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Compensation of Errors in Robot Machining With a Parallel 3D-Piezo Compensation Mechanism

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Abstract

This paper proposes an approach for a 3D-Piezo Compensation Mechanism unit that is capable of fast and accurate adaption of the spindle position to enhance machining by robots. The mechanical design is explained which focuses on low mass, good stiffness and high bandwidth in order to allow compensating for errors beyond the bandwidth of the robot. In addition to previous works [7, 9], an advanced actuation design is presented enabling movements in three translational axes allowing a working range of each axis up to half a millimeter. Based on the presented theoretical dimensioning and finite element simulation translational moves with higher bandwidth can be enabled, due to the parallel design approach of a 3D-Piezo Compensation Mechanism. For realization aspects piezo actuators are chosen due to their fast dynamics and high forces. The realization of the control loop is further outlined. In order to enable a good control performance the set-up of sensing the extension of the piezo actuator is detailed as well as the spindle position used in fast real-time environment. As a result the 3D-Piezo Compensation mechanism unit allows an active adaption of the spindle position in the range of micrometers. A description of the deployment of the compensation unit to a robot machining system as well as first experimental results conclude the paper and prove the proper functioning of the approach and outline the potential of the entire system. Measured robot paths are applied to the compensation unit and analyzed with respect to the reduction of robot path errors.

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Keywords: Adaptive machining; parallel actuation; error compensation; robot

1. Introduction

This paper shows the realization of a parallel error compensation mechanism. Within the scope of the document HDCM which is an acronym for ‘High Dynamic Compensation Mechanism’. The need occurs when machining with industrial robots. The error compensation method was already presented in [7]. Today, typical robot applications are mainly handling jobs such as pick-and-place from place A to B. For such pick-and-place operations the robot’s repeatability is sufficient. Nevertheless, complex, flexible and precise handling systems are required. Specifically the market needs for tasks of dynamical processes, e.g. machining with robots has been growing recently, [2, 13, 14]. So the idea is to use the robot for those tasks since conventional metal cutting machine tools are higher in price and less flexible compared to robots. Thus, this article describes the further development of the original idea, using an HDCM for error compensation. In [8] the original idea is explained and compared to other approaches of the state of the art. Previous works related to this aim are presented, before focusing on the new approach of a parallel actuation mechanism. This helps to increase its dynamics. The engineering process will then be pointed out showing important results of the progressive design work and FE-simulations. Finally, the manufactured and on a machine-bed installed HDCM is shown. The beneficiaries of this robot machining concept will be presented finally by showing a first implementation of a cascaded controller together with measured robot machining signals.

2. Previous Works

Error compensation using 3D-Piezo Compensation Mechanism for machining with robots has already been

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realized earlier. In [6] a 3D-Piezo Compensation Mechanism has been designed with three translational actuations based on a serial design approach. Piezo actuators combined with lever mechanisms are used in order to achieve movements which are appropriate for robot machining for a dynamic and robust actuation. The bearings were realized using ESSJs in order to enable movements with transmissions and to align the movement directions to be translational. Thereby the stiffness of the mechanism can be adjusted. Further potential has been identified in the design parameters and between stiffness and mass which determine the dynamic properties of the whole system. Due to the serial approach the Z-axis has to move the whole actuation mechanism of the X- and the Y-actuation whereas the Y-actuation only moves the mass of the end effector and the spindle. This gap of mass results in differences in dynamics. Whereas the Y-actuation showed a first eigenfrequency at 43 Hz the Z-actuation already showed a resonance at 34 Hz. Appropriate control approaches are applied in order to increase the performance of the mechanism, but this can only push the performance to a certain physical limit, see [4, 11]. As the characterized dynamics are too close to the typical eigenfrequencies of industrial robots means are needed to increase to dynamics of the mechanism without losing stability and robustness. For the used experimental set-up the eigenfrequencies are lower than 30 Hz.

3. Conceptual Design

As shown in previous works piezo-actuators combined with ESSJs-lever-mechanisms are appropriate for the real-time compensation of machining errors of robots. The new approach presented in this paper is based on the idea of a parallel actuation instead of the serial approach. This suggestion was pointed out in [6] in order to increase the dynamics significantly. Furthermore, the usage of ESSJ's became beneficial when using piezo-actuators as contradictory to conventional bearings they reduce friction, play and backlash. This new approach made it necessary to adapt the ESSJs. In combination with appropriate control algorithms this approach will increase the potential of HDCM based on ESSJs.

3.1. Criteria

Two parameters can be identified which are critical for the usability and the applicability of the mechanism. Both the stroke size and the dynamics limit the field of applications. Therefore those two parameters are particularly investigated during the design.

The maximum stroke of the mechanism depends on two key parameters. Firstly, the transmission is strongly dependent on the used lever principle. Here, the maximum extension of the piezo actuator influences the stroke. The targeted stroke of 0,5 mm leads to the lever geometry outlined in Fig. 1, already shown and optimized from [7]. Secondly, the real achievable stroke depends strongly on further characteristics of the piezo actuators. As the piezo actuators themselves only have a limited stiffness and can only actuate up to a certain force, the load also influences the work range of the mechanism [9]. So, the stiffness of the transmission system has to be chosen carefully. When stiffness is not adjusted correctly, the actuator may lose displacement, and thus a smaller effector displacement will be the result. The contact with the mechanism when contracting dynamically need to be considered during the design, but mainly has to be adapted during the installation of the actuators. In case of too high preload the actuator might not be able to sustain process forces. The preload p influences the stiffness c:

$$p = c \cdot x_0 \qquad (1)$$

with x_0 the initial extension of the actuator in zero position.

Regarding the dynamics of the system mass and stiffness of the system are important aspects. The stiffness can only be varied in a certain range due to the limited force of the actuators. Therefore, the reduction of mass is suspected to contain the highest potential to increase the dynamics of the system. As in previous work a serial design was investigated, a parallel approach is now examined in order to decrease the moved mass.

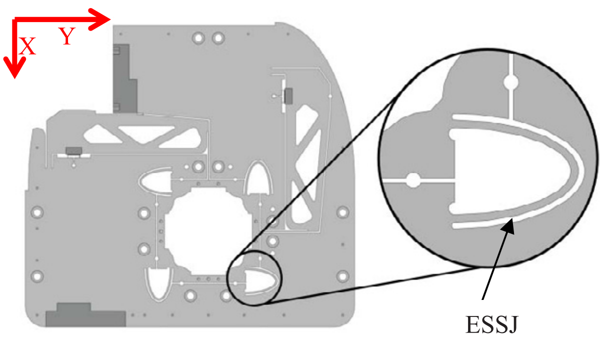

Fig. 1. ESSJs and transmission in the XY-plane

3.2. Actuation Principles

Whereas in a serial design some axis have to move the whole actuation mechanism of the following axis, in a parallel design only the end effector with the spindle needs to be accelerated. This reduction of mass results in better dynamic properties.

The complexity of the parallel design of the mechanism lies within the ESSJs. The end effector will be actuated in three directions, but the properties for each direction must be adjusted precisely in order to avoid rotational moves and to regulate the stiffness.

3.3. Mechanical Structure

In order to realize a fully parallel approach the ESSJs of the system have to be able to deal with movements in different directions. Therefore, geometry is required which provides adjustable stiffness in several directions. The ESSJs shown in Fig. 1 allow adjusting stiffness in two orthogonal directions independently. Whereas the flexure element is stiff in Z-direction, stiffness can be altered by changing the ellipse parameters or the shape of the arc.

The usage of lever mechanisms implies an original rotational movement as source for the targeted translational move. The arrangement of the four outlined ESSJs guarantees not only a specific stiffness in the translational axes, but also allows realizing a very high rotational stiffness in order to prevent rotational moves. Whereas the actuation in X- and Y-direction can be realized in a similar way, the Z-actuation has to be conceived differently due to gravity and due to installation space. The piezo actuator for the movement in Z needs to be installed parallel to the XY-Plane, but its movement must be converted to a translational movement in Z on the end effector. The red arrow in Figure 2 indicates the contact point of the piezo actuator and the force application. The orange and the green arrows indicate the movement of the mechanism resulting in a translational movement of the end effector. A new set of ESSJ has been designed in order to realize the guidance of the Z-movement (see Fig. 2). They mainly allow movements in one direction and provide high stiffness in the two other directions. The deflections in X and Y are allowed by additional flexure bar systems, directly beneath the system in Fig. 2 (a) and at the ends of the double lever mechanism.

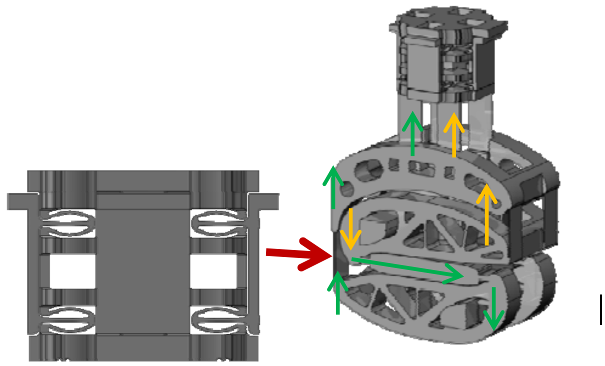

Fig. 2. (a) ESSJ-system of the mechanism in Z-direction, (b) Double-lever-transmission mechanism in Z-direction

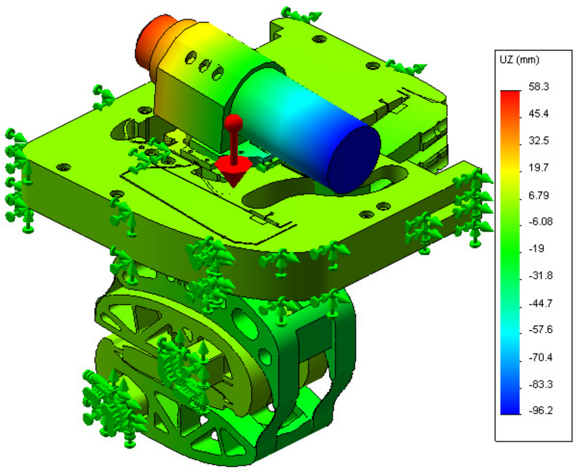

Fig. 3. Dynamical FEM analysis of the full HDCM design

4. Simulation Experiments

4.1. Finite Element Simulation

The full functionality of the HDCM with the combination of all components can be evaluated in simulation before manufacturing. A finite element simulation in CosmosWorks [12] reveales the designed stiffness of the separate axes and allows to estimate the resulting displacement with the according piezo actuators, see Fig. 3. Based on a preload L of $L \sim F_{max}/2$ with F_{max} the maximum force of the actuator, the parameters are simulated according to Table 1:

Table 1. FE simulation results

	X-axis	Y-axis	Z-axis
Stiffness [N/µm]	58.34	58.40	86.13
Actuator extension [µm]	104.09	104.04	117.01
Displacement spindle [µm]	534.77	537.68	549.63

Table 2. Eigenmodes and eigenfrequencies from the FE simulation

Eigenfrequency [Hz]	Eigenmode
56.42	Translational X
59.09	Translational Y
73.63	Translational Z
86.55	Rotational Z
115.91	Rotational Y

Another final result is the prevention of rotational movements. The guidance of the designed ESSJ allows translational moves and reduces rotational behavior to a minimum.

4.2. Modal Analysis

Another essential result from the simulation is the dynamic property of the system. Taking into account the mass and the inertia of the spindle eigenmodes and eigenfrequencies are determined. The simulation results are used to optimize the design. The final frequencies and eigenmodes are specified in Table 2.

Compared to the serial compensation approach described in chapter 2, the eigenfrequencies could be increased by 30-110%. Considering the eigenfrequencies of industrial robots the eigenfrequencies of the compensation mechanism are now at least two times higher and therefore high enough to be able to compensate high-frequency position errors.

5. Set-up and Test

In order to fulfill the criteria and to understand the new parallel system architecture a progressive design and simulation experiments were presented. The shown parallel design is a result based on the experience of [6]. It has been designed by the co-author A. Puzik within COMET [1]. But to prove the feasibility of the system it has to be manufactured, calibrated and deployed.

5.1. Manufacturing

While designing the mechanism a close look to the manufacturing possibilities was necessary. Based on the experiences the manufacturing is predominantly done with milling for rough machining and electrical discharge machining (EDM) for fine machining. All ESSJ- and dynamically penetrated parts are manufactured by EDM. The advantage is mainly the smooth surface finish without micro-cracks (compared to milling) and the force-free EDM process, which allows generating such thin and hollow structures. So the manufacturing of the flexure elements with a thickness of 1 mm and tight tolerances was evaluated in advance, [10, 5]. The manufactured and assembled HDCM is depicted in Fig. 4.

5.2. Implementation

In total the system consists of 23 parts. All parts and the piezo actuators are equipped with strain gauge sensors. Additional capacitive sensors are placed underneath the end effector. In order to achieve a high accuracy the axes are initially calibrated. The direction of each axis and the corresponding capacitive sensor are aligned and calibrated to determine the linear movement. Thus, each capacitive sensor allows the tracking of the end effector plate in one compensation direction. In order to allow the automatized positioning of a compensation axis a feedback control for each axis is established. Input voltage is set deforming the piezo actuator. The proposed control scheme for each compensation axis takes into account:

- Inner PID controller for feedback from strain gauge sensors in piezo actuators for handling parameter uncertainties and disturbances
- Outer controller for position control of the end effector plate where the machining spindle is attached. The control variable is measured by the capacitive sensors.

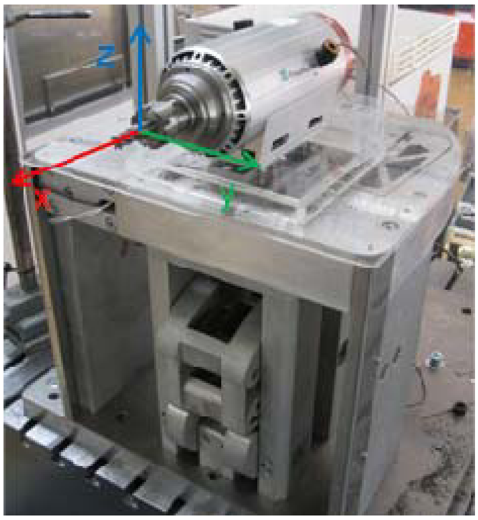

Fig. 4. Compensation Mechanism set-up

Considering the fact that the HDCM is designed for fast, but small compensations, it is clear that the limited compensation range of approximately 0.5 mm in each axis needs to be taken into account when designing the control system for the compensation mechanism. In practice, this means that the position error, as measured by the tracking system, needs to be compensated by both the robot and the mechanism jointly, in order not to saturate it to one of its end-point limits. A control approach will be required which realizes an overall control assigning low frequency errors to the robot and high frequency errors to the HDCM. At the same the robot needs to take care that the HDCM doesn't reach the limits of its work range.

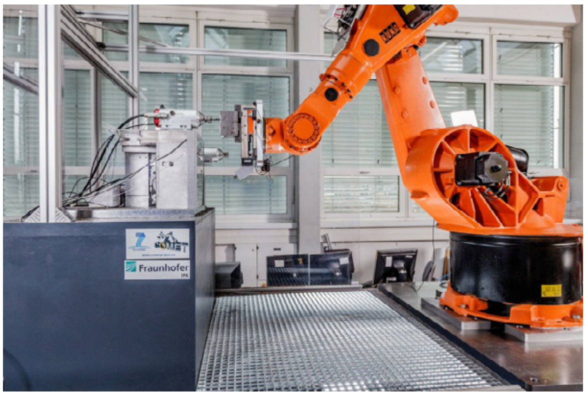

Fig. 5. Experimental environment

An error signal needs to be computed when deploying the HDCM for compensation. The error between the frames of the cutter and workpiece is essential. Static and dynamic measurements are necessary. One could obtain values of static frames from CAD. But in practice, despite accurate construction static errors in the set-up are expected. This is resolved by doing a cell calibration based on the usage of metrological tracking system (e.g. Nikon Metrology K600). Furthermore, it is essential to obtain the zero and the moving frame of the robot's end effector. This allows the measurement of dynamic errors (path deviations of the robot) e.g. generated by backlash or compliance within the robot system. Therefore, cell calibration is accomplished to introduce the framework for computation variation between tool and the end effector frame. The location of end effector frame relative to the tool frame describes the deviation with reference to an operating point during a machining process.

Due to the robot properties and its working area the HDCM is positioned on a machine bed. The table is foreseen to heighten the working space of the spindle and to locate the spindle in a position which provides good robot properties. The table is part of the machine bed. By doing so, the robot can position the workpiece in a cube by using all 6 degrees of freedom (see Fig. 5).

6. Experimental Results

Fig. 5 depicts the targeted set-up of the machining cell. Tracking information of the robot from an optical tracking system will be used as reference for the robot as well as for the HDCM. A rigidly attached spindle next to the HDCM serves to perform uncompensated machining experiments for comparison reasons. The integration of all components on a 14 t machine bed decouples the set-up from disturbances from the environment and also decouples the cell components from each other.

But first of all the actual performance of the HDCM needs to be verified. The simulated dynamics shall be verified in reality. Fig. 6 shows the frequency response of the HDCM when exciting it with a chirp signal with amplitude of ±50 µm.

For the verification of performance a one dimensional laser sensor LK-G87 from Keyence is used, the machining error of the robot in one direction can be traced and fed to the HDCM as a reference for one compensation axis. The sensor captures the robot position with 10 kHz with a resolution of 0.2 µm [4]. This signal is used to tune the control of the HDCM. Fig. 7 shows the reference following behavior of axis X. A simulation signal recorded during machining with a KR125 from KUKA is used as a reference. The plotted error between reference and position feedback of the spindle stays within the range of ±20 µm.

7. Conclusions and Future Works

The presented design augments previous approaches using elastic solid-state joints. In particular, the elastic solid-state joints allow adjusting stiffness in two orthogonal directions independently. Moreover, a parallel approach was explained and implemented in order to decrease the moved mass. As a result the reduction of mass improves the dynamic property. First experimental examinations show that the design in combination with a control scheme allows fast and precise tracking characteristics. As the applied reference signal was a pre-measured robot movement including typical deviations the proposed design of a HDCM is promising for the pragmatic compensation of errors during milling tasks.

For further research it is planned to validate the HDCM during complex milling tasks in all three axes.

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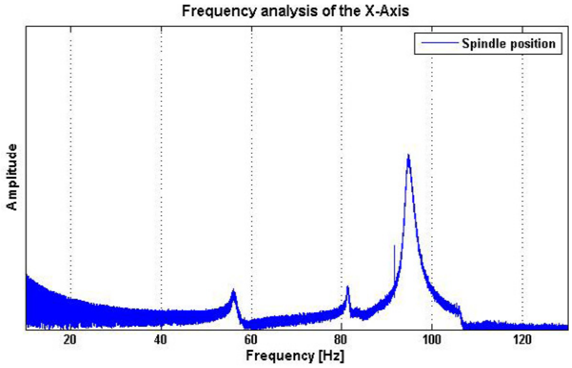

Fig. 6. Frequency analysis of the X-axis

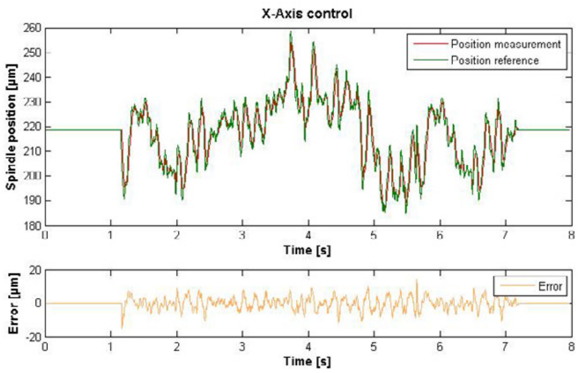

Fig. 7. Reference tracking characteristics

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