Micro Positioning System with 3dof for a Dynamic Compensation of Standard Robots

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Abstract

This paper presents our approach to upgrade standard robots in industrial use with a 3dof micro positioning system (mps) to compete with expensive high precision robots in assembling tasks. The autonomous mps consisting of different microsystems is placed between the robot's hand and the gripper. The static positioning and feeding displacements as well as the tolerances of the object's dimensions and the dynamic robot vibrations are sensed with the mps's miniature sensor system. The correction movement is done by the mps's micro piezo actuators. Thus reaching an accuracy of about 10 microns and a reduction of the mounting cycle time. The high precision can be reached because the mps is focused on the movement of the object to be mounted and the position of the target. The mps is a flexible system, that can be used with different kind of robots, because neither the robot's control system nor the robot itself has to be changed.

1 Introduction

Assembling of products consisting of microsystems has to deal with problems, which are caused by the small dimensions and tolerances of the objects. As a consequence, the manipulator in the assembling task must maintain a high precision and quality. This is the reason why automation in this field is only economic for products with a high number of pieces. In addition the high variety of micro parts in products with a midrange or small number of pieces makes automatic assembly difficult. Therefore, nowadays the most steps are done manually, e.g. the assembly of the gears of an analog radio controlled watch. This causes the problem, that human errors occur, e.g. damaging sensitive parts or not assembling precisely enough. This results in long cycle times and high personal costs. A refinement of known assembling methods in addition to the development of new approaches makes sense because the required precision in the production is determined by the respective assembling step.

Nowadays, there are many products with tolerances of some microns, e.g. 3D-MIDs[1]. Specialized high precision robots can reach an accuray of about one micron [3]. These expensive and unflexible robots can only be used in products with a high number of pieces as mentioned above. Standard robots in industrial use with 6dof are very flexible and have relative low prices, but they don't reach the needed precision (see section 2). They can only join parts with greater tolerances than their own position accuracy. Although surface mount systems are precise and fast, they have not the capability with their 3dof to perform complex mounting tasks like 3D-MID-mounting. Using a micro-macro concept is not new, but these systems are either specialized for one application [1] or not capable of assembling micro parts [2].

We present a new approach in combining an industrial standard robot as macro-actuator with the mps as a micro actuator. So we can take advantage of the robot‘s flexibility and low price and increase its precision with the mps. The mps consist of a compact actuator unit with different microsystems and a control and signal processing unit. The actuator unit is placed between the robot's arm and the gripper. The control and signal processing unit is placed somewhere beneath the robot. Figure 1 shows a sketch of the whole system with the industrial robot Stäubli RX90. In the next section we discuss the inaccuracies of this robot that have to be compensated. In section 3 we describe our miniature sensor system, that senses static displacements of the robot and the feeder as well as

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[1] Moulded Interconnect Device

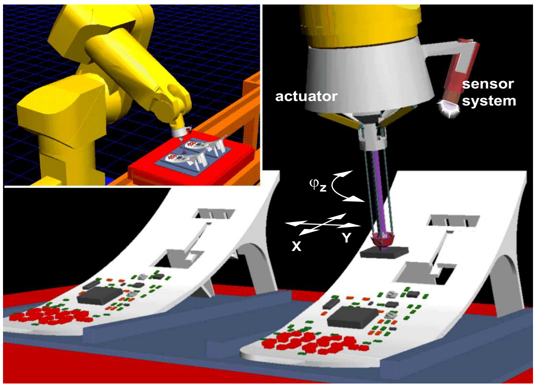

Figure 1: robot and mps in principle

the tolerances of the object's dimensions with a CCD-camera and image processing. Dynamic vibrations are measured with a triaxial accelerometer system, that is additionally used to feed the control system during the dead time of the image processing algorithm. Section 4 presents the micro piezo actuator, which performs the correction movements as an active compensation [3] increasing the accuracy of the whole system to some microns. Our control system taking advantage of the systematic inaccuracies of the robot is described in section 5. The last section shows intermediate results and the further work.

2 Standard Robots' Vibrations

A number of measurements with the Stäubli RX90 robot were processed, in order to determine the static and dynamic inaccuracies of standard robots that can carry weights of about 6kg. The results were used to derive the requirements and challenges for the mps and were partially confirmed with measurements of other robots within the same class.

We used two different measuring systems to determine the static and dynamic behaviour of the robot. The first one was a commercial measuring system with 6dof, 2dof are determined with an interferometer, the other degrees of freedom with PSDs) [4]. The verification system was a self- developed system and measured 5dof with laser triangulation sensors. We programmed (that means teaching of starting and ending point) different orthogonally oriented straight trajectories with a length between 50 and 80cm and determined the deviations with a resolution of about 1 micron, while the robot's arm was moving. Figure 2 shows a sample reading for a translatory deviation. The derived results are as follows:

- displacement, when moving to the same teached position several times: <40μm, <0.03°.
- translatory displacements: between 300μm and 700μm dependent from the length of the trajectory. The displacements of different runs on the same trajectory are reproduceable within a range of about 40 microns. This fact is used for controlling the mps (section 5).

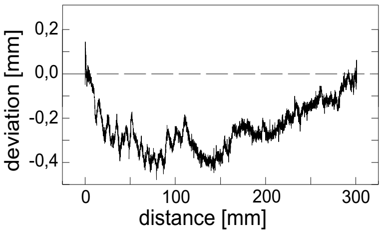

Figure 2: sample translatory deviation

- rotatory deviations: The rotations around the two axis orthogonal to the trajectory are less then 0.13°, but rotations around the trajectory are about one magnitude higher.
- accelerations: orthogonally to the movement direction below $3\frac{m}{s^2}$
- bandwidth of vibrations: Figure 3 shows the frequencies of the vibrations during movement along a trajectory. The bandwidth is limited to frequencies below 80Hz. The increasing spectral density at low frequencies during strong accelerations (start and stop) is caused by the inertia of the robot's mass.
- influence of velocity: The displacements are increasing when moving with a higher velocity, but there is a strong correlation referring to the lower velocity.
- influence of direction: The displacements between positive and negative directions are correlated up to a hysteresis.

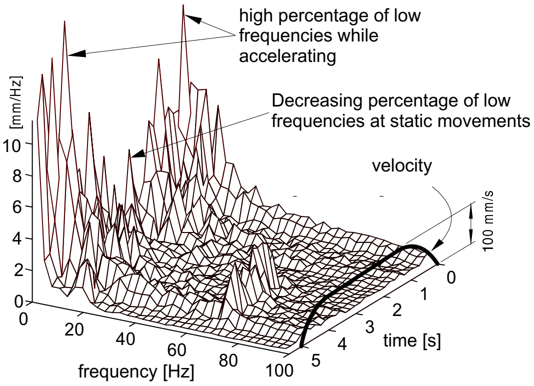

Figure 3: FFT of robot's vibrations

These results show that this class of robots can only be used in tasks with less pretentious requirements. The mps has to compensate only deviations in 3 dof, because the orthogonal rotatory deviations are small enough. Since the measured displacements along the assembly axis are below the admissible deviations for mounting tasks, a correction of this dof is not necessary. Thus the mps needs two translatory dof to be capable to compensate dynamic displacements within the range of $\pm 300\mu$m up to 80Hz plus static tolerances of about 300μm. The rotatory dof around the assembly axis has to deal with deviations of about $\pm 0.6°$.

3 Sensor system

We do not want to restrict the flexibility of the robot by applying sensor systems, that need some gadget near the target, e.g. following a laser beam. Instead we use a CCD-sensor and image processing to measure the deviations. Since image processing is computational intensive and the most CCD-cameras are working at a fixed frame rate (50Hz) that is given by the PAL-norm, we additionally use a second kind of sensor: a triaxial accelerometer system. The static and low frequency deviations ($<$ 10Hz) are measured with the CCD-sensor, the higher frequencies with the accelerometers. The synchronization of sensor data is done with the help of time stamp of a realtime clock taking into account the sensor delays.

3.1 Triaxial accelerometer system

The accelerometer system should be able to determine accelerations caused by vibrations up to 80Hz very precisely (down to 0.1mg). Therefore, we use capacitive accelerometers, which sense vibrations down to DC. These kinds of sensors can be driven in closed-loop applications. Piezo resistive accelerometers are not suitable for measuring such low frequencies with the irequired precision because of their higher typical errors [9]. Since we need the accelerometers to feed the controller within the dead time of the image processing, the incoming signal has to be integrated twice. Typical errors of an inertial measurement system have to be reduced, because otherwise the integrated signals are drifting away very fast [7]. That is the reason why we are using a triaxial system, although we have to determine only the two translatory degrees of freedom in the assembly plain. The third sensor is used to compensate measurement errors. The methods we use to avoid the typical errors are described as follows.

– assembling errors: The deviations from the ideal orthogonally oriented axis can be determined as described in [8] for triaxial systems.

– temperature drift: is reduced using a differential capacitor sensor and is compensated with a-priori determined correction values stored in a look-up table.

– static errors: e.g. amplifier offsets; are filtered off with a suitable numerical filter (backward-euler integration after numerical derivative). The integrator of the last stage (distance) is referenced after each frame with the CCD-sensor and the reference for the previous integrator (velocity) is estimated analyzing the difference between reference and integrated signal.

– off-axis sensitivity and dynamic behaviour: Each accelerometer senses an acceleration which is orthogonally oriented to its sensitive axis. The signals delivered from the triaxial sensor system are coupled as shown in figure 4 in a 3x3 transfer matrix consisting of PT2-transfer functions. The inversion of this matrix is impossible because of the delay time of a PT2-system. So we estimated the transfer functions of the 'Inverse Transfer Matrix' with a CASE-Tool directly from measured data. The p-canonical structure of the applied compensation filter is also shown in figure 4. This method has the advantage, that the delay time of the accelerometers can be reduced by adding zeros to the poles of the 'inverse' PT2-system.

The necessary preprocessing of the sensor data is done in realtime on a DSP. We have examined several different types of accelerometers from low-cost to high-end sensors. The described preprocessing methods can be successfully used with all of them. The precision of the sensors could be increased by a factor between 5-10 depending on the sensor type.

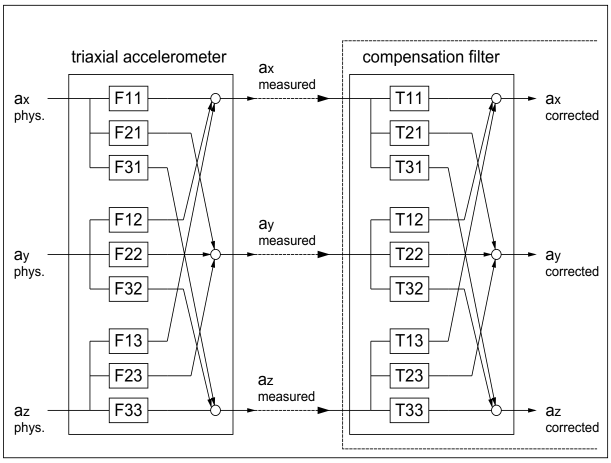

Figure 4: structure of the transfer matrix and the compensation filter

3.2 Optical sensor system

The optical sensor system of the mps is based on an optical imaging system (called smart optic), a CCD sensor and an image processing system. The system provides highest flexibility and compactness, because the CCD sensor and the optical imaging system is placed on the mps.

smart optic. There are several requirements for the optical imaging system:

- its components should have small dimensions and low mass,
- objects with different dimensions have to be imaged in rather good quality. A common approach is the use of autofocus,
- the object size must be controlled in order to estimate the distance of target and different objects to be mounted, Therefore, an suitable zoom system has to be realized.
- the entire system has to be low cost.

Commercial available state-of-the-art imaging systems do not fulfill all these above requirements. Thus a new imaging system for the mps was developed. The basic idea is to replace standard fixed focus glass lenses with flexible lenses having deformable surfaces. In principle a combined autofocus/zoom system can be realized by arranging just two flexible lenses in a row. According to the application the objective parameters such as lens aperture, lens distance, sensor position and stop position have to be calculated by using optical design tools.

The used flexible lenses have a liquid enterior (glycerine) covered with a transparent flexible membrane (silicone) and a glass plate. The surface shape is controlled by an external micropump. This lens concept makes lens powers from -30 to +30 diopters possible. In order to reduce optical aberrations such as distortion, an image analysis algorithm was developed and implemented in the controlling system of the mps.

Image Processing System. The image processing system is used to reference the accelerometer system and to sense the static displacements described above. In order to obtain high precision it is important to keep the chain of tolerances as short as possible. This is achieved by detecting directly the relative position between the target and the object to be mounted. A survey of many options resulted in the use of image processing.

Only the two horizontal coordinates (x,y) are of interest, if the camera is located exactly vertical above the assembly plain. Because of geometrical restrictions it is not always possible to mount the camera there. In many cases it has to be inclined to see object and target at the same time. So the coordinate perpendicular to the assembly plane (z) influences the x- and y-coordinates in the image. In consequence it has to be measured, too.

On the one hand the optical sensor system has to be compact and of low mass and on the other hand it should be capable to deliver the position data at a frequency of at least 5Hz. So the usual approaches for 3D-sensing like stereo imaging, autofocus and the use of structured illumination are not suitable.

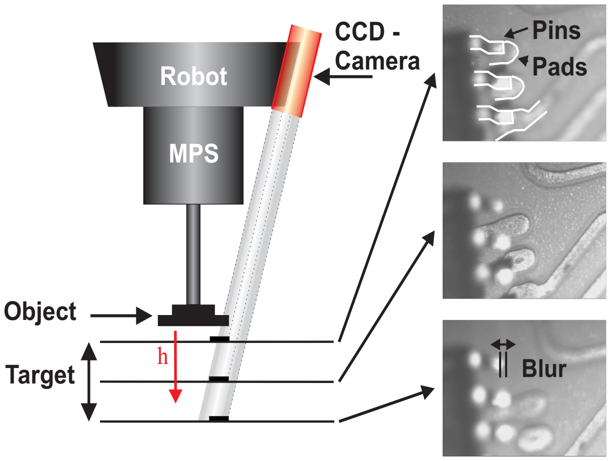

Figure 5: The x- an y-coordinates in the image depend on the z-coordinate which can be measured from the blur.

The new method developed for this project obtains the contours of the object and the target in the image plane by a fast contour tracer [6](processing time: 82.9 ms on a DEC alpha @175MHz per 512x512 frame) and matches them with given modells to get the x-y coordinates. The object distance b is deduced from the blur of the edges caused by being out of focus (figure 5)[10][5].

The convolution of the object with the lens' point spread function (PSF) yields a specific amount of blur of the edges depending on the coordinates. By calculating this blur for different object planes a lookup table can be generated. So the z-coordinate can be obtained from the measured blur very fast, just by linear regression using that lookup table. To examine the accuracy of this method, in a first step a CCD camera recorded some shifts Δz of a black-white-edge. These shifts were measured by the change of the blur and compared with the values of a Zeiss-interferometer used as reference. It was shown that Δz can be determined with a maximum deviation of 40μ in a range of 9mm and a blur of up to 50 pixels of the CCD chip. At an inclination α=5° this refers to a horizontal deviation in the image of just 3.5μm. So the position of the target can be determined with an accuracy better than 5μm including the deviation of the contour tracer.

4 Micro Actuator

The micro actuator has to perfom the compensation movements of the mps, according to the requirements described above. Therefore, a mechanism has to be found, which enables to move along distances from about 0.7 mm in the two directions in the assembly-plain and about 0.8 degrees around the assembly axis, each seen in positive and negative tendency from an equilibrium position. Furthermore good dynamic properties are needed, because the deviations proceed up to frequencies of 80 Hz. The suitability of the different actuator's principles for static and dynamic applications should be considered. A piezoelectric principle was choosen in order to obtain a good dynamic behaviour of the micro actuator. The problem here is the low strain of piezoelectric actuators. Applying electrical fields of about 2 kV/mm the strain is typically 1300ppm of the actuator-length [11]. That is the reason why usually applied actuators can only move 0.1 mm or less. A high ratio has been choosen to achieve the demanded distances. On the other hand, this ratio decreases the stiffness of the mechanism. One solution of this problem is an integral arrangement of the single actuators. This means, that for all movememts all actuators are used. This concept makes a light structure possible.

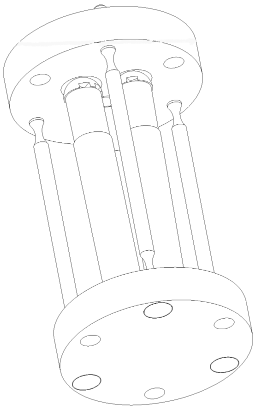

Figure 6: draft of the tripod-actuator

According to this a first prototype called 'tripod' was developed. It is not really a tripod, because it is build out of three sticks called swingle and three acuators (figure 6). The three swingles are coupled each with two ball joints between a top and a bottom plate. The ball joints are performed as elastic cantilever to prevent effects of friction. The three forbidden dofs are the two torsions in the assembly plane(ϕ_x, ϕ_y) and the translation along the assembly axis (u_z). Between the two plates three piezo actuators are disposed, which can move the bottom plate in two degrees of freedom. The third actuator is to give a constant stress to the two others in each case. Tests have shown that the strain of a constantly prestressed piezoelectric actuator is better than of one with no prestress [12] . Furthermore a piezoelectric actuator is much better in pushing a load than in pulling. In the mechanism one actuator is antagonist to the two (or one) others in every case. So the whole actuator is able to perform the reverse action by pushing.

The actuators are coupled between the top-plate and the bottom-plate afresh with two ball joints each. The joints are shaped out of a bronze-ball and a steel-cone with respect to the height of the actuator. The disadvantage of effects of friction can be minimized by polish the components with graphite-powder. The stiffness can be increased by forming the cone with a steel-ball of the same diameter as the bronze ball, to get better surface contact. The assembly positions of the actuators are like the edges of a tetraeder.

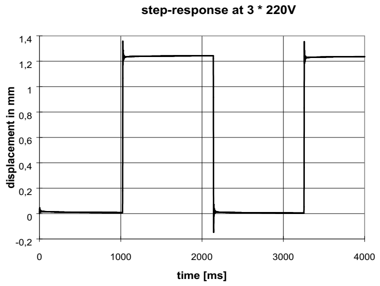

Figure 7: step response for a kartesian translation

The step response for a kartesian translation of the tripod's bottom plate (e.g. one piezo actuator is pulling and two piezo actuators are pushing) is shown in figure 7. Figure 8 shows the transfer function in the range from 100Hz to 250Hz. The additional resonant frequency at 145Hz is probably caused by a resonance in one of the restricted dof. This fact will be examined with a FEM-simulation. The dimensions of the tripod are as follows:

- height: 80 mm
- diameter: 40 mm
- weight without sensors and gripper: 125 g
- translatory movements: ± 0.6 mm
- mechanical resonant frequency: about 350 Hz
- Operating voltage: 100V±100V

Figure 8: transfer function

The rotation around the assembly axis is not yet integrated to the actuator. Conceivably the rotation can be performed with a stepper or an additionally integrated piezoelectric actuator. A prototype of the version with the fourth actuator is in process.

5 Predictive Control System

The analysis of the deviations for repeating mounting tasks, e.g. 3D-MID, has shown the important fact, mentioned in section 2: A remarkable amount of these deviations is reproducable. Each time the robot makes the same movements the major parts of the deviations are identical. The velocity influences the shape of the deviations depending on the distance from the starting point. These facts can be explained with systematic errors e.g. nonlinearities of the robot control and tolerances of the length of the robot axis.

They can be used to gain a better control if the controling system is able to adapt quickly. Based on this we have designed a predictive control algorithm. The prediction is necessary since the sensor system, the actuators and last but not least the control algorithm itself have delays.

The error measured by the sensor system is stored and matched to a reference which is taken at an initial mounting cycle (calibration) . If the match is found it is possible to look a few microseconds ahead, depending on the current delays of the system. This data is computed with the inverse transfer functions of sensors and actuators. The actuators of the mps are driven with this estimated data. Figure 9 gives an overview of the control algorithm.

The quality of the reference is continually refined by taking the deviations of every single assembly motion into account. This allows to adapt the algorithm to slow changes in the environment. An example is temperature which may change the kinematic length of the robot. As another point slight changes in the velocity of the robot can be done without stimulating the robot. This allows to increase assembly speed with increasing quality of the reference, since one initial mounting cycle supplies a good but suboptimal reference.

As a calibration the robot performs the movement necessary for the assembly task without the object to be mounted. This is necessary to prevent the destruction of the object.

The algorithm described above has been implemented and tested on real robot data. The initial deviations of up to 700μm could be reduced to about $\pm 20\mu$m. The deviations left by this algorithm should be reduced by an conventional control algorithm, e.g state space control algorithm with a Kalman state estimator. Therefore, in future work it is necessary to identify the transfer functions of the whole system.

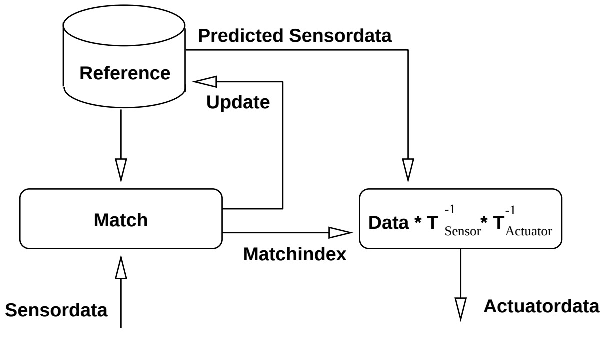

Figure 9: Overview of the predictive control system

6 Conclusion

The components of the mps presented in this article are already realized as prototypes. They all are tested only as standalone parts with real data, obtained from the measurements described in section 2. The next step is on the one hand to refine the prototypes and on the other hand to test the interaction between the single components with a hardware in the loop simulation of the whole mps. A problem will be the right synchronization of the data of each sensor for the control system. The results of the single prototypes show, that our approach will fulfill the given requirements.

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