensation algorithm integrated in the NC controller. A drastic reduction of static and dynamic errors has been observed in both linear and orientation degrees of freedom, impacting also in the resulting path errors.**

Keywords—CNC, robotics, machining, accuracy, control

I. INTRODUCTION

Industrial robots have been applied in manufacturing processes from many industrials sectors to automate repetitive, dangerous, heavy-duty, and resource-intensive tasks, and, eventually, to automate human-intelligence demanding tasks [1]. Low accuracy requiring tasks as spraying, painting, spot welding, sealing, and parts picking are usually covered by industrial robots [2].

Machining is one of the most used manufacturing processes to obtain final products that require high dimensional accuracy and surface quality. Expensive and single-task CNC machine tools are currently used for machining operations, as they can produce high quality parts with a high production rate [3]. On paper, robotic manipulators are the perfect candidates to replace expensive, single-task and big cartesian machine tools [4] as they are much cheaper, multi-functional, and provide larger relative workspace [5]. However, drawbacks like limited stiffness, low absolute accuracy, and lack of standardization of programming environment have limited their usage in such demanding applications like machining [6]. In the last years, robotic machining is receiving extensive research to overcome the mentioned problems [7].

Each robot manufacturer provides its own controllers to command the correspondent robotic manipulators, leading to manufacturer dependency from control integration and robot programming perspective. In addition, controllers of industrial robots provide no or limited possibilities to adapt or complement control loops to improve robot performance and only few of them integrate typical NC functionalities like G-code interpretation, path interpolation and smooth trajectory interpolation [8]. However, robot manufacturers are recently offering new functionalities to improve robotic system integration in manufacturing systems, allowing seamless integration of NC features and the possibility to include new control functionalities [9] [10]. The authors presented the integration of a Stäubli RX160 robot with a Beckhoff PLC-based controller with NC functionalities for a polishing application using Stäubli uniVAL technology in [11].

The repetitive positioning accuracy of six-axis robot manipulators is good, in the order of 0.1 mm [12]. This good repeatability makes the usage of this type of robots appropriate handling operations, as mentioned before. However, the absolute positioning accuracy is very low and, hence, their application in other demanding applications is restricted. The open kinematic chain that provides main advantages to industrial robot arms, like large operation space, high flexibility and low cost compared with conventional machinery, strongly decreases the accuracy performance. Serial kinematics combined with limited joint stiffness generates large position errors in the tool center point (TCP). These errors are augmented when high loads (big machining spindles) and external forces (machining efforts) are applied. In addition, typical industrial controllers are usually controlled by a decentralized approach where each joint position is controlled by reading the encoder signal located at the motor, disregard the nonlinearities of robot dynamics, such as friction and couplings between different links. This fact leads to non-acceptable deviations for applications requiring high path accuracy, e.g., laser-cutting [13]. The application of a secondary encoder at the link side is a straightforward and cost-efficient way to increase absolute accuracy in industrial robots, but it requires particular attention to controller design due to non-collocated situation [14]. Although, some few robot manufacturers have adopted this technology (www.fanuc.eu, www.mabi-robotic.com), usually third-party integrators are the ones adapting commercial systems by including complementary sensors and adapting controllers [15]. In any case, the application of this approach is not extended due to cost increase, required more complex control strategy and sensitivity to ambient conditions.

To improve absolute positioning accuracy of robots, offline kinematic calibration and compensation has been extensively researched and is currently applied in industry (for example, ISIOS [16] system by SIEMENS). It basically consists in the generation of a corrected kinematic model of the robot, normally defined using Denavit-Hartenberg (D-H) convention [17], combining discrete measurements of the absolute TCP position, using an external measurement system, and joint positions [18]. This procedure allows increasing absolute accuracy in steady-state positions, reaching levels close to the repeatability of the robot. Although this procedure does not consider load changes, the application of a stiffness model can be used [19]. In any case, it does not compensate errors caused by dynamic effects like centrifugal force, Coriolis force and dynamic coupling for the joints of robot [20] which are critical in path tracking applications.

Online error compensation has been researched in the last years. The approach consists of real-time measurement of the robot end-effector position and its usage to compensate joint setpoints. Although several technologies have been applied for the real-time measurement of the end-effector, like CCD cameras [21], conventional laser interferometry [22] or 3D scanners [23], laser tracker technology is the most used system in the literature and seems to be the most promising approach due to the high resolution, sampling frequency and the possibility to provide 6 degree of freedom (dof) information of the end-effector [12], [24], [25], [26].

In this paper, a last generation laser tracker system has been used to integrate a real-time 6 dof compensation functionality to improve the absolute accuracy of a NC controlled industrial robot during operation. The work is one of the outcomes of the IMOCO4.E project [27][28] where advanced functionalities for smart mechatronic systems are being developed.

The paper is structured as follows. Section II introduces the Dynamic Accuracy Optimization strategy based on external absolute position measurement. Section III presents the experimental set-up used to implement and validate the technology. Section IV summarizes the results obtained in the performed tests. Finally, section V presents the conclusions and future steps.

II. DYNAMIC ACCURACY OPTIMIZATION

The proposed Dynamic Accuracy Optimization approach is based on the measurement of the absolute position of the Tool Centre Point (TCP) of the robot using an external measurement system and the usage of the measurement information to dynamically compensate its position.

A. Measurement of the TCP position

Conventional approach in industrial robots is to use joint position measurement to estimate robot TCP position, applying direct kinematic functions. As mentioned in the introduction, this estimation is subject to big errors even in static operation due to kinematic configuration errors and joint gearbox backlash and flexibility, but this can be mostly corrected using static calibration. However, when the robot is moving, the joint path tracking errors combined with non-linear kinematics results in big estimation errors. A dynamic model of the robot could help improving this estimation, but model complexity and limitation to get accurate information to develop a proper model limits its application.

For these reasons a direct measurement of the TCP using an external sensor is proposed. Laser tracker technology is chosen for this application as it provides high measurement accuracy, 6 dof characterization and allows online measurement capabilities [12]. The raw information provided by these systems usually consists in:

- Distance from the tracker to the end-effector, r.
- Horizontal, θ, and vertical, α, angular positions of the laser pointer.
- Orientation of the end-effector with respect to the tracker coordinate system in quaternions $\{q_r, q_i, q_j, q_k\}$.

This information is combined and converted to a single transformation matrix, that provides position and rotation of the end-effector frame with respect to the laser tracker reference coordinate system ($T_{TCP}^{Tracker}$).

$$T_{TCP}^{Tracker} = \begin{bmatrix} 1-2q_j^2-2q_k^2 & 2(q_iq_j-q_kq_r) & 2(q_iq_k+q_jq_r) & r\,sin\alpha\,cos\theta \\ 2(q_iq_j+q_kq_r) & 1-2q_i^2-2q_k^2 & 2(q_jq_k-q_iq_r) & r\,sin\alpha\,sin\theta \\ 2(q_iq_k-q_jq_r) & 2(q_iq_r+q_jq_k) & 1-2q_i^2-2q_j^2 & r\,cos\alpha \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (1)$$

To calculate the absolute TCP position errors, measured and desired positions need to be defined in the same coordinate system. It was decided to use the robot base frame as the main reference system for this calculation and, hence, the end-effector position information needs to be referred to the robot base frame (T_{TCP}^{Base}). To do so, the end-effector position and orientation defined in the laser tracker frame ($T_{TCP}^{Tracker}$) must be multiplied by the transformation matrix that relates the laser tracker frame and the robot base frame ($T_{Tracker}^{Base}$). This transformation matrix only depends in the mounting position of the laser tracker system with respect to the robot and, hence, can be considered as a configuration input. A fast calibration procedure based on the measurement of some fiducial markers located through the robotic cell, which are referenced with respect to the robot base frame, allows determining the relative position of the laser tracker. This process is enhanced by Spatial Analyzer (SA) software (Fig. 1).

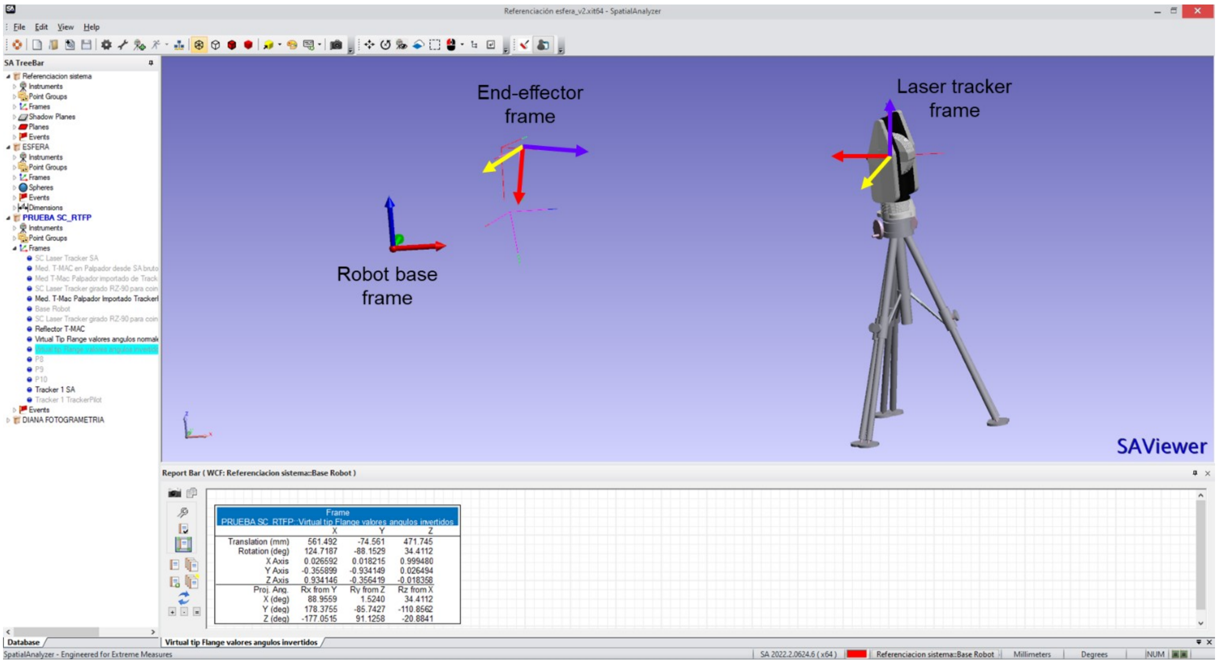
This way, the position and orientation of the TCP of the robot in the robot base coordinate system can be obtained by simply multiplying the two matrixes:

$$T_{TCP}^{Base} = T_{TCP}^{Tracker} * T_{Tracker}^{Base} \quad (2)$$

While the translation in the X, Y and Z axes is directly obtained from the resulting transformation matrix, a last conversion step is required to obtain the end-effector orientation in Euler angles. XYZ extrinsic Tait-Bryan convention has been used to obtain yaw (ϕ), pitch (θ) and roll (ψ) angles as it is the convention used by most CNC controllers.

B. Real-time compensation of robot TCP position

Once the desired (p^*) and real (p) TCP positions are defined in the same coordinate system, it is possible to determine the position errors (e) for the three cartesian linear axis and three rotations used in the main controller.



Frame PRUEBA SC_RTFP::Virtual tip Flange valores angulos invertidos	X	Y	Z
Translation (mm)	561.492	-74.561	471.745
Rotation (deg)	124.7187	-88.1529	34.4112
X Axis	0.026592	0.018215	0.999480
Y Axis	-0.355899	-0.934149	0.026494
Z Axis	0.934146	-0.356419	-0.018358
Proj. Ang.	Rx from Y	Ry from Z	Rz from X
X (deg)	88.9559	1.5240	34.4112
Y (deg)	178.3755	-85.7427	-110.8562
Z (deg)	-177.0515	91.1258	-20.8841

Fig. 1. Representation of the three main coordinate frames in the Spatial Analyzer (SA) software used for the calibration of the tracker position with respect to the robot base frame.

$$\begin{Bmatrix} e_x \\ e_y \\ e_z \\ e_\phi \\ e_\theta \\ e_\psi \end{Bmatrix} = \begin{Bmatrix} p_x^* \\ p_y^* \\ p_z^* \\ p_\phi^* \\ p_\theta^* \\ p_\psi^* \end{Bmatrix} - \begin{Bmatrix} p_x \\ p_y \\ p_z \\ p_\phi \\ p_\theta \\ p_\psi \end{Bmatrix} \quad (3)$$

A proportional controller is applied to obtain the new compensated position setpoints (p_{comp}) to be sent to the robot controller. Each component of the calculated error (e) is multiplied by a constant value (K_{comp}). This scaled error value, calculated at each time step, is then accumulated to determine the compensation that is added to the position setpoints generated by the NC interpreter (Fig. 2). To avoid applying large compensation increments that could overcome the safety limits (velocity, acceleration) of the robot controller, a saturation is applied just after the constant gain (K_{comp}). This saturation is basically affecting when the initial static errors, which can be quite large, are compensated when activating the compensation. During the dynamic compensation stage, once the static errors are corrected, the saturation does not affect.

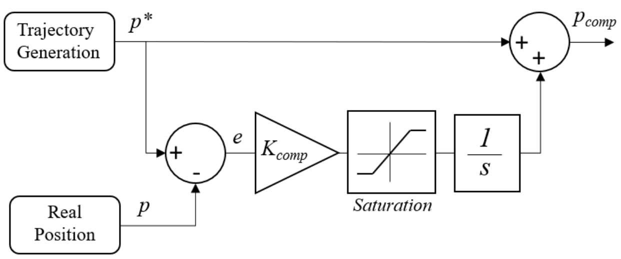


Fig. 2. Schematic diagram of the compensation system.

III. EXPERIMENTAL SET-UP

A Beckhoff C6920 PLC has been used as a main controller of the proposed system, that commands a Stäubli RX160HD robot manipulator using Stäubli uniVAL drive technology. EtherCAT is used to communicate the C6920 controller and the CS8 controller of the Stäubli robot. Joint position commands (q_{rob}) are synchronously exchanged at a sampling rate of 250 Hz.

The required control functionalities have been implemented in Beckhoff TwinCAT environment, an open, PC-based technology that provides real-time control capabilities. It provides a flexible environment for the development and configuration of control systems. For the set-up of the NC controlled robotic system, the TwinCAT Numerical Control Interpolator (NCI), which offers 3D interpolation functions like NC code interpreter, trajectory interpolation and setpoint generation, was used. TwinCAT Kinematic Transformation has been also applied to facilitate the required joint to cartesian transformations, and vice versa. The same base set-up was used by the authors in previous research [11], where more details can be found.

As described in Section II.A, a laser tracker based external position measurement system is used. In this case, the combination of a AT960 laser tracker and a T-Mac device, both from Leica, has been used. T-Mac is a measurement target that allows 6 dof characterization and, fixed to the robot wrist, allows accurate characterization of the robot TCP absolute position and orientation. By integrating the so-called Real Time Feature Pack (RTFP), the AT960 + T-Mac system is upgraded to meet the deterministic measurement data-delivery requirements of real-time robotic control. The RTFP enables data to be delivered with accurate timestamps at a rate of 1 kHz and, hence, allows error calculation to be performed with updated position information in the main controller, with sampling rate of 250 Hz. RTFP information is red by the main controller through EtherCAT interface and, after the required convention and frame transformations, is fed to the compensation algorithm.

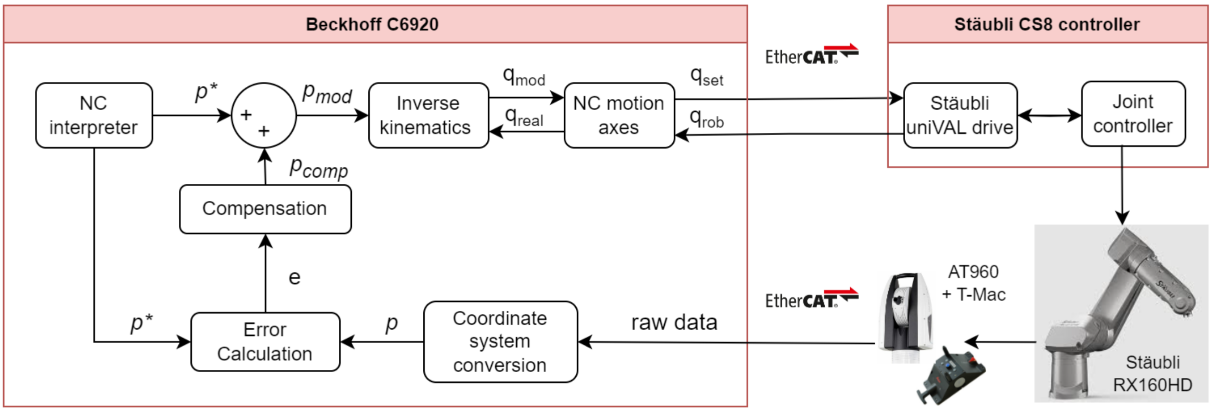


Fig. 3. Applied control architecture for the Dynamic Accuracy Optimization approach.

Dynamic Accuracy Optimization has been implemented in the TwinCAT environment in structured text. Using a modularized approach, traceability and flexibility is guaranteed (Fig. 3). Code modules are organized as follows:

- Coordinate system conversion: The procedure described in section II.A has been implemented in this module. The raw data sent by the laser tracker is, first, converted to a single transformation matrix; then, converted to the robot base coordinate system; and, finally, to the end effector pose (p) adapted to the required convention (XYZ extrinsic Tait-Bryan convention for orientation).
- Error calculation: the difference (e) between each component of the converted measured position (p) and the setpoint generated by the NC Interpreter (p^*) is calculated.
- Compensation: the compensation strategy presented in section II.B is implemented in this module. A value of K_{comp} of 0.01 has been set after a trial-and-error tuning procedure. A more analytical approach for optimized tuning of the compensator will be considered as future work.
- Compensation coupling: The position variations determined by the compensation module (p_{comp}) are added to the nominal position commands (p^*) determined by TwinCAT NCI setpoint generator using a master slave coupling.
- Inverse kinematics: TwinCAT supplies a kinematics library that allows the definition and parameterization of kinematic chains, including 6 dof robot manipulators, and the utilization of standard kinematic functions like coordinate transformation and inverse kinematics. This way, the modified cartesian setpoints (p_{mod}) are then converted to joint coordinates (q_{mod}) by applying the inverse kinematics according to instantaneous robot configuration.

These steps are executed within every controller cycle at a sampling rate of 250 Hz. As a last step, the compensated joint coordinates (q_{mod}) are passed through NC-type motion axes objects in TwinCAT and sent using uniVAL drive to the Stäubli controller, where control loops of each joint are closed.

The proposed system has been set-up in the Robotics Laboratory at TEKNIKER (Fig. 4). A simple interface to activate and deactivate the compensation algorithm is available.

IV. RESULTS

Experimental tests were carried with the presented set-up. To evaluate path tracking performance of the new approach, two types of tests were performed. Path programming was done using standard machining programming language, G-code, made available by the NC capabilities of the proposed system.

First, a square geometry is programmed to evaluate the performance in cartesian linear movements and corner traversing. Fig. 5 a presents the robot TCP linear dof's errors during the realization of a 400 x 400 mm square geometry at 700 mm/min of continuous feedrate in the horizontal plane (XY plane of the robot base frame). It can be observed that static errors from 0.1 to 0.4 mm are present in the linear axes,

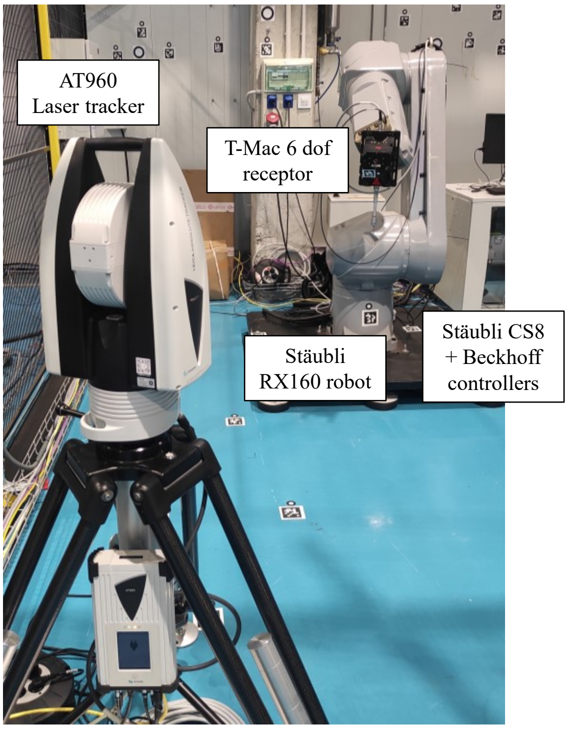


Fig. 4. Stäubli RX160 robot and laser tracker system.

that increase above 1 mm during movement. Fig. 5 b presents the results during the same movement after the activation, at t = 22 seconds, of the Dynamic Accuracy Optimization strategy. It can be observed that both static and dynamic errors are drastically reduced, reaching close to the laser tracker resolution level (approximately 25 µm, for cartesian axes). Several peaks with higher magnitude are present, which corresponds to acceleration/deceleration stages at the corners of the square and the inversion processes at joint configurations. As the available architecture does not allow to modify control strategy neither controller configuration, only two alternatives can be studied to mitigate these peaks: first, to reduce dynamics of the generated setpoints (velocity, acceleration, and jerk); second, to avoid, abrupt kinematic configuration changes. Fig. 5 c and d present the same comparison but for the rotation dof's. As for the linear dof's, static errors, originally in the range of 0.1-0.15 degrees, are drastically reduced, Dynamic fluctuations, above 0.05 degrees during the motion without the compensation, are also minimized with only small sections with errors.

The second test consisted in a circularity test, typical in machine tool characterization [29]. It is usually used to evaluate continuous interpolation between joints, as well as behaviour in axis inversion phenomena. A 150 mm radius circumference has been programmed, again in the XY plane, to be traversed at a constant feedrate of 700 mm/min. Fig. 6 presents the resulting path with amplified errors. It can be

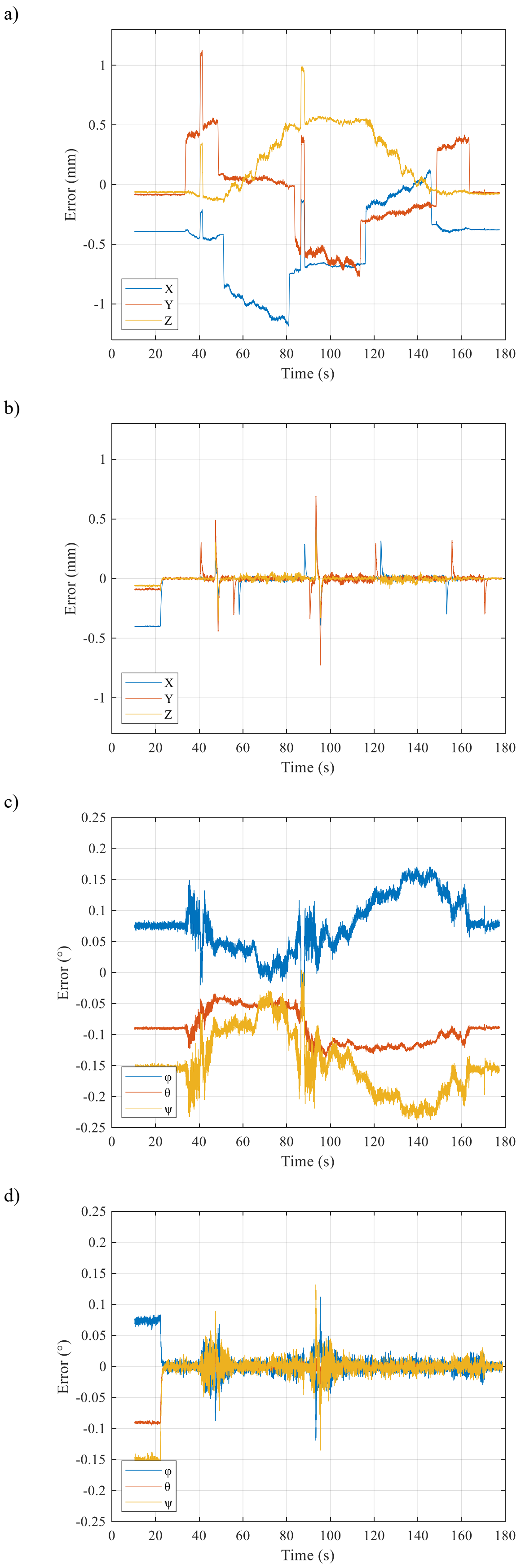


Fig. 5. Resulting individual errors of the 6 dof of the TCP during a square path: a) linear dof's without compensation, b) linear dof's with compensation, c) rotation dof's without compensation, d) rotation dof's with compensation.

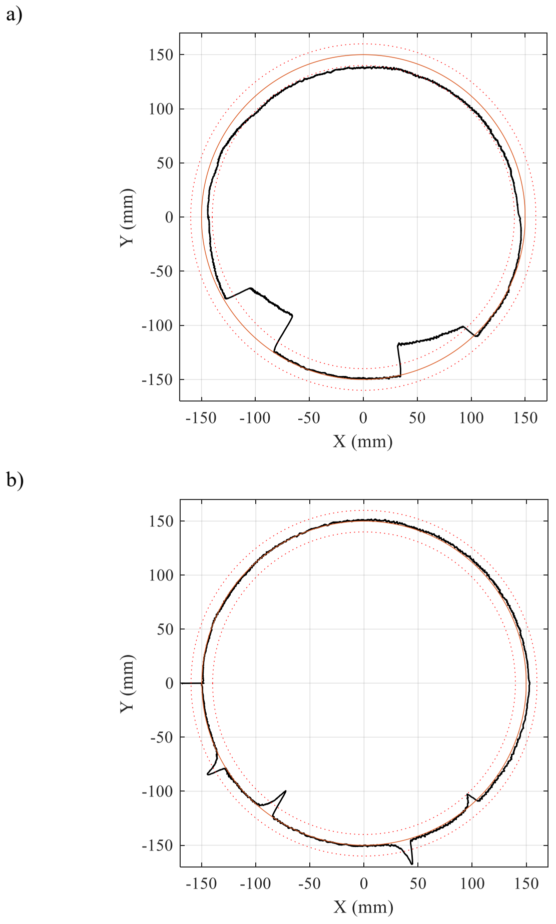


Fig. 6. Circular path with amplified errors (200 µm distance between circumferences) during a 150 mm circle at 700 mm/min without (a) and with (b) compensation.

observed that, without the compensation, the performed circumference is far from the expected one, with large parts with errors of up to 200 microns and specific sections with even higher errors. When the compensation is activated, path errors are greatly reduced (by a 66%, Fig. 7) and the expected circular path is perfectly tracked, with only some small inversion peaks located in an arbitrary position, which are caused by abrupt joint configuration changes. While in conventional cartesian CNC machines inversion peaks are logically present at the quadrant changes of the circle, in robotic manipulators this phenomenon can appear in any place of the circle depending on robot configuration and the required inversions caused by any occurring abrupt joint configuration change. It is clear that both initial joint configuration and the required configuration changes to traverse the defined path must be carefully considered during machining process design to reduce geometrical errors.

V. CONCLUSIONS

A dynamic compensation system for the absolute TCP position of a NC-controlled industrial robot has been developed using an Stäubli 6 dof manipulator controlled by a Beckhoff C6092 controller with NC functionalities. A state-of-the-art laser tracker system that provides accurate and online 6 dof information of the robot end effector is used to implement a real time compensation system.

The implementation of the Dynamic Accuracy Optimization strategy allows a drastic reduction of path errors (80-90 %) minimizing both static and dynamic error sources. As the proposed system can also compensate the effect of external disturbances, like machining forces, it can be an alternative to make conventional industrial robots a valid alternative for conventional machine tools.

The authors acknowledge that the major drawback of the proposed system is the high cost of the applied external measurement system, which can overcome the one of the robot itself. However, the main aim of this work is to prove that, with the application the proposed approach, conventional industrial robots can be used for demanding machining operations. The usage of other measurement technologies, like photogrammetry, will be evaluated in the future to reduce the cost of the solution. Nowadays, limited sampling rate of these technologies (< 30 Hz) is the most limiting factor for dynamic compensation application.

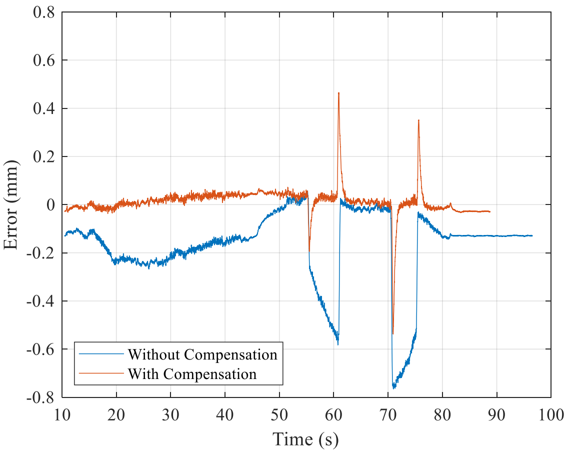


Fig. 7. Absolute path errors during execution of the 150 mm circle at 700 mm/min without and with compensation.

In any case, online characterization of robot TCP during two-dimensional path execution has provided new insights regarding the effect of the combination of explicit following error at joint level and non-linear kinematics of the robots in the path errors, which totally differ to the well-known phenomena existing in cartesian machine tools. These insights will lead to investigate new control approaches for accuracy and dynamics improvement.

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