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Sensor-guided motions for robot-based component testing

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***Abstract*—This paper presents the use of sensor-guided motions for robot-based component testing to compensate the robot's path deviations under load. We implemented two different sensor-guided motions consisting of a 3D camera system to minimize the absolute deviation and a force/torque sensor mounted directly to the robot's end effector to minimize occurring transverse forces and torques. We evaluated these two sensor-guided motions in our testing facility with a classical tensile test and a heavy-duty industrial robot. From the obtained results, it can be stated, that transverse forces as well as the absolute deviation were significantly reduced.**

***Index Terms*—Industrial robots; robot-based testing; online compensation; sensor-guided motions; robotics**

I. Introduction

The manufacturing industry is shifting from mass production to mass customization in order to produce individual products in small quantities [1]. However, this shift in production also requires a change in the way these unique products or components of products are tested. It is no longer profitable to build complex test benches for each individual component, nevertheless it is essential to test these components to ensure quality. Standard testing machines commonly cover only simple testing motions and are specially designed to meet test requirements of a single component. Therefore, a flexible test bench is required to test various types of components with different testing motions. With focus on destructive component testing, in which the component is actively and irreversibly deformed until it fails [2], we developed a concept to perform robot-based destructive component testing with heavy duty industrial robots [3]. The six degrees of freedom (high number of movement directions) and the large working range of an industrial robot enables applying forces and torques to different components. This flexibility is also accompanied by some challenges. When referring to precision tasks under load, the robot's performance in terms of accuracy is worse than the one of a typical machine tool, which can be mainly attributed to the robot's lower stiffness [4]. Since destructive material testing often requires very high forces and torques and at the same time a high accuracy the robot's tool deviations under load needs to be improved. To overcome these challenges we propose an approach of using sensor-guided motions for robot-based component testing. This paper contributes in this area by implementing and evaluating two different sensor-guided motions to control an industrial robot under high loads e.g. up to $3500\,\mathrm{kg}$.

The paper is divided into five sections. The following section first gives an overview over the state of the art (II) in component testing and sensor-guided motions in robotics. The experimental setup for the sensor-guided motions for robot-based component testing is described in section III. Section IV presents the preliminary results and finally section V draws a conclusion and points out further research.

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II. State of the art

Robots offer the advantages of high reproducibility and flexibility in their movements. Various research facilities developed test rig concepts in form of Stewart platforms for multi axial component testing. Such a structure, also known as hexapod, offers 6 degrees of freedom due to its six legs which are each able to vary in length independently. Hexapods for closed loop load application have been developed by the University of Paderborn (Germany) [5] and the University of Cachan (France) [6] away others. Despite hexapods achieving high loads, they are restricted in their range of motion and limited in size of test components. To overcome these limitations industrial robots can be used for component testing. However, the use of industrial robots involves additional challenges. Due to their lack of accuracy when exposed to high external forces or torques, methods are needed to solve these problems [7]. The online compliance error compensation system for industrial robots in contact applications currently represents a very large field of research [8], [9]. For example, deflection models are used in this field to minimize tool deviations under load. Dumas et al. [10] proposed a conventional stiffness model, which estimated translational and rotational displacements of the robot end-effector subject to an external wrench (force and torque). Other models include the use of online force feedback from a force/torque sensor, because an offline compensation is not precise enough e.g in milling operations [7] or in robot metal cutting operations [11]. Finally, online path corrections can also be carried out, for example using external camera systems [12]. For the communication between an industrial robot and an external control system additional interface are often required. The KUKA robot sensor interface (RSI) provides such an interface and is a technology package which enables the cyclic ($4\,\mathrm{ms}$) fine-tuning of predefined robot motions e.g. with live sensor data. The integration of sensors can now even be done via a graphical user interface (RSIVisual). [13] In addition to the interface for the robot, there are also different interfaces for sensors or actuators. A commonly used language to access these interfaces are the Standard Commands for Programmable Instruments (SCPI). It is a command language for controlling instruments in a standardized manner by providing a consistent programming environment for instrument control and data usage. It defines specific command sets to enable standardized access to different instruments with the same functional capability. The physical communication layer is not prescribed by SCPI. Therefore SCPI commands can be sent for example via ethernet. [14]

III. Experimental Setup

Since the internal positioning of the robot is too inaccurate to control the robot under high loads (see [7]), e.g due to gear backlash, we developed two types of sensor-guided motions for robot-based component testing to correct this deviation and evaluated them in our testing facility by using a selected use case. In order to obtain a better overview of the facility, it will first be briefly described, followed by the details of the experimental setup, the used interfaces and the implementation as well as the selected use case.

The testing facility consists of two industrial robots (KUKA KR1000 Titan) with one ton load capacity each (see figure 1). These robots are arranged around a clamping field ($7\,\mathrm{m}$ length x $2.5\,\mathrm{m}$ width) that allows flexible fastening of components.

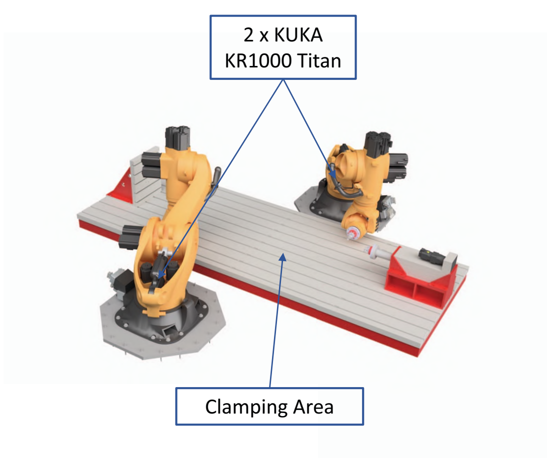

Fig. 1: Robot-based component testing facility consisting of a clamping area ($7\,\mathrm{m}$ x $2.5\,\mathrm{m}$) for flexible positioning of testing components and two KUKA KR1000 Titan robots.

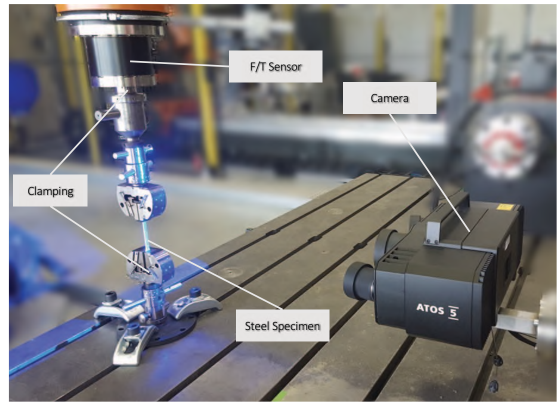

Fig. 2: Overview of the tensile test setup with the specimen setup mounted on clamping field on the left side and the camera on the right side. The F/T Sensor is directly mounted on the robot between its flange and its end effector.

This facility is described in more detail in [3]. For the sensor-guided motions, we used two additional sensor systems (see figure 2). Firstly both robots are each equipped with a 6-axis force/torque sensor K6D175 from ME-measuring systems and coupled with a GSV-8DS EC/SubD44H measuring amplifier (see on the left side of figure 2). The measured data can be accessed via EtherCat with a measuring frequency of $250\,\mathrm{Hz}$. Forces and torques can be measured up to +/- $100\,\mathrm{kN}$ and +/- $10\,\mathrm{kN\,m}$ in z-direction and up to +/- $50\,\mathrm{kN}$ and +/- $5\,\mathrm{kN\,m}$ in x- and y-direction with accuracy class of 0.5 % specified by the manufacturer. Secondly we use an ATOS5 camera system manufactured by Carl Zeiss GOM Metrology GmbH. Different measurement volumes and resolutions can be used. For our use case we used the CP40/MV700 lens with a measuring volume of 700 x 530 x $520\,\mathrm{mm}$. The used software for this device is called ARAMIS, which provides an SCPI Server to access e.g. the measured absolute position of the robot end effector with a sample rate of $10\,\mathrm{Hz}$ via ethernet (TCP). Finally the robot was controlled with the help of the robot sensor interface over UDP (RSI) of the KRC4 control and the software for processing the sensor data and controlling the robot ran on a B&R Automation PC 910 industrial PC (IPC) with an Intel Core i7-3615QE quad-core CPU running at $2.30\,\mathrm{GHz}$ equipped with an i210 network card. To evaluate one possible sensor-guided motion we selected a tensile test, which represents a classical use case for the early determination of certain properties of material components (see figure 2). In such a test a specimen is loaded in one direction until it tears. The specimen is clamped between two clamping jaws. The lower part is fixed on the clamping field while the upper part is the end effector of the robot. Steel (St 1.4301) was chosen as material which needs a minimum force of up to $20\,\mathrm{kN}$ until it tears. Subsequently the clamps fix the specimen perpendicularly to the clamping field and the test motion points in the direction of the clamped specimen (negative z-direction

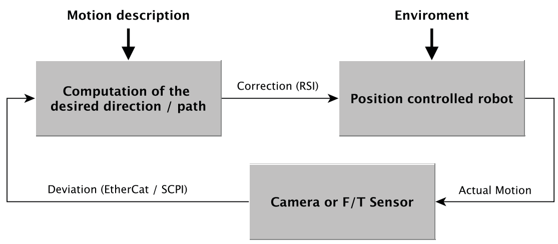

Fig. 3: Control architecture with a position controlled robot and the computation of the desired path or direction from measured values of the camera or the f/t sensor.

in the robot's tool coordinate system). The motion velocity loads the specimen at a very low speed of $5\,\mathrm{mm/min}$ and after reaching a force threshold of $100\,\mathrm{N}$ the speed is increased to $10\,\mathrm{mm/min}$. The goal of this experimental setup is to load the specimen only in the z-direction by minimizing transverse forces and torques. This can either be achieved by minimizing the absolute position deviation with the help of the camera system or by minimizing the transverse forces and torques with the help of the f/t sensor. An overview of the software implementation of the motion execution including the deviation correction is given in figure 3. The motion description consists of the desired motion in which the robot moves. This motion is transferred to the robot stepwise as a position correction using the RSI interface in a $4\,\mathrm{ms}$ cycle. The deviation is determined in each cycle with the help of the sensor, either the camera or the force sensor and is then included in the calculation for the next cycle. In order to perform the test motion in z-direction with the given speed, as described above, a constant correction value in z-direction was passed to the robot. To minimize the occurring deviations in our case study either a position correction (camera based) or force/torque correction (f/t sensor based) with a PID controller was used for control. This was differently implemented for the two correction types and more detailed research is planned here, e.g comparing and parameterizing different controllers. For the absolute position correction the deviations were measured and corrected in the robot base coordinate system. For this purpose, the transformation from the camera system into the coordinate system of the robot was calculated. This enables to move the robot in the coordinate system of the camera and furthermore it provides the calculation of the translational and rotational deviation at the same time. Finally, to minimize the noise of measured values by the camera system, a sliding average filter for the last ten measurements was applied. These deviations are then transmitted to the robot incrementally as a position correction via the RSI interface, as already described above. In contrast to the first type, the force torque correction was measured and corrected in the robot tool coordinate system. The occurring transverse forces were converted into position corrections with the aid of a PID controller and transferred to the robot via the RSI interface. In our case study, the transverse forces occurring in x/y-direction were minimized, since the pull motion was in z-direction. The achieved results will now be explained in more detail in the next section.

IV. Preliminary Evaluation

We evaluated our two sensor-guided motions in our testing facility with a classical tensile test, as described in the experimental setup. For this purpose, we performed one tensile test for each control mode and one tensile test with the internal KUKA control system to compare the results. Figure 4 depicts the transverse forces in N and the deviation in mm of the end effector while loading the specimen in z-direction (yellow for the force and brown for the travelled distance in z-direction) without the use of online correction. As you can see, the deviation increases as the force increases. This leads to transverse forces of up to approximately $100\,\mathrm{N}$ in x/y-direction at a maximum load of $20\,000\,\mathrm{N}$ in z-direction and a deviation in x/y-direction up to $0.75\,\mathrm{mm}$ in x-direction and up to $1.5\,\mathrm{mm}$ in y-direction. Whereby an initial assumption for the first bend in the curve is the the alignment under load of the two clamping jaws. Nevertheless, the coordinate system for the motion was calibrated with the help of the camera and the deviations could not be detected without a load on the end effector. Comparing the deviations with the position correction carried out with the help of the camera, it can be concluded that the deviation can be reduced to approx. $0.1\,\mathrm{mm}$ in x and y-direction (see DX, DY in figure 5). Finally, by comparing the correction with the the force torque sensor (see figure 6), it can be stated that also the transverse forces in x- and y-direction can be minimized to a range of $0\,\mathrm{N}$ to $10\,\mathrm{N}$. In this case study, only one very simple motion was evaluated and further research will be discussed in the next chapter.

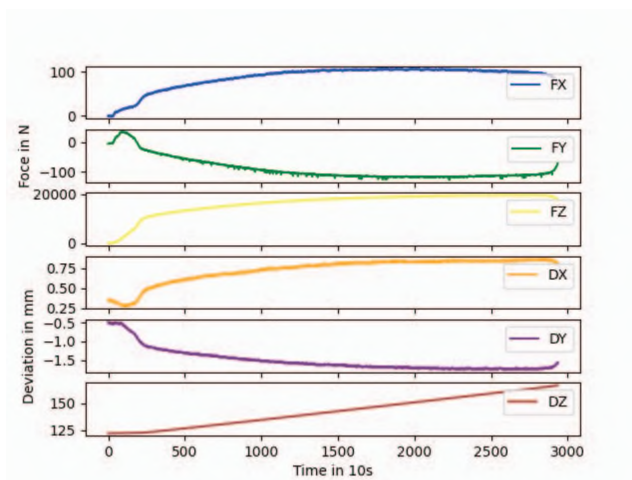

Fig. 4: Transverse forces in N (FX, FY) and deviation in mm (DX, DY) in x,y-direction of the end effector under high load without the use of online correction with sensor-guided motions.

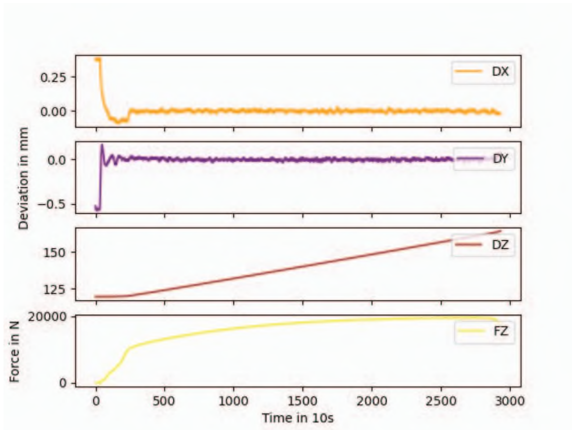

Fig. 5: Deviation in mm in x,y-direction (DX, DY) of the end effector under high load with the use of a camera based position correction.

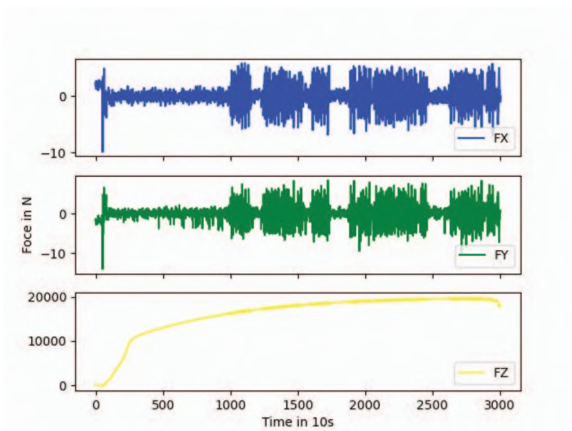

Fig. 6: Transverse forces in N in x,y-direction of the end effector under high load with the use of a force based position correction.

V. Conclusion and Further Research

Using industrial robots for destructive component testing includes many challenges. One major challenge is to keep the test motion paths under load as accurate as possible. Since the robot's accuracy is usually worse than that of a typical machine tool, mainly attributed to the robot's lower stiffness [4], the robot's tool deviations under load need to be compensated. We used two different sensor-guided motions to correct the occurring deviations. For this purpose we utilized two external sensor systems. A 3D camera system to minimize the absolute deviation and a f/t sensor mounted directly to the robot's end effector to minimize the transverse forces and torques that occur. We evaluated our sensor-guided motions in a classical use case in material testing, namely a tensile test. In this experimental setup we were able to minimize the absolute deviation to $0.1\,\mathrm{mm}$ in x- and y-direction and to reduce the occurring transverse forces and torques to $0\,\mathrm{N}$ to $10\,\mathrm{N}$ under a maximum load of the end effector of $20\,000\,\mathrm{N}$.

In further research we plan to extend the evaluation of the chosen use case by comparing the force controlled motion with torque motions. These simple motions will also be evaluated with other components of different materials, e.g. synthetic materials which are much more elastic or carbon composites that can withstand even more force or torque. In addition, other filter and controller types are being evaluated to check if they are even better suited for this type of motion and whether they might also be affected by the tested material. Furthermore we are planing to implement more complex testing motions, e.g. superimposed loads, by superimposing a force load with a torque motion. Moreover more research is planned to explore the possibilities and benefits of implementing a combined (hybrid) position-force approach. Finally, we are investigating whether such movements can also be simulated to shorten the parameterization time of the motion controller.

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