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3D-Piezo-Compensation-Mechanism for Online-Error-Compensation of Robots

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Abstract

This paper introduces a new and innovative method for machining with an industrial robot. Today, tasks for a typical robot application are simple handling jobs such as pick-and-place from place A to B. For such pick-and-place operations the robot's repeatability is good enough. Nevertheless, complex, flexible and precise handling systems are required. Specifically the market for tasks of dynamically processing, e.g. machining with robots has been growing recently. So the idea is to use the robot for those tasks since conventional metal cutting machine tools are higher in price and more inflexible compared to robot applications. Thus, this article describes the development of a 3-D-Piezo-Compensation-Mechanism (3-D-PCM) due to the idea of online error compensation, [12]. Aspects and rules related to the design of an actuation mechanism based on elastic solid-state joints (ESSJ) are presented. The results of the iteratively finite element analysis (FEA) and designing are following along with its static and dynamic results. Finally, the manufactured and on a test-bed installed 3-D-PCM will be shown. The beneficiaries of this robot machining concept will be presented finally by showing first machined work-pieces and measured results of those, respectively.

Keywords:

Piezo, Robotic, Machining

1 Introduction

Metal cutting machine tools were designed for highly accurate machining tasks. The idea of integrating handling capabilities for loading and unloading the machine was originally not considered. Therefore, small robots were applied now for those tasks of handling and equipping with new parts. Compared to these conventional machine tools a robot system is built for flexible handling tasks. Since industrial robots were used more and more for simple tasks like deburring, grinding, milling, and drilling the requirements for such robot systems are increasing in the same way. But since the structure, mechanics, drives, and gears of a robot are not designed for those tasks their possible accuracy is limited due to these boundaries. Since there are decisive requirements for machining processes of sheet metal, at Fraunhofer IPA the idea arise how to obtain, find and develop a machining robot with higher accuracy at the requirements of smaller costs and higher flexibility compared to conventional metal cutting machine tools. If these requirements can be fulfilled an industrial application can be found and will be likely.

The acceleration of the development and the entry of new products to the market, which reflect the wishes of customers get a decisive key property to meet the international pressure of competition. In order to deal with the industrial competition one needs to increase the number of developments and therefore, to reduce time to market and costs of manufacturing prototypes. Both, the increasing number and speed of developing innovative products compared to the decreasing time of merchandise are reasons for an increasing dynamic behaviour of innovation [1].

In order to improve the accuracy of a standard industrial robot several things need to be done. The idea is to compensate the positioning error by an additional actuation mechanism, which is characterized by a high accuracy and a small deflection. A few of such mechanisms for positioning can be already found in industrial applications [2, 4], especially in drives of conventional machine tools, or micro-positioning tasks in the production of microchips where such positioning concepts are already available. These actuation mechanisms are equipped with precise sensors and achieve high dynamic and resolution by using active piezo-electric materials. The elements of guiding these actuators are often realized by elastic solid-state joints (ESSJ). Their advantages are firstly to increase the displacement of the effector and secondly non-linear effects such as statically and sliding friction do not occur which leads to good dynamical behaviour compared to standard mechanical mechanisms. Non-linearities mainly exist in the sensor characteristics of the actuator and actuation mechanism, hysteresis, creeping effects, and during the control of those values [3, 11]. Nevertheless, it is well known how to encapsulate these control issues that the mechanical component as a whole can be considered to be linear.

2 High Precise Robot Machining

A new aspect of the new machining method is to maintain the flexibility of the robot and combine it with the accuracy suitable for machining. In order to obtain both advantages one can add a second self-operating positioning system in order to compensate the positioning error between its computed and actual position of the robot's Tool Center Point (TCP). Figure 1 shows the configuration of the entire system. The idea includes that the advantage of the handling capability of the robot remains. This enables that this new robot machining system can be applied in existing serial production lines without any cost-intensive adaptations. Compared to conventional metal cutting machines where an additional handling system in term of a smaller industrial robot is needed these costs for additional robots and applications can be reduced.

Before the main parts are detailed one need to know why such a system is needed. A robot cannot be used as stand-alone system. In Figure 1 the disturbance variable is signed as a red flash. The magnitude of the disturbances needs to be considered since it results in a range up to the absolute accuracy of 2 mm for standard industrial robots, [5, 6].

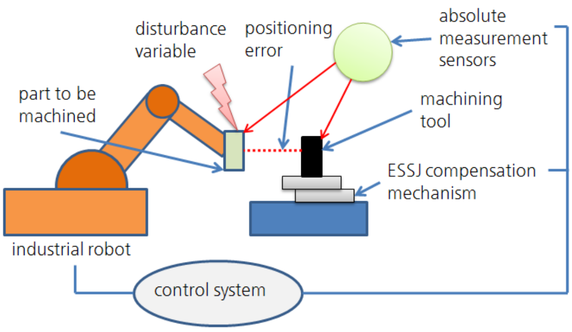

Figure 1. Concept of a robot system for high precise machining tasks.

Most serial applications of standard industrial robots require repeating tasks, such as movements from A to B. The accuracy for those processes is represented by the repeatability of the robot, which can be assumed an order of magnitude better than the absolute accuracy. These repeating processes require an iterative programming, e.g. if the accuracy of one programmed point in sequence is not accurate enough it will be changed in its position until the accuracy is good enough. Compared to machining processes where the tasks and sequences changes from part/task to part/task normal machining processes in serial production require a higher accuracy lesser than 50 µm. The accuracy of conventional tooling machines, comparable for the aimed processes is in a range of 1 to 5 µm [8]. This means standard industrial robots need to be improved in accuracy before they can be applied. [6, 7] describe the main error sources. Errors can arise because of machining forces, which are induced by static and dynamic errors. Further errors can have their origin in the tool, mechanical components, gears, and bearings, as well as user-errors due to individual human failures in control, programming and work-piece manufacturing. The main robots´ errors occur from low stiffness of the robots´ mechanics, drives, and bearings as well as external disturbances such as temperature effects. [6, 7] tried further to improve the robots´ accuracy by identifying these effects and by performing real-time deformation compensation. By using force and positioning control they reduced the surface accuracy from 0.9 mm to 0.3 mm. Their goal of application was to reach an accuracy of 0.5mm as a pre-machining application. So this approach could be a reason to increase the robots´ accuracy at all.

This paper focuses on the creation of an additional 3-D-actuation mechanism for error compensation, in order to reach the required machining accuracy. The main parts are the robot and the PCM. The PCM consists of several ESSJ for each single axis where a piezo-drive is used for the displacement of the effector. Figure 2 shows the mechanism of all ESSJs as mechanical scheme with the stiffness, the rate of damping and the masses for each axis. Furthermore, each displacement and piezo-actuator forces are shown. The applied piezo-actuator is symbolized with the force, e.g. Fx for the x-axis.

The ESSJ enables to integrate a gear with the ratio γ by placing the position on the lever where the force Fpiezo-actuator is applied. The maximum displacement of the piezo-actuator is limited and can be influenced through the ratio γ.

When applying a piezo-actuator in an ESSJ one needs to consider that the piezo-drive works versus a spring. That means the real displacement of the piezo-actuator will be reduced by

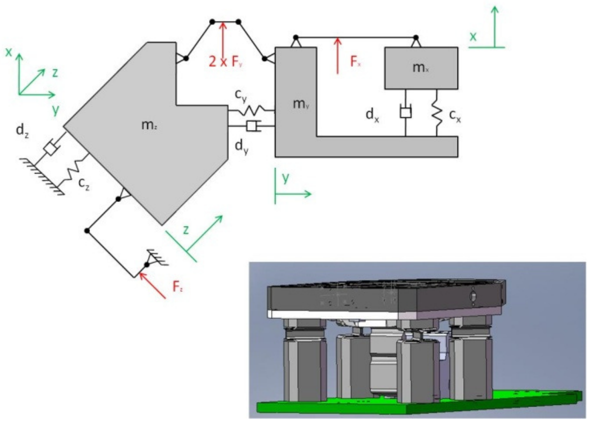

Figure 2. Mechanical scheme of ESSJ-Mechanism of the 3-D-PCM and its CAD-design of FEA.

$$\Delta L_R \approx \Delta L_0 \cdot \left(1 - \frac{k_T}{k_T + k_S}\right) \qquad (1),$$

where ΔL_R is the lost displacement caused by the external spring load, ΔL_0 the nominal displacement without external forces or restraints, the piezo-actuator stiffness k_T and k_S the spring stiffness of the ESSJ. This results due to the natural behaviour of a spring. Operating the actuator the external force

$$F(V) = -k_S \cdot \Delta L(V) \tag{2}$$

is proportional to the displacement $\Delta L(V)$ of the piezo-actuator, which is dependent upon voltage V. Due to this spring behaviour one needs to consider these effects in the design of the ESSJ using FEA-methods. The simulation enables the calculation of displacements versus a defined force, so the stiffness of the entire compensation system can be calculated. The remaining displacement of the piezo-actuator ΔL is determined by

$$\Delta L = \Delta L_0 \cdot \frac{k_T}{k_T + k_S} \tag{3}$$

Furthermore, the piezo-actuator is equipped with a strain gauge. This sensor enables to control the hysteresis behaviour of the piezo-materials, so that hysteresis can be fully compensated with this closed-loop piezo-system. The closed-loop works through measuring the actuator position by the strain gauge and comparing it with the computed actuator position. The difference needs to be controlled to zero. A further effect which is supposed to be controlled by the internal strain gauge measurement is the rate of creep. Due to remnant crystalline polarization and molecular material effects (dielectric and electromagnetic large-signal behaviour) the piezo-actuator is creeping a few percent of its displacement with the time (voltage gain remains at same level after a changing in positioning). The creeping behaviour as change in position after voltage change is a function of time $\Delta L(t)$ and follows

$$\Delta L(t) \approx \Delta L_{t=0.1}\left[1 + \gamma_{Cr} \cdot \lg\left(\frac{t}{0.1}\right)\right] \qquad (4),$$

where $\Delta L_{t=0.1}$ represents the creeping shift 0.1s after voltage change and is the creep-factor. So the non-linearity of the piezo-actuator can be excluded using the closed-loop control architecture, which is named as inner control of the cascade control in this paper.

A further part as functional device of the proposed machining system (Figure 1) needs to be applied and is named as absolute measurement sensors. The measurement sensor is applied for the purpose of identifying the current positioning errors, arising from static and dynamic effects. Knowing the absolute position of the measurement sensors one can measure the relative position of the robot's TCP and of the ESSJ-compensation-mechanism. The ESSJ-compen-sation-mechanism can be assumed to be rigid compared to the robot which handles the work-piece and due to the named errors and disturbance variables can vary within the range of the positioning accuracy. Thus, only the absolute position of the TCP needs to be measured during the machining processes and programmed positioning sequences. With the information of this measured current position and the programmed position, which can be read from the robot controller, one can calculate the translational error between work-piece and tool. The idea of the approach presented here is to have two compensational concepts. One follows greater errors in a range between 0.5mm and 2mm (equal to the robot's absolute accuracy) as described in [7] and the second compensation will be controlled with the additional ESSJ-compensation-mechanism. Using a real-time operating system data can be read and continuously processed with the interpolation frequency of the robot´s control in order to command appropriate correction values to the ESSJ-compensation-mechanism, which will be further detailed in the next paragraph.

The control system is a further part, as seen in Figure 1. As explained before it consists of the inner cascade control of the piezo-actuator by using the strain gauge and the outer cascade of firstly controlling greater errors of the robot and secondly controlling the position of the ESSJ-effector by measuring the effector position using a capacitive sensor. The data processing of all sensors and actuators is built by using a dSpace real-time-system in combination with the Matlab real-time workshop. So, the outer cascade controls the position of the ESSJ-effector with the tool spindle fixed on it.

3 Design Apects of EESJ using in Combination with Piezo-Actuators

Based on the above presented concept and requirements to increase the machining accuracy of robots, the design of this additional actuation mechanism for error compensation is presented. Therefore, several rules based on the theory of piezo-actuators [9, 10, 11 and 12] have to be adhered.

3.1 Application of lever and knee-lever motion amplifiers

A survey on piezo-actuators shows that it is possible to obtain actuators with great diversity of displacement, stiffness, and dimensions (e.g. as piezo-stacks). The aim of an additional ESSJ-mechanism is to compensate displacements in a range up to 500 µm. Because of the length of an actuator with a maximum displacement capacity of 180 µm which is about 200 mm no greater piezo-actuator was intended to be applied in an ESSJ-mechanism. So motion lever amplifiers with lever transmission ratios between $\gamma = 4 \div 6$ were designed to increase the 180 µm up to about 500 µm displacement. The use of a lever motion induces some loss-effects, thus, a greater ratio γ must be applied in order to compensate the main problem in loss of stiffness. Since the lever mechanism are supposed to be free of backlash and friction to maintain the desired dynamic behaviour and resolution ESSJ with optimum guidance characteristics was applied. Alternatives such as roller bearings were not considered due to backlash, [12]. Using this lever gear the advantages of a compact size (compared to an actuator with same displacement and length of the piezo-actuator) and greater displacement will be exploited. The disadvantages of reduced stiffness and capacitance of displacement due to working versus a spring, and lower resonant frequency need to be considered in the design. A further requirement is to ensure that no loss of stiffness occurs due to coupling between the piezo-stack and the lever motion system. This coupling must be very stiff in direction of the displacement and should not transmit forces and moments in all other directions to avoid material damages of the piezo-stack. Thus, a ball tip is used, as also described later for further reasons.

3.2 Straight displacement with use of ESSJ’s to build a flexure guiding system

The common application of ESSJ is to build a flexure guiding system to ensure only a one-directional linear behaviour of the ESSJ-effector. Limiting the stresses to appropriate values the mechanism is designed to have fatigue resistance and thus free of wear. Compared to mechanical guiding systems ESSJs are less sensitive to shock and vibration, they are maintenance free, and require no lubrication or further consumables.

Different types of ESSJs exist. Some are working as parallelogram principle, linear system, lever motion, knee-lever, parallel or serial kinematics. All these ESSJs have special requirements which need to be adhered for designing.

The way of finding a compensation-mechanism is iteratively and follows the theory of [10]. The designer obtains the idea from the diversity of ESSJ-types. From this point one needs to decide the type, which is appropriate for the application. In this case, motion lever mechanisms for the x- and z-axis and a double knee-lever mechanism for the y-axis has shown best results in the transmission.

For the iterative design process one need to consider the lever transmission ratio γ, the force F of the piezo-actuator and the stiffness k_S of all ESSJs together. With all these considerations several finite element analysis (FEA) computer simulations were carried out to optimize the translational displacement of the effector while avoiding rotation.

3.3 Mounting and Handling of Couplings

Because of axial pulling loads on the piezo-actuator which can arise from the effector the piezo-actuator is provided with a preload of 2 kN at an entire load capacity of 12,5 kN for the planar x- and y-axis and a capacity of 30 kN and stiffness of 160 N/mm2 for the z-axis. Tilting and shearing forces have to be avoided because they can damage the piezo-actuator. So with the use of ball tips at the end of the piezo-actuators these forces can be excluded.

4 Installation of the 3D-PCM

The final results of the FEA-simulation are shown in Figure 5 for the x-axis and Figure 6 for the y-axis. For a better understanding the results are well explained in [15], so only the results are shown in Figure 5 to 7. Figure 8 shows the manufactured 3-D-PCM. For the manufacturing process several aspects for ESSJs were considered, especially that all were manufactured by wire-cut EDM. After the delivery of the 3-D-PCM the installation for experiments of the setup of Figure 1 has been done, which led to the test-system in Figure 9, equipped with a machine bed, which consists of a welded steel-construction filled with polymer concrete in order to reduce and damp the magnitudes of oscillations.

Before milling experiments can be conducted the preparation of the test-bed with the entire signal-processing and implementation of a cascade-control need to be done. For the close-loop control an inner cascade in order to linearize the piezo-actuator by using a strain gauge and the outer cascade using a capacitive sensor, measuring the spindle position were implemented. Afterwards several milling experiments have been conducted in order to gain the required experiences. Since the degrees of freedom of parameters for the installation, milling and close-loop-control are huge, the focus for a first attempt was based on gaining experiences of milling along with the 3-D-PCM. Thus, milling parameters as shown in Table 2 were found as adequate for the Reis robot RSV40 when milling with the parameters of Table 1. These parameters were applied for milling with error-compensation of the z-axis whereas the x- and y-axis were kept stable on there working-point position in the middle of the several displacement ranges. The experiments were both conducted with clock- and anticlockwise milling.

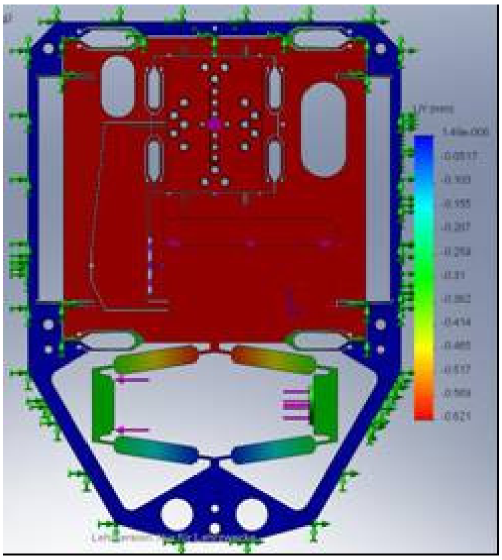

Figure 5. FEA-displacement of the x-axis.

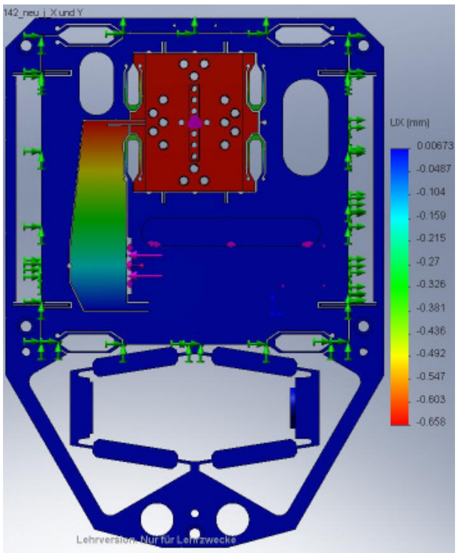

Figure 6:FEA-displacement fo the y-axis.

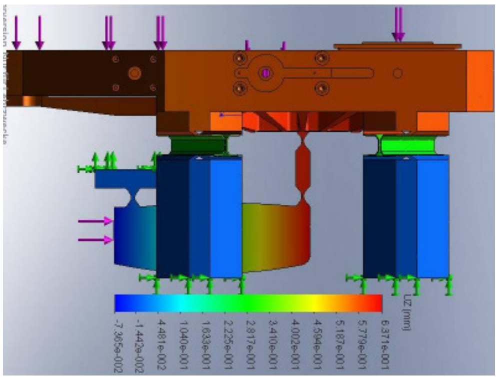

Figure 7. FEA-displacement of the z-axis.

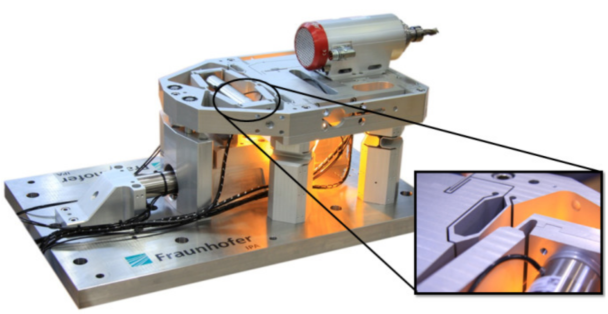

Figure 8. Manufactured 3-D-PCM.

Figure 9. System on a machine-bed along with a Reis-robot RSV40.

5 Results of Robot Machining with the 3D-PCM

Figure 10 shows the milling operation. The aim for measuring the precision of the 3-D-PCM was to machine three straight lanes with different depth parameters, like a_e the radial infeeding and a_p the axial infeeding, which are shown in Table 1.

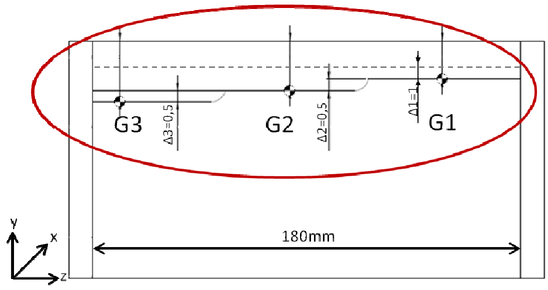

Figure 10. straight lanes to be machined along with 3-D-PCM.

Table 1: List of milling parameters for G1 to G3

Operations	a_p [mm]	ae [mm]
G1	10	1
G2	10	0.5
G3	5	0.5

Table 2: List of milling parameters for clockwise and anticlockwise run

Operations	Rotational frequency [1/min-1]	v_f [mm/s]
Clockwise	30.000	5
Anticlockwise	20.000	15

Table 3 shows the results for the milling operations, measured with a coordinate measuring machine VideoCheck HA (high accuracy) 400 of Werth. The measured errors are really small. Compared to the errors with no control, means that the 3-D-PCM is not in action and passive this concept enables to machine more precise than with standard robot machining. Furthermore one needs to mention that the errors with no control, shown in Table 3 are randomly and expected to be much higher when increasing the volumina of machining or the feed rate. Compared to the machining process with error-compensation of the z-axis absolute accuracies could be highly increased and the error could be decreased by 86%. Compared to [14] the results of the z-axis are in compareable good range.

Table 3: Results of milling for clockwise and anticlockwise run

Operations	**Absolute error G3-G2 [µm]**	**Absolute error G2-G1 [µm]**
Clockwise with no control	38.6	48.7
Clockwise **with control**	**24.0**	**11.5**
Anticlockwise with no control	152.1	139.7
Anticlockwise **with control**	**33.5**	**7.3**

6 Conclusion and Perspectives

This article describes the development of a 3-D-PCM in order to enable high-accurate machining tasks along with industrial robots. Firstly, the concept is introduced based on measuring the current position error and superimposing a correction motion. The advantages of using piezo-actuators in combination with ESSJs for error compensation were discussed. Further aspects of design for piezo-actuators and ESSJs were highlighted and being considered. A design study for a motion lever mechanism based on ESSJ is presented as well as for a knee-lever-mechanism. An iterative process of FEA-simulations and redesign of the ESSJs was used to optimize the range of pure translational displacement while increasing the stiffness and minimizing von-Mises-stress for each axis. Additional ESSJs were added to avoid unintended z-rotation. Again an iterative process of FEA-simulation and redesign followed due to maximum displacement and minimum von-Mises-stress. Simulation results of the optimized mechanism were presented as well as six design-studies for the z-axis. Furthermore, a FEA-simulation of each axis with its displacement and von-Mises-stress was calculated. The frequency analysis of the entire system shows the eigenfrequencies of each axis in the desired direction of motion.

After design and FEA-simulation further tasks contained the installation of the manufactured and assembled 3-D-PCM with all the designated parts. Sensors and actuators have been installed and linearized. First milling results have shown the potential of the 3-D-PCM. During the named milling tasks absolute accuracies of the robot machining could be highly increased. The remaining error remains lower than around 10µm and compared to milling with no 3-D-PCM the error could be reduced up to 86%. Thus the milling operations have shown how the 3-D-PCM works and the results show what capabilities are possible in future tasks when milling with robots and additional error-compensation.

An interesting point in future work will be assigned to the close-loop control setup along conducting milling experiments as well as the correct finding of milling parameters for the applied and specific robots. Further work could also be considered on the fatigue endurance limit, where a parameter need to be found, which characterizes the process behaviour of oscillation by finding correct values of amplitude and mean stress. Continuing the implementation of the control system an important task in future work concerns the entire compensation-mechanism together with the real-time data-processing and the application of adequate filter algorithms in order to avoid hissing and non-linearities. Based on these experiences of the named future works the final goal is increase the experiences of different milling operations in order to aim to more industrial solutions.

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