NC controlled robot for adaptive and constant force 3D polishing

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Abstract— **Industrial robot manipulators have been historically used for applications requiring high flexibility and repeatability. However, in the last years new applications linked to direct involvement of the robots in manufacturing processes have arisen, with increased demands in path tracking, dynamics, and accuracy. In this paper, an external Numerical Control based controller is used to command an industrial 6 dof manipulator, allowing the possibility to command the robot using ISO G-Code, and integrating control functionalities like kinematic transformations and Adaptative Impedance Control. An adaptive and force controlled robotic polishing cell has been set-up as a demonstrator, showing successful polishing performance.**

Keywords—CNC, robotics, Impedance Control, polishing, machining, force tracking

I. INTRODUCTION

Since their first appearance, industrial robots have been applied to automate manufacturing processes on many production floors by automating repetitive, dangerous, heavy-duty, and resource-intensive, tasks, etc., and, eventually, to automate human-intelligence demanding tasks [1]. Low accuracy tasks as spraying, painting, spot welding, sealing and parts picking have been covered by robotic manipulators in recent times [2].

Machining is one of the most important manufacturing processes to convert raw materials into final products. Expensive and single-task CNC machine tools are currently used to perform machining operations, as they are able to provide high accuracy and productivity [3]. Robotic manipulators are the perfect candidates to replace expensive and big cartesian machine tools [4] as they provide a lower cost solution, with higher flexibility (multi-function), and larger relative workspace [5]. However, the inherent drawbacks like limited stiffness, non-lineal serial kinematics and lack of standardization of programming environment have limited their usage in applications with high accuracy requirements [6]. Vast research is being carried out in the field to overcome these problems [7].

Usually, after machining operations, a polishing or deburring process is required to provide the final required part quality. It is a process that is usually performed by hand, incurring in high productivity losses and potential quality faults, and should be automated. Research works have covered the utilization of commercial NC machine tools, dedicated polishing cells and robotic systems [8]. Robotic manipulators perfectly adapt to this application as they provide the required degrees of freedom to the polishing tool, so that it can be adapted to free form surfaces. Even if stiffness is one of the drawbacks of robot application in machining process, this factor is not so critical in polishing operations due to the low material removal rate and reduced accuracy requirements.

Contact pressure is the most important process parameter affecting the surface quality [9], but contact force is controlled instead as it is easier to monitor than the former. Several research works have covered the optimization of polishing operation by applying adaptive force control systems. While some authors present hardware-based solutions consisting in compliant end-effectors, like [10] and [11], others use software-based approaches based on force sensors [12], vision systems [13] and even IoT data [14].

While, ideally, polishing operation should be performed in the NC machine by using the same controller and fixtures used in the previous machining operations, a controller has not yet been developed for an NC machine to control both the machining center and the polishing equipment [8]. Each robot manufacturer provides its own controllers to command the correspondent robotic manipulators, leading to manufacturer dependency from control integration and robot programming perspective. However, robot manufacturers are recently offering new functionalities to improve robotic system integration in manufacturing systems. Stäubli uniVAL drive (https://www.unival-drive.com/) is the more mature solution and can be used for driving Stäubli robots at joint level by an external controller. Real time communication protocols (Profinet, EtherCAT, Sercos…) are available to exchange joint position data (setpoints and real values) at high rates and in a deterministic way. This technology has already been used in different applications like robotic surgery [15] and machining [16]. KUKA robot manufacturer provides an NC kernel as an option of their KR controllers. Although it provides the possibility to launch NC part programs and improves the path contour performance comparing to conventional robot controllers, its performance is below general purpose CNCs [17]. COMAU and SIEMENS provide an integrated approach called DirectControl where Sinumerik NC and SIEMENS drives replace conventional COMAU controllers [18]. Although this solution allows complete flexibility for motion control application development in both the NC and drives, it is single manufacturer solution.

In this paper, an NC controlled polishing robot is presented that combines an external controller that allows seamless integration, independent to robot manufacturer, in manufacturing lines, NC interpolated smooth trajectories and force controlled adaptive polishing process. The work is one of the outcomes of the IMOCO4.E project [19, 20] where advanced functionalities for smart mechatronic systems are being developed.

The paper is structured as follows. Section II presents the Adaptive Impedance Control algorithm used to control polishing forces and the approach followed to tune the controller parameters. Section III presents overall control architecture of the solution, with a detailed description of the different hardware and software modules, including the implementation of the NC controller and Adaptive Impedance Controller. In Section IV the polishing demonstrator is presented together with the obtained results. Finally, section V presents the conclusions and future steps.

II. ADAPTIVE IMPEDANCE CONTROLLER

Impedance Control for robot manipulation was initially suggested by Neville Hogan [21]. Manipulation requires a supervised and controlled mechanical interaction. For this purpose, Impedance Control method regulates the relationship between robot position and exerted force, increasing robot adaptability to interact with its environment. This relationship is obtained by variables and parameters from a Single Degree of Freedom (SDOF) equivalent system, whose basic equation is:

$$f = m\Delta\ddot{x} + b\Delta\dot{x} + k\Delta x \qquad (1)$$

being k the impedance stiffness, b the impedance damping, m the impedance mass, f the exerted force and Δx the resultant instantaneous displacement of the mass m.

Conventional Impedance Control is particularly feasible for applications in which there is no specific model for interaction. Hence, this strategy only needs a set of parameters that guarantee stable performance to provide a proper contact interaction. The configured parameters will define how much force is exerted on target and how fast is settlement. While mass, m, and damping, b, determine how the interaction transitional behaviour is, the steady state interaction is proportional to stiffness, k.

Although Impedance Control provides compliant manipulator motions for both constrained and unconstrained applications, it does not provide an explicit control of the interaction force and, hence, it is not valid for force tracking applications. Many efforts have been made to adapt standard Impedance Control approach and provide force tracking features. Some authors present an adaptive control approach to compensate deviations of the environmental stiffness [22]. Another approach consists in the adaptation of the commanded trajectory using an outer force control loop [23]. Lee and Buss [24] proposed a control scheme that achieves a contact force regulation control by adjusting the target stiffness of the Impedance Controller, as an analogy of human arm force control over an object. In the last years, more complex learning-based approaches like [25] and [26] have been investigated with the aim to provide a more humanized and intelligent interaction with the environment.

The Adaptive Impedance Controller applied in this work is based on [24] and modifies stiffness based on the difference between the measured contact force and the desired force (Fig. 1). This strategy has been selected due to its simple implementation in an industrial controller and its feasibility for the polishing application. More complex strategies will be studied in the future for other applications.

For each of the axes where the new control will be applied, a nominal stiffness (k_{nom}) value is defined, as for a conventional Impedance Controller. An outer force control loop is implemented with a PI controller to determine the stiffness variation (Δk) required to track the required force (f_s). This stiffness variation (Δk) is added to the defined nominal stiffness (k_{nom}) and the resultant value (k) is used in the Impedance Controller.

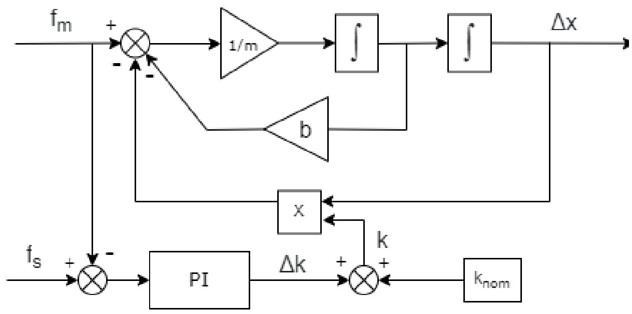


Fig. 1. Applied variable stiffness Adaptive Impedance Control approach.

As mentioned, as a SDOF system, the Impedance Control stability depends on its stiffness, damping and mass. A simulation desktop application has been designed to choose a set of impedance parameters that fits into the dynamic requirements (Fig. 2). As the surface adaptation and force tracking response does not need to be very dynamic in polishing applications, a configuration has been selected so that it provides smooth and stable response.

Once a stable set of parameters has been selected for the conventional Impedance Controller, simulations to evaluate the performance of the proposed Adaptive Impedance

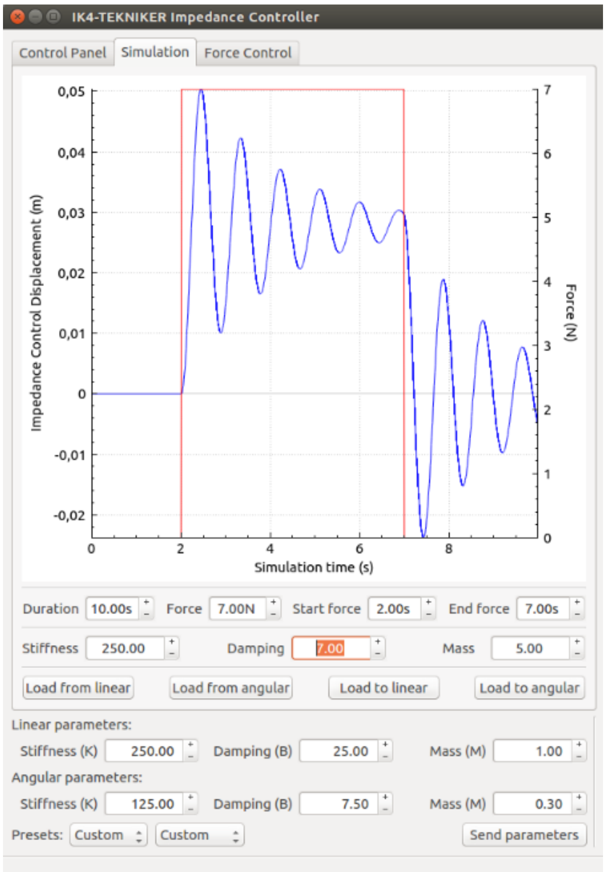


Fig. 2. Impedance Control parameter tuning simulation software, showing limited stability performance.

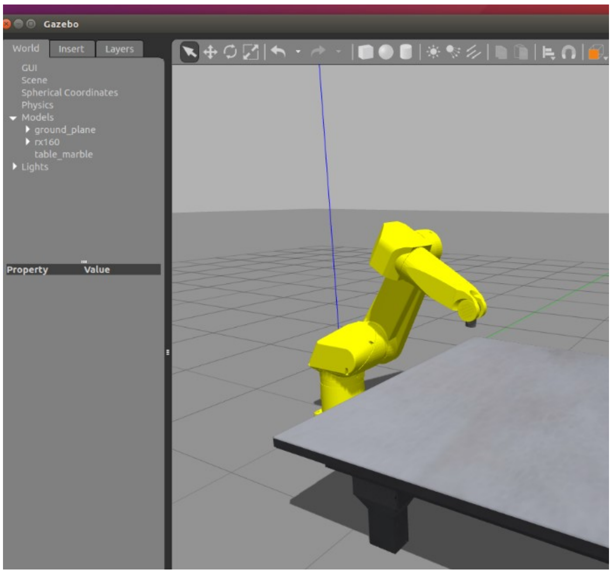


Fig. 3. Simulations of robot contact interaction in Gazebo.

Controller have been performed, considering a dynamic contact interaction and robot kinematics. Gazebo (Fig. 3), an open-source software which offers a wide range of possibilities in terms of robotics simulation, has been used for this purpose. A model of the Stäubli RX160 robot used in the application was integrated in the simulation environment, integrating the proposed Adaptive Impedance Controller. Contact simulations confirmed that the defined approach and configured parameters provide a stable performance and a correct kinematic response of the robot in a configuration that is close to the one used in a polishing operation.

III. External NC based robot controller

A Windows-based Beckhoff C6920 controller has been used as a main controller of the proposed system (Fig. 4), 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

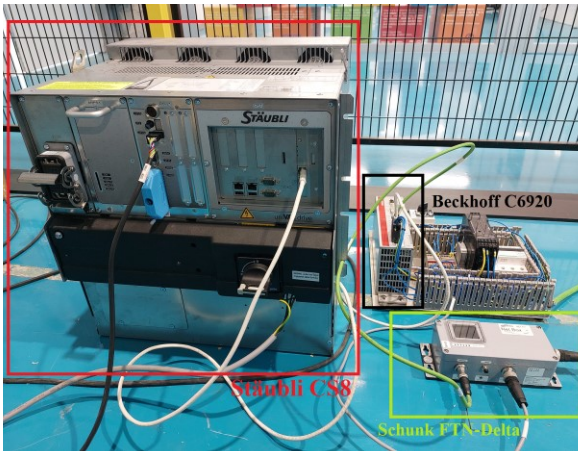


Fig. 5. Control hardware configuration for the robotic cell.

commands (q_{rob}) are synchronously exchanged at a sampling rate of 250 Hz. Stäubli VAL robot programming and trajectory generation interface is bypassed, but dynamic compensation and servo tuning are still performed on the Stäubli CS8 robot controller (Fig. 5).

The required control functionalities have been implemented in Beckhoff TwinCAT environment. TwinCAT is an open, PC-based technology that provides real-time control capabilities. It provides a development environment for the development and configuration of control systems. Next, the applied control functionalities are described.

TwinCAT Numerical Control Interpolator (NCI) offers 3D interpolation functions like NC code interpreter, trajectory interpolation and setpoint generation and manages a group of axes representing Tool Center Point cartesian position referred to robot base (x_{NC}). It provides a NC management interface that allows selecting among different operating modes like jog, manual data input (MDI) and automatic program execution as well as user interaction like start/stop/reset program and feedrate override. The automatic operating mode allows the possibility to load and edit part programs in standard G-code. This allows the utilization of

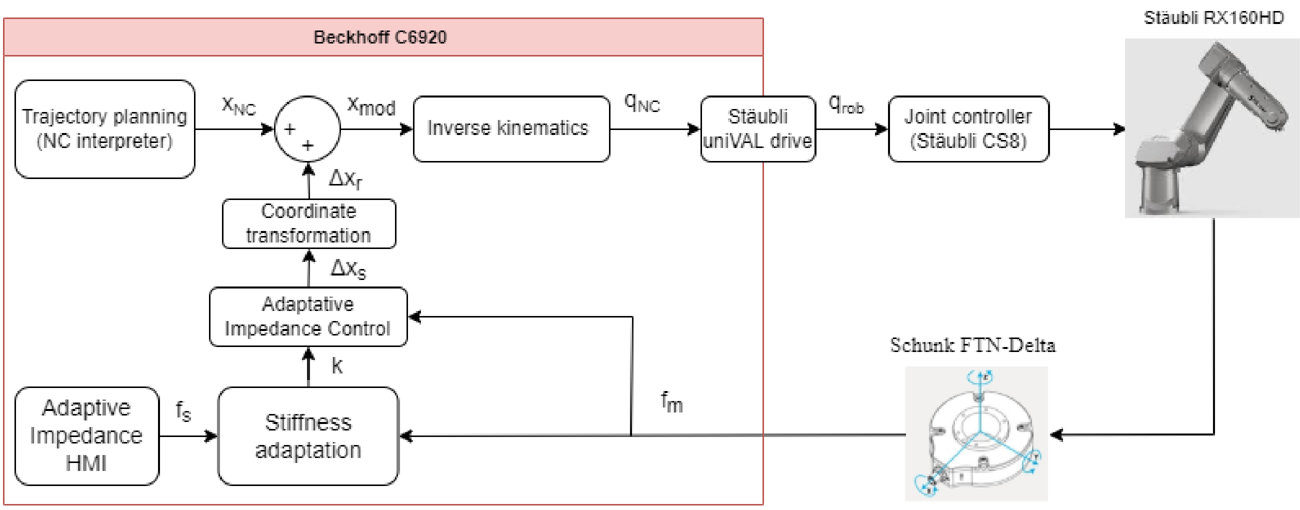


Fig. 4. Schematic reprsentation of the applied overall control architecture.

Computer Aided Manufacturing (CAM) software tools for complex polishing path generation.

Adaptative Impedance Control has been implemented in the TwinCAT environment in structured text. Using a modularized approach, traceability and flexibility is guaranteed. Code modules are organized as follows:

- Force/Torque Measurement: A Schunk FTN-Delta SI-165-15 sensor installed at the robot Tool Center Point provides contact force/torque measurements (f_m) to the main controller using Ethernet/IP connection. TwinCAT environment includes Ethernet/IP protocol management and, hence, data from the sensor is integrated into PLC program. Raw measurements are converted into International System Units according to calibration data.

- Stiffness adaptation: The procedure described in section II has been implemented in this module. The impedance stiffness parameter (k) is updated by closing a force control loop that compares desired (f_s) and measured (f_m) contact forces and applies a PI controller. Upper and lower impedance stiffness bounds are set to avoid defining extreme values which could result in unstable configurations. In addition, in absence of contact, stiffness adaptation is not active, and the impedance stiffness remains on its nominal value.

- Impedance Control: applying impedance algorithm described in Equation 1, a position variation (Δx_s) is calculated using the instantaneously measured force value. This position variation is defined in the force sensor coordinate system.

- Coordinate transformation: 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. Using the available functions, calculated position variations (Δx_s) are converted to the robot coordinate system (Δx_r) considering instantaneous robot joint configuration.

The position variations determined in the Adaptive Impedance Control module are added to the nominal position commands (x_{NC}) determined by TwinCAT NCI setpoint generator using a master slave coupling. The modified cartesian setpoints (x_{mod}) are then converted to joint coordinates (q_{NC}) by applying the inverse kinematics according to instantaneous robot configuration. The function available in the TwinCAT kinematics library is used for this purpose. The joint coordinates are sent using uniVAL drive to the Stäubli controller, where control loops of each joint are closed.

With the aim of providing tools to operate the complete system, two user interfaces have been developed. The first one manages general robot control utilities, such as uniVAL drive control activation and robot joint status monitoring. The second one is used to configure and monitor Adaptive Impedance Control implementation (Fig. 6). This interface provides means for recalibration of force sensor signal to offset signal drift and polishing head weight. Although this approach is valid for the current application, a gravity model

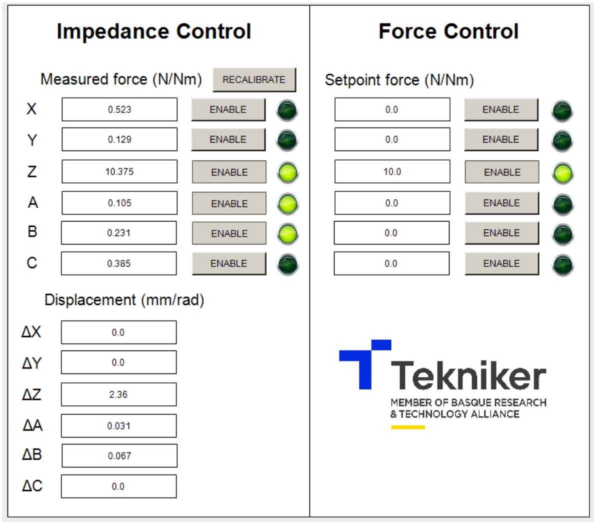


Fig. 6. User interface for the configuration and activation of Adaptive Impedance Control in the different cartesian axes (force sensor coordinate system).

of the polishing tool will be implemented in the future to allow dynamic compensation of gravity forces during larger orientation variations. The second interface also allows individual activation of Impedance Control for each cartesian axis in the force sensor coordinate system. In the same way, force tracking functionality can be independently activated and the force setpoint can be configured. This user interface allows live monitoring of the forces measured by the sensor and the position modifications resulting from the application of the Adaptive Impedance Control and the selected configuration.

IV. Robotic Polishing Demostrator

A. Set-up

A force-controlled NC commanded robotic polishing station has been developed (Fig. 7) based on the system presented in section III. This system has been complemented with a 77 mm diameter MIRKA Airos 350CV polishing spindle head and a MIRKA 1230 M AFC dust extractor. The MIRKA spindle head is mounted on the Schunk force sensor that, at the same time, is mounted on the Stäubli robot wrist (8). The MIRKA system is connected to the Beckhoff C6920 controller using a serial communication module. The control application running in the C6920 controller is able to activate/deactivate spindle rotation and set rotation speed using standard M commands included in the NC instructions, as it is usually done in machine tool spindles.

Polishing operation requires, first, the adaptation of the polishing head orientation so that its rotation axis is set normal to the surface to be polished and, second, the control of the contact force in the direction normal to that surface. Hence, Adaptive Impedance Control has been configured differently in the 6 axes of the process coordinate system (the same as the force sensor coordinate system, Fig. 8):

- A conventional Impedance Control with low stiffness (k_{nom} = 5 Nm/rad), high damping (b = 100 Nms/rad) and small mass (m = 2 kg) has been configured for the rotations in the X (A) and Y (B) axis, allowing smooth adaptation to 3D surfaces and

Fig. 7. NC commanded adaptive robotic polishing demostrator.

always keeping the spindle head normal to the surface.

- An Adaptive Impedance Control is set in the Z axis to control the normal contact force. The impedance parameters set are k_{nom} = 350 N/m, b = 3000 Ns/m and m = 25 kg. The proportional and integral gains of the PI controller for the stiffness adaptation are, respectively, 0.025 m^{-1} and 0.02 $(m \cdot s)^{-1}$.

- Impedance Controller is deactivated for the rotation in the Z axis (C) as this is linked to spindle rotation.

- Impedance controller is deactivated in the X and Y axes to avoid variations in the commanded path.

Adaptive Impedance Control activation and parameter configuration, as well as definition of force setpoints, is performed used the specific user interface presented in Fig. 6.

Although the proposed approach allows the usage of CAM software tools for complex polishing path generation, one of the key features of the system is that it is suited to perform polishing of 3D surfaces without the need of complex path generation stage, as the robot is able to adapt its joint configuration to keep the polishing spindle normal to the surface. Fig. 9 shows how the spindle is perfectly oriented even if a path parallel to the table with a vertical orientation was programmed.

B. Results

The polishing cell presented in the previous section has been used as part of a comprehensive comparative study of surface finishing methods for Inconel 718 alloy [27]. Successful results were obtained using the polishing process helped by the possibility to, first, command polishing trajectories using NC commands and, hence, path generation using SIEMENS NX CAM software, and second, to keep a constant normal polishing force by adapting the polishing spindles to the surface geometry and controlling the contact forces.

As results presented in [27] are focused on surface quality and do not only depend on the performance of the robotic polishing cell but also in the applied process parameters and sandpapers, they are not covered in this work. Instead, Fig. 10 presents force tracking performance during polishing of a curved surface like the one presented in Fig. 9 by programming a linear path. Conventional Impedance control is applied to the A and B axes for curvature adaptation and force tracking is applied in the normal direction (Z axis), with a force setpoint of 10 N. It can be observed that, after a first settlement stage, force tracking is within ±5% of the commanded force, if the noisy component of the force

Fig. 8. Integration of the robot wrist, sensor force and polishing spindle, showing force sensor coordinate system.

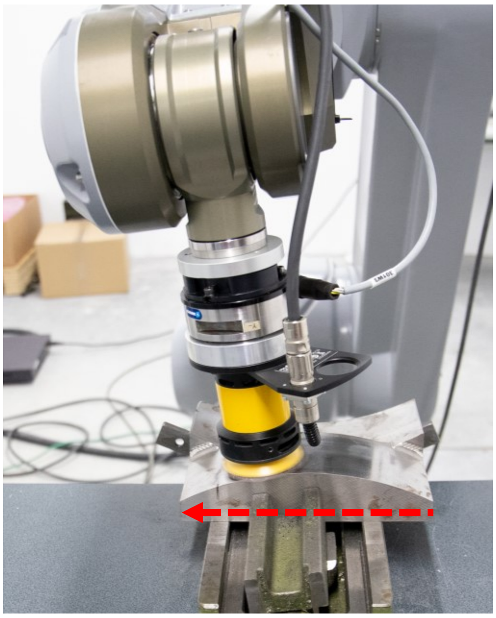
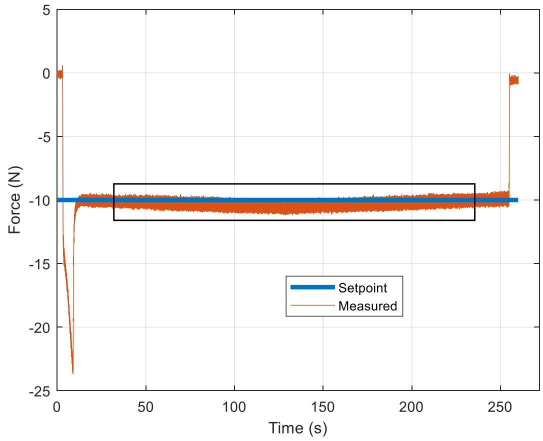
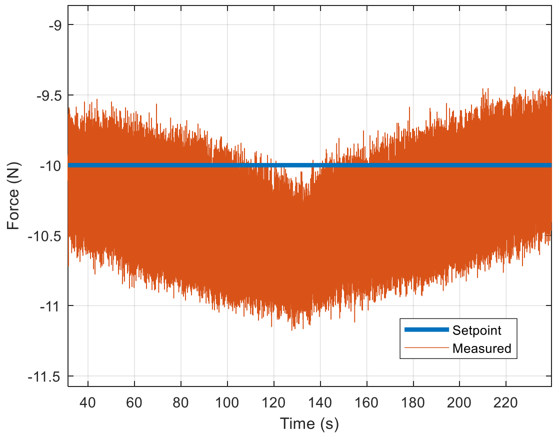


Fig. 9. Spindle orientation capability when programming simple linear paths with vertical spindle orientation (red dotted line).



a)



b)

Fig. 10. Force tracking performance during a polishing operation of a curved surface (Fig. 9): a) Complete polishing swept; b) detail of the squared area in a).

measurement, caused by the polishing process itself, is not considered. The settlement stage is caused by the fact that the commanded setpoint is still deepening into the workpiece, increasing the contact force that cannot be compensated by stiffness variation. Once the position setpoint reaches its final value, the contact force is correctly tracked. Both the settling effect and the small tracking errors could be greatly improved if a path that roughly replicates the curved surface is programmed.

V. CONCLUSIONS

An adaptive force controlled polishing robot cell has been developed using an Stäubli 6 dof manipulator controlled by a Beckhoff C6092 controller. The developed controller also integrates auxiliary systems like the control of a polishing spindle and the data monitoring of the force/torque signals of a sensor located at the interface of the robot wrist and the polishing spindle.

The implementation of an Adaptive Impedance Control algorithm in the main controller, that is fed by the measured force/torque signal, allows smooth and controlled interaction with the surfaces to be polished, as well as force tracking. This allows adaptation to freeform 3D surfaces without complex path planning, keeping polishing spindle in a specified orientation with respect to the polishing surface, and keeping polishing pressure constant through all the process. Both features lead to successful polishing performance, as has been reported in [23].

Due to the utilization of TwinCAT NC kernel ISO code-based part programs can be executed. This is the same programming language used for conventional machining operations, like milling, and allows, for example, the utilization of CAM software for complex path planning. The integration of a robotic manipulator in a NC based motion control system is the first step towards an integrated machining plus polishing station controlled by a single NC controller an providing great productivity (simultaneous operations) and excellence quality (utilization of same fixtures). The combined and synchronized operation of a machine and a robot is a promising application, not only considering polishing operations, but also for the enhancement of machining processes by complementary machining or process assistance (e.g. chip removal using cutting fluids or adaptive support for slender workpieces).

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