8th International Workshop on Research and Education in Mechatronics

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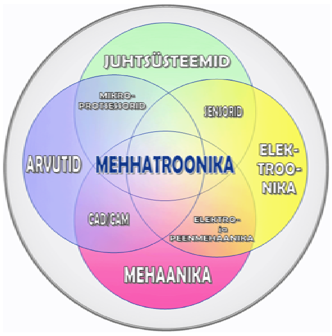

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Contents

Automated Assembly of High-Precision Parts

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***Abstract* — A new method for the assembly of high-precision parts is presented. It reduces the complexity, technical effort, and costs of the process automation. A smooth assembly force generated by vacuum avoids damages to the assembled parts. Cant effects are reduced by oscillations of the work piece holder. The method was exemplarily implemented as a prototype device for the assembly of injector nozzles of diesel engines. A standard industrial robot is used for the supply, pre-positioning, and removal of parts. No position and force measurements or control algorithms are used. For a detailed analysis of the assembly process, the test bed is equipped with a high-speed camera. The camera observes the motion of the parts in extreme slow motion. In a further stage of development, the method offers the possibility to assemble multiple parts in one parallel step. Thus, the costs and time of the assembly process can be reduced drastically.**

***Index Terms*— high-precision assembly, oscillation, vacuum, high-speed camera**

I. Introduction

The assembly of precision parts with clearance tolerances in the range of micrometers poses high requirements on assembly automation. In the production of diesel fuel injection-systems or gear boxes, shaped parts with clearances in the range of micro meters have to be joined. This requires a machining technology with an accuracy class < 1µm.

As an example, figure 1 shows the needle and body of a common rail diesel injector nozzle. During the assembly process, the needle, lying in front of the body in figure 1, has to be inserted into the central bore of the body. Common rail injector systems work with just one injection pump. The fuel is injected into the cylinder through outlet holes at the tip of the body. The high system pressure of 1600 – 2000 bar demands a fitting accuracy and shape accuracy < 1.5 µm of the needle and the body.

Fig. 1: Body and needle of a common rail diesel injection system

In current industrial production processes high-precision parts are joined by means of complex and costly control technology with measurements of positions and applied forces. Some industrial applications even require a pre-classification of parts according to their accuracy to size. The recess or hole are measured inside and combined with a compatibly shaped part. An exact positioning of the parts to each other is a precondition for an efficient assembly. Furthermore, only small assembly forces may be applied to avoid damages to the parts.

In mechatronics, robots with parallel kinematics have been developed to achieve high-precision requirements. However, robots with parallel kinematics have not yet come to common industrial application due to their limited workspace and complicated control. Thus in this paper, the application is based on a standard robot.

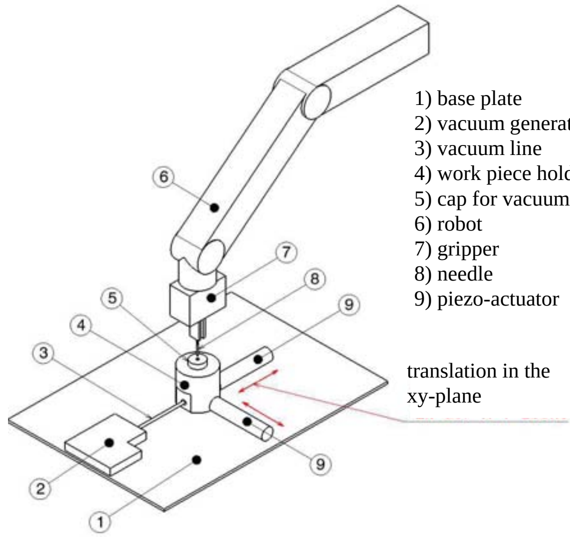

Fig. 2: Principle structure of the assembly device

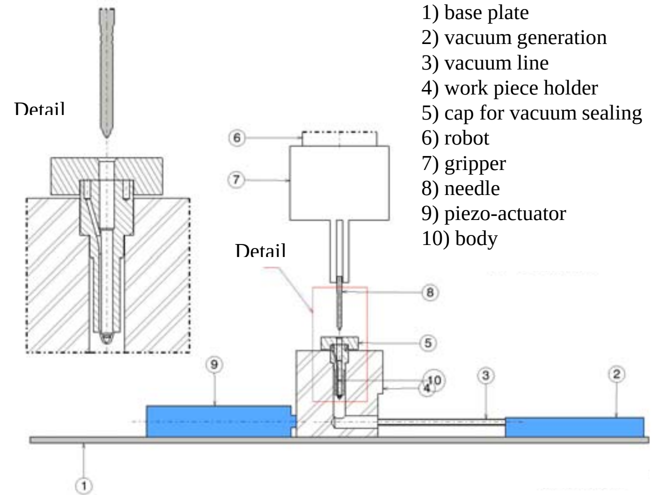

Fig. 3: Cross-section view of the assembly device

II. METHOD

In the following, a new assembly method for high-precision parts is presented. It does not depend on sophisticated control technologies with measurements of the positions of parts or the assembly force. The basic concept has already been described in [1]. The method utilizes oscillations that reduce friction and cant effects and bring the parts into an appropriate relative position before joining according to shape deviations and clearance tolerances. The assembly force for the joining procedure is provided by gravitation in addition with a vacuum force. Thus, a smooth assembly force is obtained, which carefully handles the parts. The authors have applied for a patent [2].

Figures 2 and 3 illustrate the principle of the method. It is applied here on the assembly of the diesel injection nozzle. A standard industrial robot can be used for the handling, supply and removal of parts.

In a *first step*, the body (10), that later on has to incorporate the needle (8), is placed in the work piece holder (4). This step can be carried out by the robot without extraordinary accuracy demands.

Secondly, the work piece holder is closed by a cap (5). In the cross-section view of fig. 3, the body (10) is visible in the work piece holder (4). It is connected to a vacuum generator (2) by a vacuum line (3). The cap (5) makes sure that the body (10) is vacuum-sealed against the work piece holder. The cap (5) possesses a hole in its middle, where the needle (8) can be inserted into the body (10).

In the *third step* of the assembly process, the robot places the needle (8) in the hole of the cap (5). Again, the standard position accuracy of the robot is sufficient. After opening the gripper (8), the needle (8) is able to rotate around its longitudinal axis. Due to friction and cant effects, it does not fall into the body (10). The work piece holder can be moved in the xy- plane parallel to the base plate (1).

In the *fourth step*, two piezo-actuators (9), mounted in a rectangular position as shown in fig. 2, generate arbitrary oscillations in the xy-plane. Thereby, a rotation of the needle around its longitudinal axis is stimulated and the friction and cant effects are reduced. An sweep frequency stimulation avoids problems that might appear due to the natural frequency characteristics of the parts.

In the *fifth step*, a vacuum is generated underneath the body (10). Through the fuel hole in the tip of the body, the vacuum is transferred into the inside of the body and the needle is sucked into the body. Due to the rotation, caused by the oscillation, the needle finds an appropriate assembly position according to the deviation of roundness. The vacuum creates a smooth assembly force that does not damage the parts. Furthermore, the vacuum evacuates the air cushion under the needle in the body.

Finally, in a *sixth step*, the cab is opened again and the assembled injection nozzle can be removed by the robot.

III. EXPERIMENTAL SETUP

To examine the functional principle of the method, an experimental setup with a standard industrial robot and a prototype assembly device was build. To analyze the assembly process, the setup is equipped with a high-speed camera.

In the lab, an articulated robot with six joints (KUKA KR3) is available. As shown in fig. 4, the robot is mounted hanging over the assembly device. The robot offers a repeat accuracy of 50 µm whereas the fitting accuracy of the assembled parts is < 1,5 µm. The robot is used for supplying and removing the assembled parts. The experiments were carried out with a number of nozzles. The parts were provided in palettes.

Fig. 4: Experimental setup

The piezo-actuators can be operated with oscillation frequencies up to 300 Hz. It is possible to perform tests with different modes and amplitudes of oscillation in x- and y direction.

Fig. 5 depicts the assembly device during an experiment. At the time of the picture, the body of the injection system has already been placed in the work piece holder. The cap with the hole for the needle is shown in an inclined position. The cap will be pneumatically swiveled on the work piece holder. In fig. 5 the robot has already picked up the needle, which is visible in the gripper. The robot will insert the needle in the hole of the cap. After releasing, the needle and the body will be assembled supported by oscillations of the work piece holder and the vacuum force.

IV. Measurements and Results

In this method the two-dimensional oscillation of the work piece holder reduces the friction force as well as clamping force, so that the inner assembly part slides into the outer one only by its weight. For this purpose two synchronized waveform generators, adjusted with two 90° dephased sinus function, and two power amplifiers activated the piezo-electric actors, monitored by oscilloscopes.

The presented assembly robotics was tested with hole-type nozzles which are used in direct-injection diesel engines. The nozzle consists of nozzle body (outer part) and needle (inner part). There are high requirements on nozzles for shape accuracy, surface roughness and clearance tolerance. Nozzles are manufactured in sophisticated processes using the latest production technology to achieve a tolerance of nozzle needle and nozzle body of ± 0,5 μm with a clearance tolerance of 2 – 3 μm and are paired together in a costly selection procedure. In current assembly processes without classing, the precision parts could be damaged. Therefore the nozzles are suitable to try out the new method.

Fig. 5: Assembly device

In practice, the deviation of roundness of nozzles is minimal but it has a significant influence in case of small clearing tolerances. To determine the impact of deviation on the assembly, the nozzles have been measured. In order to illustrate and analyse the relation between shape deviation of nozzle body and nozzle needle during assembling, figure 6 shows the roundness measurement by a coordinate measuring machine. The measurements are scaled up in radial direction with a factor of 100. The minimum zone circle method from Tchebyscheff is applied to show the deviation of roundness according to ISO 1101. In the worst case the point of minimal bore diameter of the nozzle body can superpose with a maximal diameter of the nozzle needle and therefore the friction and cant effects would be increased. For monitoring, the needle has been marked with a cross on face.

In small-sized assembly parts, e.g. injection nozzles, the *weight/friction ratio* of the inner part is small so it could be a hindrance if the nozzle needle and nozzle body superpose in an unfavourable position together as described. To avoid this phenomenon the frequency of oscillation has been varied automatically between a lower and upper limit so the needle turns around its own axis (this behaviour is shown in fig. 9). This effect can be used for rotation-symmetric parts to achieve the best position for assembling and process improvements.

As a necessary feature of this method, the work piece holder is disconnected to the assembly parts before the oscillation starts. Thus, the relative motion is enabled.

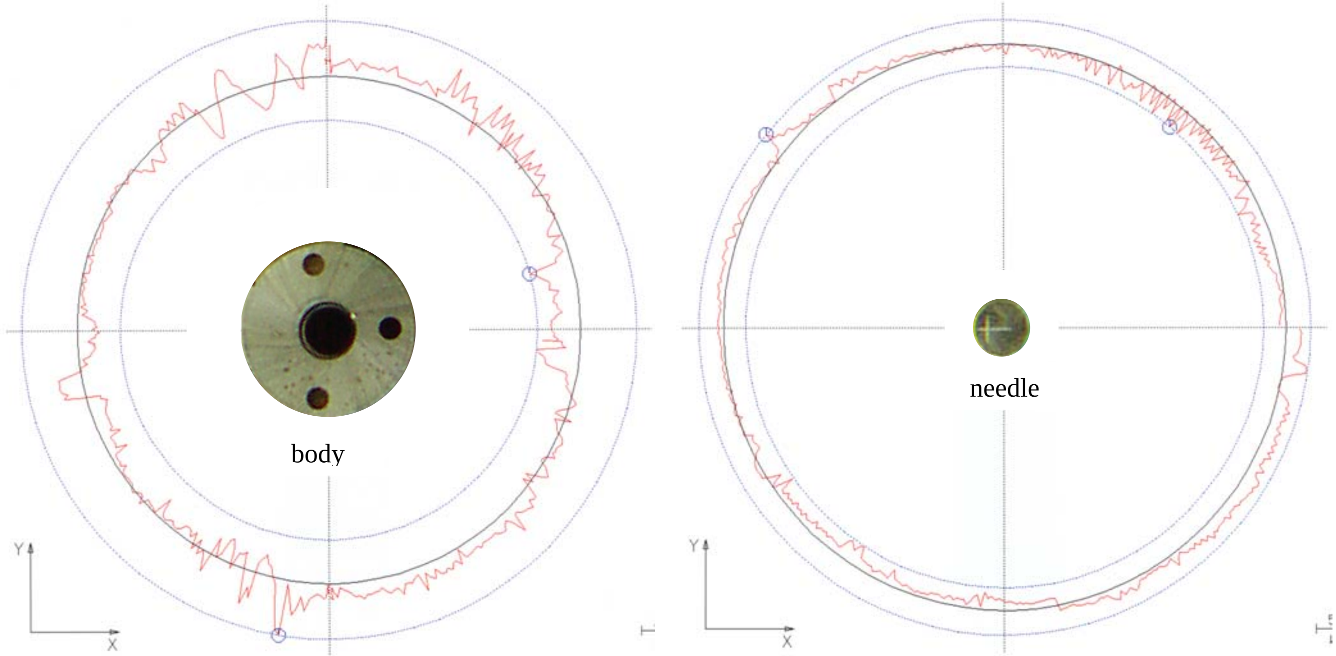

Fig 6: Hole type nozzle - deviation of roundness

In this method the inner part slides into the outer part caused in the manner described. If the assembly parts are constructed in an appropriate manner, the process can be supported by vacuum. For this purpose the work piece holder is equipped with a *vacuum* connection and *suction pressure* p_u of 300 mbar (see fig. 7). The resulting suction power improves the process especially in such cases where air cushion disables the assembling.

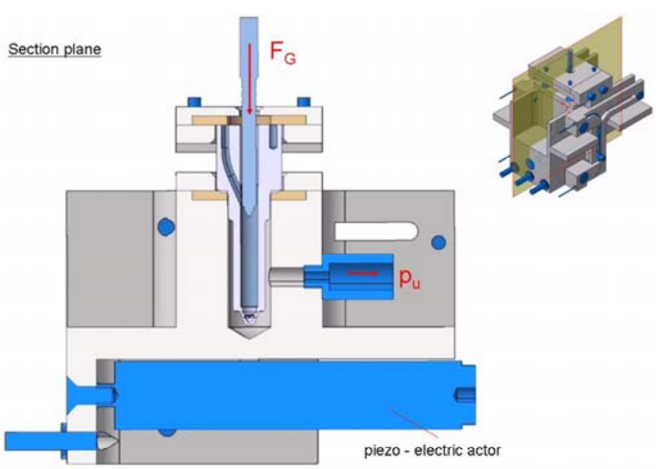

Fig 7: Section plane of the work piece holder with vacuum connection

In order to verify the new method for the assembly process of high-precision parts, the ultra high-speed camera HyperVision (Shimadzu) has been applied in order to analyse and "see" each step in slow motion. This camera has been developed within an international cooperation [3], including the authors, thereby resulting in a digital camera with up to 1 Million frames per second. The camera has to be triggered by an external signal, as for example a TTL-signal or an optical light barrier and captures the corresponding image sequence.

The camera allows the analysis of all steps described above. As for examples figure 8 shows images from a sequence of step 4, where arbitrary oscillations in the xy-plane are generated. The time difference between the images of fig. 8 is 10 milliseconds. In step 5 of the method, a vacuum is generated underneath the body in order to support the transfer of the needle into the body. Two images of a corresponding video sequence are shown in figure 9, the time difference is 20 milliseconds.

The video sequences demonstrate the expected behaviour through all process steps. Moreover, high-speed imaging has been shown to be a strong technology for future analysis of this method. With the selection of even higher frame rates up to 1 Million images per second, friction and cant effects within an extreme short time window down to 1 μs can be analysed. Moreover, comparison of video sequencies and simulations results supports the development of realistic modelling. Finally, if new combinations of bodies and needles are implemented, the quality of the method and possible problems can be analysed prior to production.

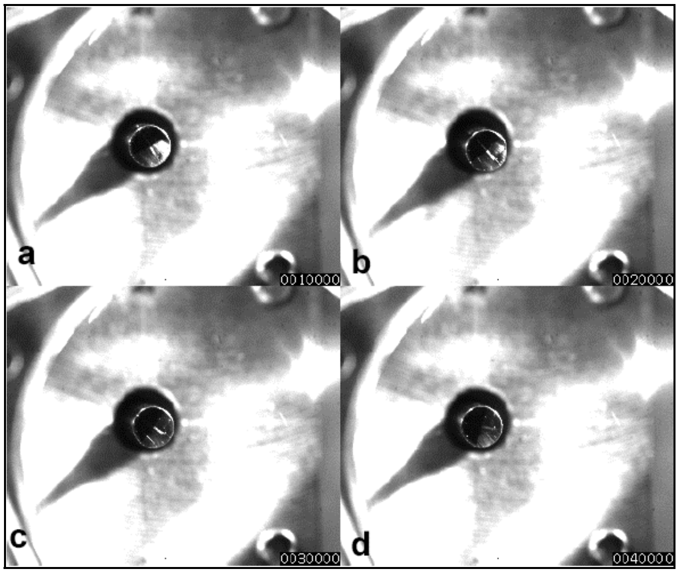

Fig. 8: Images of a video sequence for step (arbitrary oscillations).

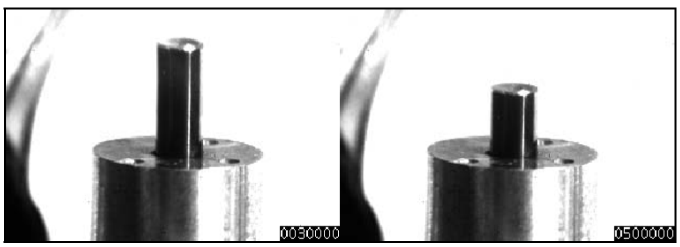

Fig. 9: Images of a video sequence for step 5 (before the application of a vacuum)

. The principal functionality of the assembly method has been proven in the tests. In a further step of development, the time span for the assembly per pair could be reduced drastically by joining multiple pairs in one parallel step. Fig 10 illustrates a simulated scenario. A portal robot is used to supply and remove a matrix of parts. The work piece holder is constructed as an array. The oscillation and the vacuum force are applied to the entire array in a similar way as it was done for one work piece in the tests described above. This requires only a singular vacuum source and one pair of piezo-actuators mounted underneath the array. The proposed method would lead to an enormous improvement of the efficiency.

However, it poses new questions e.g. concerning local minima of the oscillation modes of the planar array of the work piece holder. It has to be made sure, that each particular pair that shall be assembled, is stimulated in an adequate way. This is subject of on-going research work.

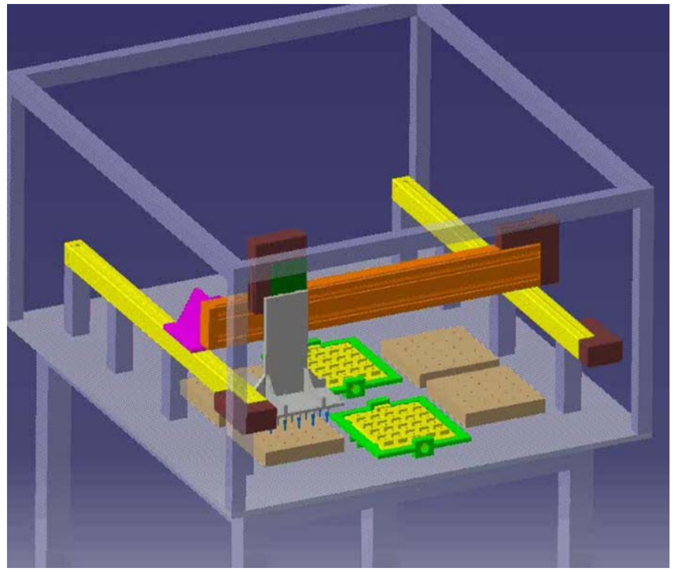

Fig. 10: Parallel assembly of multiple parts

V. Conclusions

A new method for the automated assembly of high-precision parts has been developed. It does not require advanced control strategies or sensor information about positions and forces. Tests have shown that an inner part, in that case a nozzle needle, slides into an outer part (nozzle body) by oscillation of the work piece holder. Cant effects and friction are overcome. If there are rotation-symmetric parts to be assembled, the inner part e.g. nozzle needle turns around its vertical axis to achieve a suitable position. Moreover, a sweep frequency stimulation has proven to support these effects. As another main feature of the method, a vacuum force is drawing the inner part into the outer part. Vacuum is very important especially for assembling small-sized parts with little weight of the inner parts. The method has been analysed and verified with an ultra high-speed video camera, where the slow-motion analysis of the different process steps opens opportunities for further analysis and modelling of the assembly of high-precision parts. In a next step of development, multiple parts shall be assembled in a parallel procedure. This would lead to a huge improvement of the performance of the method.

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