Nanorobotics for Micro Production Technology

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ABSTRACT

“The step from micro-technology to nano-technology requires more than a reduction of size by a factor of a thousand. If you want to move precisely in the nano-world, you don’t succeed by perfecting proven techniques.” Handelsblatt. This quotation shows a new approach to Nanotechnology that is somehow unusual. Exactly this new approach is realised in a new system of Nanorobotics. It allows the development of a production system that is by orders more precise than classical production lines. Moreover, it includes the adhesive bonding technology which oftentimes is the preferred joining technology on this scale. The described system is the result of an industrial demand to solve the actual problems of micro production technology.

Keywords: Nanorobotics, Microassembly, Microgripper, Micro Production Technology, Adhesive Bonding

1. DEMANDS FOR MICRO PRODUCTION TECHNOLOGY

In the last years the demand for ultra-precise production facilities increased rapidly. The revolution in MEMS technology and in communication technology lead to a variety of small objects that have to be assembled and bonded with nano-precision. On the way to new handing and assembly systems a set of tasks has to be fulfilled[1]:

Task 1: Reproducibility of positioners: better than 1 µm
Task 2: Adjustment of the microparts orientation: better than 20 nm
Task 3: Many degrees of freedom in smallest volume
Task 4: Compatible system of modules
Task 5: Handing over from coarse approach to microassembly
Task 6: Protection of sensitive microparts and grippers (force limitations)
Task 7: Transport “without” gravity
Task 8: Integrated sensors
Task 9: Quality control with suitable resolution
Task 10: Micro adhesive bonding technology.

Approaches to solve these tasks will be presented in the succeeding chapters.

As an actuator for microtechnology the Nanomotor® developed by Klocke Nanotechnik is a central element that allows to solve most of the items listed. It is a linear motor with a positioning stroke of up to some centimeters at atomic resolution. This is a bridge over eight orders of magnitude. The small version of the Nanomotor is half the size of a matchstick (see Fig. 1) and can lift six times its own mass or make indents even into a diamond.

The Nanomotor can be combined to many kinds of positioners: From scanning tunneling microscopes with atomic resolution on a normal table over positioning tables and manipulators up to microassembly stages with different kind of grippers and glue dispensers. It is the driving element for the Nanorobotics series presented below.

Fig. 1: The Nanomotor.

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1.1 REPRODUCIBILITY

The assembly line for mobile phone production has a typical movement reproducibility of 20 µm. Special assembly lines are offered with a guaranteed resolution of 10 µm. These systems can be tuned to a reproducibility of about 5 µm by using granite plates at constant temperatures. For glass fiber assembly the demand in reproducibility is 3 µm at the moment, a value that may be achievable. Next generations will need 1 µm and a future-proof system should allow a reproducibility below 1 µm. But thermal expansions in the classical design of meter sized robots and actuators will already avoid a precise positioning.

The reproducibility of positioners enclosing Nanomotors is better than 50 nm. The resolution is even much better: atomic without damping systems, see Fig. 2. The picture was taken at a fair with a Scanning Tunneling Microscope (STM) without any vibration damping system. Using a Nanomotor as central element reduces the size and makes the STM insensitive to vibrations.

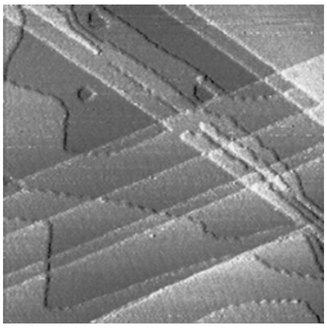


Fig. 2: Atomic structures of a gold surface

1.2 ORIENTATION OF MICROPARTS

A good reproducibility is only the first step. At the moment when the micropart shall be fixed it is often necessary to adjust its orientation with a resolution far below 1 µm. Sometimes optical fibers have to be aligned with a precision better 10 nm. Sharpen a hair... or bring a tip onto the end of a glass fiber and focus it! This microassembly example of a detection element in Scanning Nearfield Optical Microscopes (SNOM) needs a resolution of better 20 nm^2. A pyramid-shaped microtip is glued onto the end of a glass fiber. A 150 nm small hole in that tip forms a lens as sub-λ light source. The adhesive bonding process requires a very high precision. During the adjustment and the following curing of the adhesive, laser light is coupled through the glass fiber. The light emission of the microtip is measured to control the orientation of the microtip and glass fiber continuously. A misalignment of only 30 nm is clearly visible. The glass fiber with such a pinhole at its end then is assembled beside a shear force sensor. This device is used as central detection element in SNOMs. Fig. 3 shows a SEM picture of the assembled parts:

a) Cantilever with microtip
b) Glass fiber
c) Shear force sensor

The amount of adhesive applied between the parts a, b and c is critical: too much adhesive and the shear force sensor is damped. Too little adhesive allows for the cantilever of the microtip to oscillate freely. In both cases the device would be destroyed. The adhesive is applied with one of the Nanorobotics manipulators, see chapter 1.4, Fig. 6.

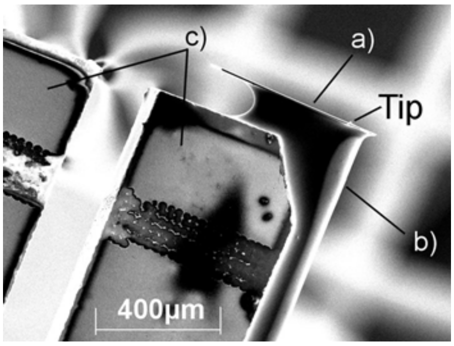


Fig. 3: Assembled SNOM tip

1.3 MANY DEGREES OF FREEDOM IN SMALLEST VOLUME

When the size of a positioning system is doubled, a factor of 16 more acoustic noise will couple into it. A small size is essential to achieve a good resolution without expensive damping systems. For many assembly and handling tasks it is necessary, that a set of different sensors and actuators can move to one point. This point is defined e.g. by the focus of three or more video microscope cameras. The smaller the actuators are the more of them can operate in this area.

1.4 COMPATIBLE SYSTEM OF MODULES

For assembly lines, the easy exchange of compatible positioners is necessary to reduce down time. Flexibility is also necessary, when new MEMS products are developed. During development, the assembly stage can vary often in strokes and degrees of freedom. Positioners, micrograppers, adhesive dispensers, or e.g. nano-indenters should be screwed onto each other within some minutes, all controlled with the same network compatible electronics and software. In the last years Klocke Nanotechnik and partners developed a new Nanorobotics system[3]. Loads of up to two kilogram can be moved over strokes up to 70 mm at resolutions down to 2 nm. This system allows microassembly, interconnection technology, analysis and reliability testing with plenty degrees of freedom in smallest volume without backlash. All Nanorobotics modules can easily be fixed onto each other. Equipped with high resolution position sensors they allow automation with a repeatability far below 50 nm. The following pictures show examples of the Nanorobotics modules:

Fig. 4: Linear stage with 10 mm stroke at 2 nm resolution, burdened with 2 kg.

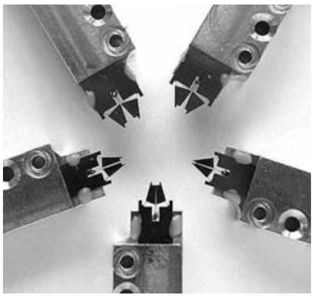


Fig. 5: A set of microgrippers with different tips. Resolution of movement: atomic.

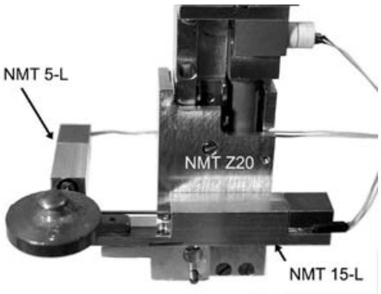


Fig. 6: A small manipulator with 5 x 15 x 20 mm^3 stroke.

The combination of a manipulator like shown in Fig 6 and a microgripper (Fig. 5) is already a small microassembly stage.

The primary objective during the development of these Nanorobotics modules was a resolution in movement of a few single Nanometers. This is made possible in principle by the Nanomotor: Compared with other high stroke piezo drives the Nanomotor has a real fine positioning stroke of more than a micron. Within this stroke the Nanomotor behaves exactly like a piezo, without backlash. The combination of the Nanomotor with mechanical guiding elements like ball bearing tables or gears should also eliminate the play of the mechanical guiding element and lead to a superior movement resolution, free of any backlash. But it didn't. The movement of a first prototype showed a kind of backlash with 50 nm amplitude in an Electron Microscope. This value is much smaller than mechanical play and too big for a piezo drive. The analysis of the whole mechanical chain in this linear stage with a high resolution Electron Microscope led to the source of this backlash. The movement of this small motorized stage caused a compression of materials used in this setup. Even the elastic constants of materials reduce the performance of this device. After this result the linear stage was developed in a new design with other materials and geometries. The backlash caused by compression could be reduced from 50 nm down to an amplitude of only 2 nm. This is the distance of 10 atoms! Furthermore, compared with other piezo drives the Nanomotor does not press in this design against the mechanical guiding elements from the side and so avoids additional off-axis movements. The design was defined for linear stages as well as for rotary devices or grippers. Only with this precision the Task 1 and Task 2 (see chapter 1.1 and 1.2) could be fulfilled in one system. These Nanorobotics modules are the key elements for the precision of the Micro Production System described in chapter 2. Also for manipulation tasks in Electron Microscopes the achieved resolution is essential.

1.5 HANDING OVER FROM COARSE APPROACH TO MICROASSEMBLY

A glass fiber is a typical object that has to be assembled with (sub-) micron resolution, but comes from a cable drum, perhaps in a machine hall. The robot supplying the glass fiber stops its movement not exactly in the zero position of the microgripper. Pattern recognition systems may help, but they are expensive. The Nanomotor driven microgrippers can solve the problem of handing over from coarse to good accuracy. The gripper structure can grip a fiber even when it is out of the grippers center: Both tips close until one is stopped by the fiber. The second tip continues its movement until the gripper is closed. Then the fiber is released (e.g. by the robot) and the gripper structure moves into its own center position.

1.6 PROTECTION OF MICROPARTS AND GRIPPERS

The combination of microassembly stages and microgrippers with classical CNC technology includes miscellaneous risks that may be new for both sides. It is possible to fix a microgripper onto a CNC robot. But what happens, if this robot drives the microgripper a few mm too deep into the table? It happens in practice, for example during setting-up the operation. The microassembly stages made with the Nanorobotics modules are inherently protected against a crash. Each axis posesses a force limitation and the microgripper is designed compatible to this force limit. The gripper can be driven down onto a base plate without damaging its small tips or its bending elements. Horizontal movements slightly hitting the gripper structure against a small wall also do not harm the gripper. The protection of microparts is important as well. A task that required superior sensitivity and manipulation skills was solved at KOSMA[4]. The assembly of substrate bars for RF devices with a profile of 35 µm x 80 µm could only be done with Nanometer resolution, because coarser tools would have damaged or flipped away the components. The sensitivity of the substrate bars for electrostatic discharge is much higher than the sensitivity of semiconductor devices. The small size of the assembly stage allowed an easy grounding and a secure handling. This assembly stage is now used by RF groups from all over the world to produce high frequency devices (800 GHz or higher).

1.7 TRANSPORT “WITHOUT” GRAVITY

When the size of microparts is smaller than the edge sharpness of a microgripper, other methods of transport should be used. Then, the influence of gravity onto the objects to be handled can be smaller than other forces which in turn can be expolited for the transport. The developments of such processes and tools were made in an electron microscope[5]. The enhancement of the electron microscope from the pure device for analytics to a material processing system was enabled with the Nanomanipulator, see Fig. 7. Small as a film cartridge even several manipulators fit into the vacuum chamber. The manipulator can be moved half a cubic centimeter with a resolution of one Nanometer. It can contain various micro tools for cutting, scraping, gripping, spark erosion or for laser ablation. The combination of Nanomanipulator and SEM leads to a powerful tool as a workbench. It allows manipulation and even assembly with Nanometer resolution in combination with all kinds of analytical methods (EDX, WDX, EBSP).

Fig. 7: The Nanomanipulator

The sequence of Fig. 8 is an example of handling 1 µm small objects in a SEM. The left manipulator lifts up a cluster of these balls with the first force. The second manipulator captures this cluster with a second higher force. In this case the first force was adhesion, the second magnetism[6].

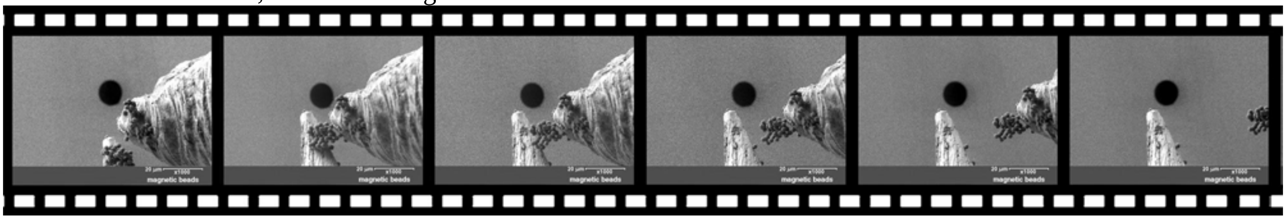
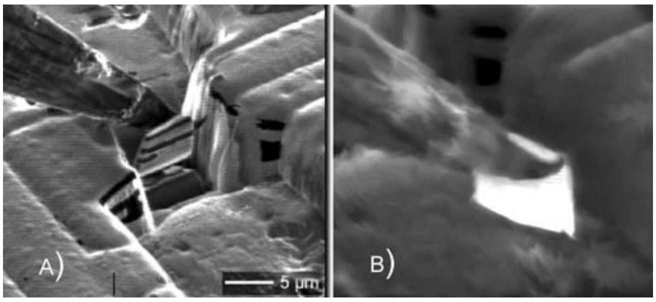


Fig. 8: Nanomanipulation of magnetic beads

In the handling process of Fig. 9 another force is used[7]. Electronical drop outs in integrated circuits that result from structural defects can be inspected by high-resolution transmission electron microscopy measurements. This requires to cut a very small lamella out of the drop-out-area.



Using Nanomanipulators renders the complicated preparation techniques much easier. First the Nanomanipulator breaks a sample out of a chip structure and then a voltage is applied only to the tip of the Nanomanipulator. This additional charge allows to grip the sample and raise it.

Fig. 9: Breaking a lamella (A) and lifting it by charge (B).

1.8 INTEGRATED SENSORS

Additional sensors can help during assembly. Besides vision control systems force sensors are important. Imagine a tool with 2 nanometer resolution that is controlled by a joystick and answers with the corresponding force feedback. Then, manipulating small objects manually becomes very intuitive, because the operator uses his own senses for controlling the stage. The forces applied to the tool tip can be so high, that even imprints in diamond surfaces can be produced. The force sensor between manipulator and sample allows to apply or measure calibrated forces in mN range by moving the actuator within some 100 nm. Values like friction forces, adhesive stiffness, breakage limits or elastic constants of microparts can be determined in high resolution (Fig. 10).

The force sensor can also be assembled between a z-axis and a microgripper.
Calibrated snap-in forces can then be applied, e.g. to press glass fibers into spring structures.

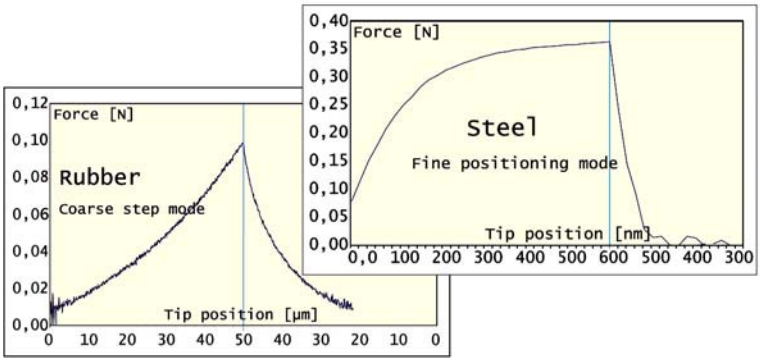


Fig. 10: Force-stroke diagram of a) rubber and b) steel.

1.9 SUITABLE QUALITY CONTROL

In classical precision mechanics the device size is about 1 m and the precision is up to 1 µm - a ratio of 6 orders of magnitude. A micropart produced with 0.05 mm size leads to 50 Picometers as comparable precision, one tenth of the radius of a gold atom. Instruments to measure the precision of microparts and the alignment of them should have Nanometer resolution. Such ultra precise quality control systems like the MicroProf® from FRT[8] are integrated in the Micro Production System described in chapter 2.

Some quality control instruments have to face an additional problem: an imprint to measure the hardness of a sample must be much smaller than the micropart that shall be analyzed. But when such a small imprint is made and the micropart is transferred to the analysis instrument that shall measure the depth of that imprint - where is it? If microassembly and quality control can be made in one absolute positioning system many problems are solved at once, see Fig. 11.

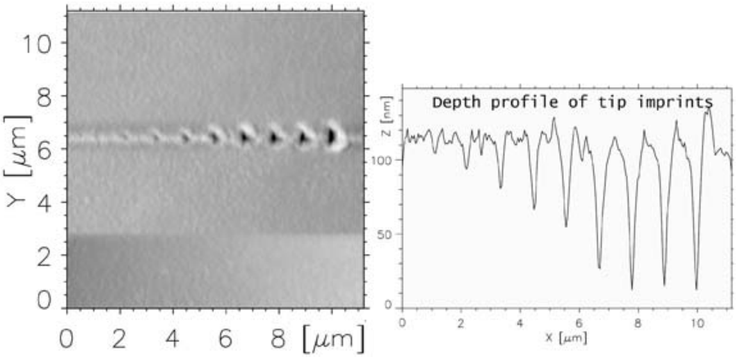


Fig. 11: Tip imprints made in ruby with a Nanomotor that is the central sensor in an AFM at the same time. Imprint the left image and the depth profile diagram on the right are made with the same device at the same position.

1.10 ADHESIVE BONDING TECHNOLOGY ON THE MICRO-SCALE

In many instances, adhesive bonding is the only bonding technology feasible in the micro world. This is due to the small size of the parts to be joined and to the great variety of very specialized materials. Each of these materials has its specific requirements for the bonding technology which oftentimes can only be simultaneously fulfilled by the adhesive bonding technology. Fortunately, adhesive bonding can offer a couple of advantages:

- Joining of many, dissimilar materials
- Multi-functionality of the joint (e.g. mechanical fastening plus conductivity)
- Low heat/ cold joining
- Small mechanical stress
- Even stress distribution
- Galvanic isolation of the parts (no contact corrosion)
- New freedom for design
- Innovative technical solutions

The development of an adhesive bonding process consists of several steps:

- Specification of the end-product and deducted specification of the adhesive joint, e.g. mechanical, thermal, electrical stress, media, precision, optical properties, service life
- Selection of the parts to be joined (material, surface): The chemical nature and topography of the surface effect the choice of adhesives and the necessity of a surface pre-treatment prior to bonding. The temperature resistance and the transmission characteristics impact the possibilities for thermal or radiation curing.
- Geometrical construction/ design: There are general guidelines for optimal design of adhesive joints. However, they must be harmonized with other requirements, e.g. stemming from the production process or regarding the functionality of the system
- Requirements of the production: The host of the respective aspects to be considered include degree of automation, prevalent equipment for mixing, dosing, curing adhesives, on-line inspection/ monitoring, precision, environment, subsequent production steps
- Selection of adhesive: Characteristics to be considered are state of the adhesive as delivered (paste, foil, no mix, 2 component ...), shelf life, pot life, reactive/hotmelt/combination, curing mechanism(s), rheology (=> mixing, dosing, application technology, wetting), requirements for the environment (e.g. humidity), adhesion (surface pre-treatment/ primer necessary?), properties after curing (mechanical, optical, chemical...), repair/recycling.
- Micro assembly: A discussion of the aspects of micro assembly can be found throughout the other parts of the paper. The micro assembly device has to cater for the requirements of the adhesive bonding process such as a defined gap of the adhesive bondline, or a defined force for placing the component to be bonded.
- Cure: There are different curing mechanisms available, which can be tailored to the task. A two stage curing allows for a fast first cure – e.g. for fixing a precision alignment – followed by a second, slow, final curing step.
- Quality Control: The Quality Control can encompass the control of the adhesive as delivered (e.g. chemical reactivity or chemical groups present), the on-line inspection of crucial steps (e.g. application of the adhesive or precision of the assembly before cure), or the quality of the final joint (mechanical strength, electrical resistance ..).

Properties of adhesives in small dimensions:

The particularity of adhesives in small dimensions is their large surface and their small volume. Before curing, this means that there is a great interaction between the adhesive and the surrounding atmosphere. This can render the adhesive sensitive to the atmosphere’s composition (e.g. humidity or oxygen) and it can change the adhesives constitution. Thus, the adhesives curing behaviour or its properties after curing can be altered compared to bulk adhesives. As a consequence, adhesives which may be suitable for a similar task, however, on a macroscopic scale can be utterly unsuitable on the microscopic scale. Therefore, the development of an adhesive process has by all means to take the geometric size of the adhesive into account and according investigations have to be undertaken.

The well known finite element calculation tools can be applied to calculate the bond properties. However, the material laws and data must be true for the small dimensions (see next paragraph).

Adhesive bonding quite often is the only feasible joining technology on the micro scale, especially when dissimilar materials are to be bonded. At the same time, adhesive bonding can offer substantial technical advantages and allow for novel designs. Many aspects of the Micro Production System were developed with respect to adhesive bonding procedures. A team of experts in this new technology offers the development of micro-manufacturing steps as a service in combination with this Micro Production System. It includes Nanorobotics modules, microassembly, micro adhesive bonding, and quality control in one absolute positioning system, as described in the following chapters.

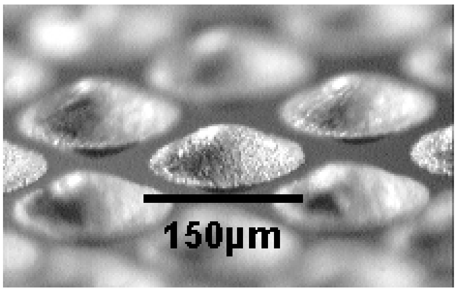


Fig. 12: Dispensed micro-dots of an electrically conductive adhesive[9].

2. MICRO PRODUCTION SYSTEM

The Micro Production System developed by Klocke Nanotechnik and partners bridges the gap between nanotechnology and the classical mechanical engineering[10]. It combines the advantages of both technologies: the backlash free movement with Nanometer resolution and the capability of up to kilograms of load at huge strokes. The included Nanorobotics modules offer plenty degrees of movement and a repeatability of better 50 nm, a value far away from the Micrometer values of classical production systems (see chapter 1.4.).

The Micro Production System is available in a lot of different levels of complexity. It was the main goal during the development of this system to allow for flexibility:

- Modular design, to be able to add, combine, or exchange components such as force sensors, wafer prober, manipulators, vacuum- and microgrippers or Scanning Probe Microscopes in order to produce different products.
- Ability to scale-up the production beginning from first manually assembled samples up to fully automated mass production.
- Process control with an easy to use software.

An example shall detail the second option. The first step to a product is a prototype that has to be assembled, e.g. with a 4 axis microassembly stage (X, Y, Z-stages plus microgripper) and a joystick. Then about 10-100 prototypes are necessary and some assembly steps should run automatically, e.g. by integrated position sensors and a small software packet. An adhesive dispenser may be added, perhaps also an electrical prober or a Nanofinger.

In the next step a first production series of 1000-5000 pieces needs more assistance and closed loop operation. Some video cameras and a vision system help to identify microparts, a base stage and rotary drives arrange these microparts for the gripper and a sequencer software allows to program complete assembly processes just by “drag and drop”.

When prototypes turn into products quality control gets more important and the system can be expanded for example with Scanning Probe Microscopes, nano-indenters, surface inspection systems or wafer probers.

The compatible modules of the Nanorobotics series allows this scale-up from a single microgripper over small microassembly stages up to a Micro Production Systems with plenty of different configurations – always with nano-resolution. In the same way the Ethernet-based electronics and modular software can grow with the system. This concept is the result of our experience in our Microtechnology network and with a lot of companies who have to overcome the scale-up problem.

2.1. COMPONENTS OF THE MICRO PRODUCTION SYSTEM

The Micro Production System includes different groups of positioners, actuators and sensors that are summarized in Fig. 12:

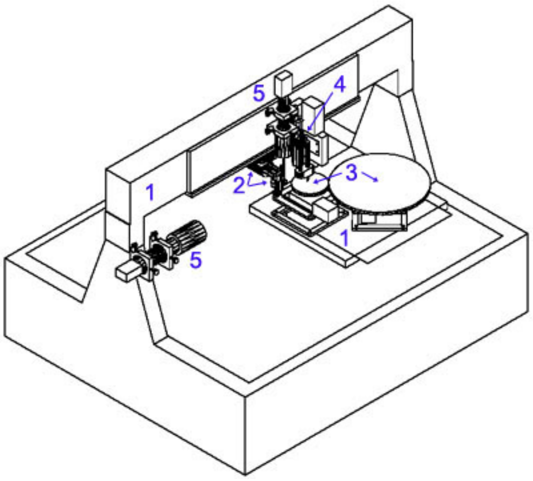


Fig. 12: Scheme of the Micro Production System:

1: High precision xy-stage with 100x100 mm^2 or 350x350 mm^2 stroke from LPKF[11], resolution better 200 nm.

2: Nanorobotics modules, Microgripper, Nanofinger, Waferprober...

3: Two rotation stages to change the orientation of the source and target area.

4: Adhesive dispenser, Nanomanipulators, Scanning Probe Microscopes or e.g. a MicroProf® from FRT[8].

5: Video cameras and vision software for pattern recognition with a resolution of up to 400 nm used for orientation detection and quality control. Up to 6 cameras can be included.

6: Process control with graphical user interface.

2.2. DIFFERENT HARDWARE ARRANGEMENTS:

Starting from a microassembly stage made with Nanorobotics modules like shown in Fig. 13 the system can be expanded e.g. by an additional manipulator with an adhesive dispenser or some more modules to move additional devices like a vacuum gripper or a wafer prober.

When a bigger high precision xy-stage is necessary there are two systems defined by the size of this stage: an xy-stage with 100x100 mm^2 stroke (Fig. 14) or a big version with 350x350 mm^2 stroke (Fig. 15). Both stages have a resolution better 200 nm.

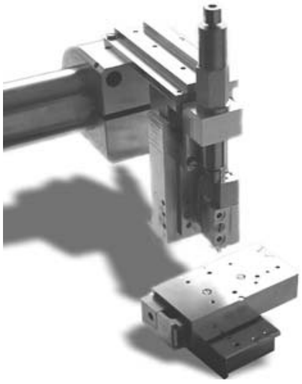


Fig. 13: Microassembly stage made with Nanorobotics modules, 20 mm stroke each.

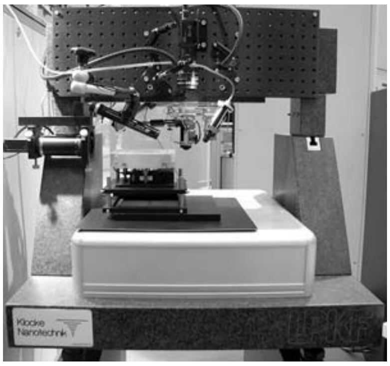


Fig. 14: Micro Production System with small xy-stage (100x100 mm^2 stroke)

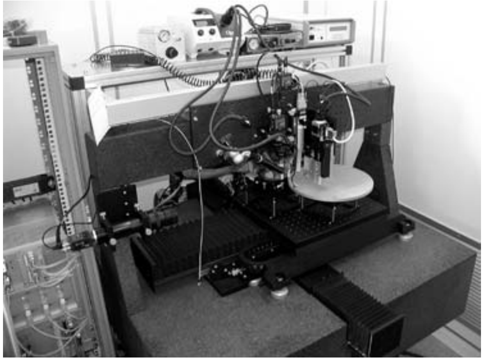


Fig. 15: Micro Production System with a bigger xy-stage (350x350 mm^2 stroke)

The different stroke of the two xy-stages is coupled with a different size of the whole system. In the small system (Fig. 14) only one rotary drive fits onto the xy-stage. Source and target area have to fit onto this rotary drive. The bridge over the bottom area is big enough to include a set of Nanorobotics modules that can operate with 5 independent tools. Three video microscope cameras can be fixed at the frame structure. In comparison with this setup the bigger xy-stage offers much more space for equipment (Fig. 15). Two rotary drives can be moved with the bottom xy-stage, one for the source area, the other for the target area. Besides the Nanorobotics modules of the smaller setup many additional components like adhesive dispenser, surface inspection systems or wafer prober can be included. One video camera is fixed on the moving part of the xy-stage for a programmable inspection position. This big system can include up to 6 video cameras.

2.3. OPERATION MODES AND VISION SYSTEM

The scale-up process is not only made possible by a modular hardware concept. The way from manipulation by hand up to automatic production with vision control is also possible.

The manual mode allows to control all axes of the system with up to 2 (force feedback-) joysticks. Each joystick can move 4 different axes without changing the configuration.

The second level of process control allows to generate sequences over menus and teaching with the manual control program, a programming language is not necessary.

In theory microparts are delivered well oriented in carrier structures. But the reality delivers more something like micro chicken food. A flexible assembly system should also be able to handle these objects. Sorting mechanisms to orient these small parts in a flowing process are not always useful, because the microparts stick at these alignment structures by adhesion. Therefore the third level of process control allows to generate a closed loop process including vision control. Up to 6 video microscopes can grab pictures, and a pattern recognition software determines the position of not oriented microparts. Therefore a few millimeter picture size are necessary to keep an overview. At a field of view of 4x3 mm^2 the pattern recognition operates with a repeatability of 400 nm. The Server PC with the vision software includes a command parser that allows a remote control over Ethernet commands from the Client PC. The client PC can switch between different cameras and ask for the position of recognized objects. The transformation from the coordinate system of the video camera to the world coordinate system is included and invisible for the user.

Other functions of the system are e.g. the automated generation of a three-dimensional adhesive beads. For example, when conductive adhesive is dispensed this line can be used as electrical wire to support a micro-device with power or signals.

Furthermore, arrays of operations can be executed for parallel production. Automatic intensity adjustments are included, e.g. to couple a glass fiber into a device.

2.4. PROCESS CONTROL

The Micro Production System is controlled by a network of computers (Fig. 16). A „Client-PC“ is responsible for the global process as a master. A PC with a vision system as well as some embedded server PCs act as slaves and react only on commands from the master. The communication between these parallel operating devices is made by Ethernet.

This structure has two main advantages:
- Flexible and easily configurable by adding or removing Ethernet-devices.
- Fast and reliable by parallel operation on different levels.

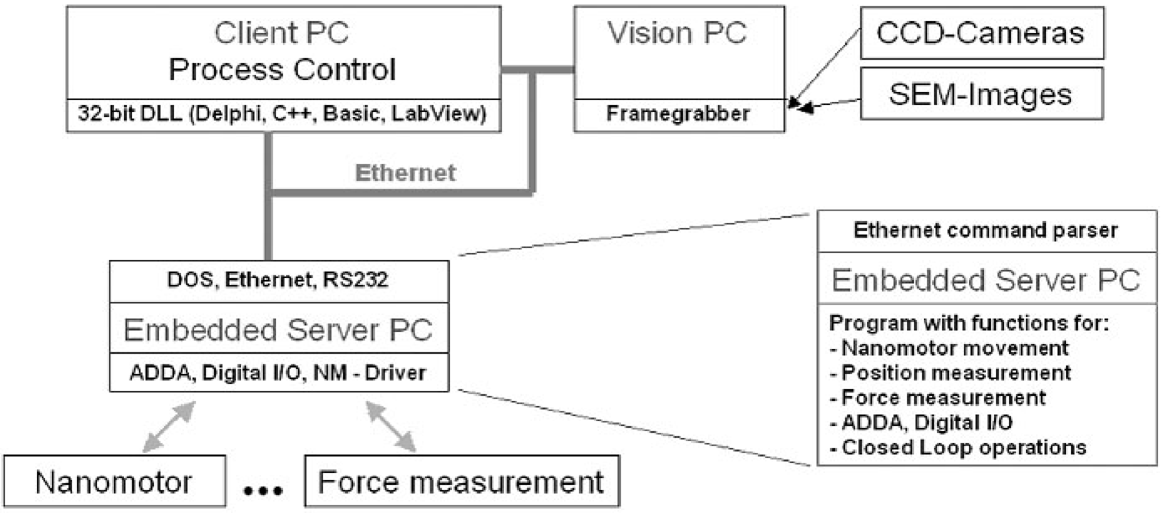


Fig. 16: Scheme of the Ethernet based process control.

3. SUMMARY

The attempt to solve a set of tasks for micro production technology led to the development of a complete Micro Production System including Nanorobotics, that is up to 100 times more precise than classical production systems. The modular setup allows a scale-up for the production and an easy exchange of equipment, like at a CNC machine. Predefined software modules like vision controlled movement, programming of arrays or e.g. 4 axis synchronous movements allow to control complex procedures easily.

The Micro Production System can be used to develop new high resolution production processes, also as a service – including the development of adhesive joints.

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