2014 IEEE International Conference on Robotics & Automation (ICRA)
Hong Kong Convention and Exhibition Center
May 31 - June 7, 2014. Hong Kong, China

Automated Robotic Assembly for a Micro-Cartridge System inside the Scanning Electron Microscope

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Abstract— **The AFM is a common tool for ultra-precise surface characterization and a standard instrument a variety of research and development disciplines. However, the characterization of three dimensional high-aspect ratio and sidewall structures remains a hardly accomplishable task. Novel exchangeable and customizable scanning probe tips -** ***NanoBits*****- can be attached to standard AFM cantilevers offering unprecedented freedom in adapting the shape and size of the tips. These NanoBits of few µm size have to be assembled into micro-cartridges. This challenging assembly task is performed inside the SEM by a micro-gripper. A powerful automation framework has been developed facilitating image based automation and visual servoing for this task. Template matching, BLOB-detection, and special SEM-based detection approaches are used to achieve the automated assembly.**

I. INTRODUCTION

Today's industry for micro- and nanotechnology produces devices which are expected to offer a particular performance. Hence, they are required to have well-defined, reproducible and traceable properties. This can be guaranteed only by precise controlling, metrology steps and especially measurements at the critical dimension - the threshold is where the measurement system reaches its resolution limit - and the systems are already pushed to that limit.

Atomic force microscope (AFM) has become a precious and widespread tool for surface characterization; it is the primary metrology instruments in the micro- and nanoscale and can be found in all kinds of research and development disciplines. Nevertheless, the capabilities of the AFM are still limited by the geometry of the AFM-tips. The standard task is the analysis of horizontal surfaces with low aspect-ratios. Many research projects tackle this issue: some works have shown that refinement or decoration of AFM-tips can improve the imaging quality especially of the aspect-ratio by orders of magnitudes. In addition to the problem of the tip geometry, many researchers already have developed approaches to control AFM scans with different scanning orientations than just a flat surface [1], [2], [3], [4], [5].

This contribution is about the realization of novel, exchangeable, and customizable AFM-tips. These tips, so-called NanoBits, can be mounted at the end of special flat-tip cantilevers, whose remaining design is equal to standard cantilevers. Thus, the integration of NanoBits is possible in every conventional commercial AFM system. NanoBits are customizable and provide a more detailed characterization of complex structures than has been achieved to date [6]. The fundamental idea of the project is an automated in-situ exchange of NanoBits in the AFM, since this guarantees seamless integration into conventional AFM systems and processes. For this reason, NanoBits have to be perpendicular freestanding and accessible for the AFM cantilever, which is a remaining challenge for a direct microfabrication process. Although there are attempts to achieve this [7], the most suitable approach at the moment is a NanoBits carrying cartridge system. Such a cartridge, filled with NanoBits, can be fed into a standard AFM system, equipped with special cantilevers, which are capable of picking them up. Previous papers have presented the idea of the NanoBits project[8], [9], their fabrication [10], [11] and all components [12], [11] in detail.

This contribution focuses on the automation challenges, which arise on the micro- and nanoscale and under scanning electron microscope (SEM) conditions. A simple pick-and-place handling is not possible, and also visual servoing (VS) approaches have to be redeveloped and improved to solve these problems properly. Few attempts have been made for robotic automation under SEM conditions, but none for the automated assembly of building blocks [13], [14], [15].

II. AUTOMATION ENVIRONMENT

The final product of the assembly process is a cartridge filled with NanoBits. Nevertheless, the assembly process on its own requires many more components: a mircrogripper for the actual handling, positioning stages as robotic basis, as well as control hardware for all these components. Finally, the entire process is controlled by a software backend using several control and support strategies.

A. Automation Setup

All handling tasks are performed inside the SEM. The SEM at hand is the combined SEM and FIB microscope type "Lyra" from TESCAN. The electron beam is generated by a high resolution Schottky-emitter, while the ion beam origins from a conventional gallium liquid metal ion source. The vacuum chamber is equipped with a standard motorized sample stage carrying the actual robotic handling setup as shown in figure 1.

1) Robotic System: The robotic handling setup consists of two major components, a fine positioning for the gripper and a coarse positioning unit as sample exchanger:

*This work was supported by NANOBITS

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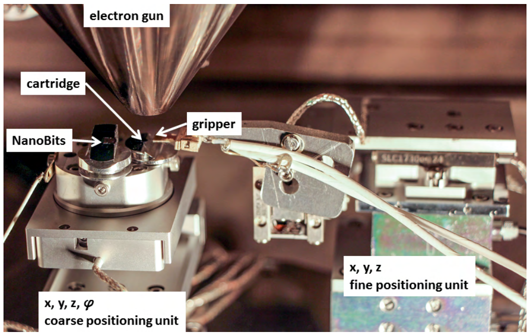

Fig. 1. Image of the robotic handling setup inside the SEM vacuum chamber. The x,y,z,ϕ-coarse positioning stage carries both samples: NanoBits fabrication substrate and the cartridge. The x,y,z-fine positioning stage carries the gripper.

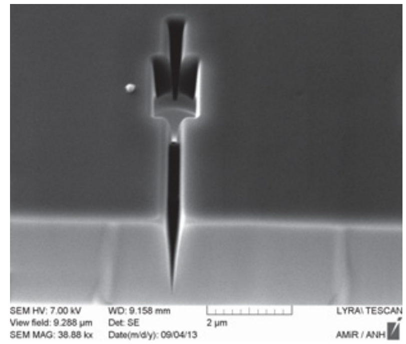

Fig. 2. Design of the receiving structure of the cartridge. The opening has a $1 \times 1.5\,\mu m^2$ opening, the receiving trench a width of 300 nm and the whole silicon structure has a thickness of 4 µm.

The *fine positioning unit* is a "Hera P-620" stage from Physikinstrumente (PI) with three linear orthogonal axes. The axes are equipped with internal capacitive sensors enabling a closed-loop positioning accuracy of about 1.6 nm. This systems allows high precision, smooth and vibration free movements. The working range is up to 100 by 100 by $50\,\mu m^3$. The system is close-loop controlled by an analog "E-509" controller, which is fed by the automation-PC via a NationalInstruments AD PCI-card. This system is used to perform the actual gripping and insertion tasks.

The *coarse positioning unit* is a SmarAct stage with three linear orthogonal axes and a 360° rotatory axis, driven by stick-slip piezo motors. All axes are equipped with optical encoders enabling a closed-loop positioning accuracy of several nanometers and microdegree, respectively. The full traveling range is 21 by 21 by $21\,mm^3$. The system is connected to an external control-unit, which is directly controlled by the automation-PC via USB. Due to the comparably large vibrations of this slip-stick driven systems, this system is used only to pre-align all components within some tens of µms.

By combining these two systems the advantages of both can be used while avoiding most drawbacks: On the one hand, fast sample exchange is realized, since stored positions can be approached automatically. On the other hand, fast, ultra precise and vibration free closed-loop positioning is feasible for the actual handling task.

In conclusion, the coarse positioning unit is used to exchange samples and bring them as close to the gripper (roughly 20 µm distance) as necessary. All these steps are performed without vision feedback and rely only on the internal sensor feedback.

2) Microsystem Components: The goal of the automated handling task is the filling of a micro-cartridge with NanoBits. Therefore, three micro-scale components are involved: the NanoBits, a transferring gripper, the receiving cartridge.

The *micro-scale gripper* is the crucial tool for the assembly. It is electrothermally actuated and just the two states (open/closed) are used. Intermediate states are hardly controllable and hence not used. Fabrication and properties are well approved and described in [16].

The *NanoBits* handled in this work are fabricated by electron beam lithography and come in batches of about 50 items. The have a size of about 10 by $4\,\mu m^2$ and a thickness of about 200-300 nm. The full production process is described in [11]. In the final handling setup, gripper and NanoBits are pre-tilted by 45° in order to determine the in-gripper rotation properly (cf. [9]).

The *cartridge* acts as the NanoBits' carrier storage system [11]. It has to fulfill the following demands: i) During the insertion, the tip of the NanoBit should not touch any surfaces, since it has to be protected from any damage. ii) After the insertion, the NanoBit has to rest in the cartridge stable enough for the gripper to be retracted. iii) The NanoBit should be well aligned with the entire cartridge structure. For this reason a prototypical design is developed, which meets these criteria. It is fabricated from conventional cantilevers by focused ion beam (FIB)-treatment. The final design is shown in figure 2.

B. Automation Framework

The automation of all handling sequences is based on a self-developed automation framework specialized on the automation of micro- and nanohandling tasks. This software, called OFFIS automation framework[1], enables rapid prototyping and significantly reduces design times.

The communication to all involved hardware components (SEM, robotic stages, and gripper) is realized by remote-controlled units providing a high-level access. These units run as plugins inside the software framework..

The most common image processing algorithms are implemented from OpenCV; some are self-developed. Complex image processing pipelines can be created as chains. The automation environment allows for interaction with the image processing from automation scripts.

Finally, the actual automation of tasks can be realized in the high-level script language Python. The scripting level can access all interfaces of the remote-controlled units and vision chains. Hence, a vision based control loop can be established.

[1] http://automation.offis.de/

III. AUTOMATION IMPLEMENTATION

The automation of the assembly process is realized using the SEM as only image source, in order to develop an technique, which is even implementable in cost-efficient Desktop-SEMs. In the system at hand, the additional FIB capability is used to verify the handling process afterwards, and to build some microsystem components.

The entire system is set up as a dual closed-loop system, engaging internal positioning sensors and visual servoing.

A. Implemented Algorithms

All automation sequences of this project are based on two fundamental algorithms and approaches: template matching and binary large object (BLOB)-detection. Coarse position steps (up to 50 µm, without intended contact of moved objects) are performed based on absolute image information. Regardless of the used detection technique, movements with higher accuracy are realized by determining the actual and target position from the same image and performing relative movements.

Template Matching: The template matching is implemented from the OpenCV library. It is used to realize three different tasks:

For the *gripping process*, a simple template of a NanoBit is used to detect all of them in an overview image of 50 µm edge length. In this step, the number and coarse positions of the NanoBits are determined.

For the *insertion process*, the coarse position of the receiving trench is determined in an overview image by a simple template.

For *both processes*, the position of the gripper is derived from the same overview image in the respective process.

BLOB detection: A BLOB detection algorithm is derived from the OpenCV-contour-detection and is used for two tasks:

1) The point of interest of the gripper is the so-called gripping-point: the point where the distance to both gripper jaws is the same and aligned with the tips of both jaws. The automated determination of the gripping-point guarantees a minimal uncertainty and high repeatability since it does not depend on an operators sight (cf. figure 4).

2) The alignment of gripper and NanoBit during the gripping process is realized using BLOB-detection. Template matching doesn't work for this task, since the edges are important for this positioning task. (cf. figure 4).

Line-scan technique: A detached NanoBit has to be inserted into a cavity of the cartridge. For this reason, the position of the NanoBit's tip in respect to the gripping point has to be determined exactly. For this, a line scanning approach is used: by scanning a particular region line by line and monitoring the grayscale distribution of each line, the position of the highest outlier can be determined easily.

B. Application and Usage of SEM Environment

Image aquisition under SEM conditions involves particular problems due to its working principle: An electron beam is used in order to interact with atoms of the sample. This interaction of fundamental particles results in a current through the sample from the grounding. Hence, even a conductive sample has a certain resistance depending on its material properties and its geometry. In general, this can cause local charging, which is not severe but effects the path of the electron beam. This appears as static SEM-image displacement[17].

These effects can be used as an information source for the automation:

1) The topology dependency of the contrast for the so-called secondary electron SEM can be used for *depth-from-shadow*-detection[18]. In fact, it allows the alignment of two objects with very high accuracy in z-direction.

2) The static image displacement can be exploited to establish a powerful touch detection. The amount of displacement depends on the charge of the sample, which effects a deflection of the electron beam. This charge depends on the equilibrium of the incoming electrons, the emitted electrons and the resistance for the grounding current. For NanoBits inside the gripper jaws, this resistance is comparably high, since both are suspended on small structures. If another object touches the NanoBits or the gripper jaws, this resistance changes tremendously, which causes a discharging and hence a change in the static displacement. This approach can be called *touch-detection-from-discharge*.

C. Handling Sequence

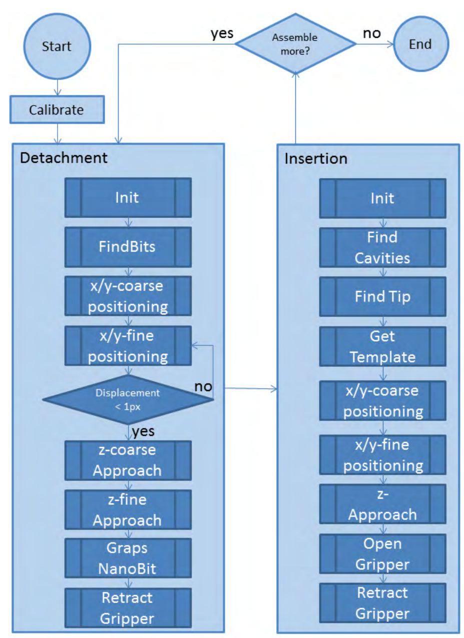

Fig. 3. Process chart of the automated assembly process.

All handling steps (manually or automatically) are performed using the same beam configuration of the SEM: 7 kV beam energy, probe current index 10, size of the overview image 50 µm, focal-plane and all other SEM parameters are constant. The only parameters which are changed are the positions of the robotic platforms, the scanspeed of the SEM and region of interests (ROIs) are set. The latter corresponds to image update rates between 0.5 Hz (initial overview images) and roughly 10 Hz for small ROIs.

Few manual steps are required as prerequisites in order to facilitate the automation:

1) A template of each object is needed: NanoBit, upper gripper jaw, the reservoir's cavity

2) two positions have to be stored for the coarse positioning system: i) a position where the NanoBits are visible (x,y alignment) and in same orientation with the gripper (ϕ-alignment); all at the left side of the overview image; the grippers uppermost position must be higher than the NanoBits. ii) a position where the reservoir is visible at the left side of the overview image; the grippers uppermost position must be higher than the reservoir.

3) The first automation sequence starts moving the gripper to a center position, here the operator has to center the stage of the SEM manually.

The complete cycle of the automation process is shown in a process chart in 3. In general, all positioning and alignment tasks apply to simple process rules:

1) Due to several image acquisition constraints for SEM-images, working using an absolute coordination system is not feasible for accuracy below a few µm: Drift, charging and beam deflection cause severe image distortions and limit the reliability of global information.

2) In order to perform positioning steps requiring an accuracy better than few a µm, the relative position information of two objects is derived. The relative displacement of these two positions can be transferred into a relative displacement in the global coordination system. This approach is used for all fine positioning steps with accuracy down to a few dozen nanometers.

3) The first step of positioning/alignment is in x/y-plane only. This is a straight-forward task, based on template matching or BLOB-detection.

4) The second step is always the positioning/alignment in z-direction. Since the derivation of this information from the image is not sufficient, the techniques *depth-from-shadow* and *touch-detection-from-discharge* are used.

Calibration: The calibration of the entire visualization and robotic system is needed as the first step. During the calibration process, either the NanoBits sample or the reservoir is close to the overview section in order to establish comparable conditions for the electron beam. This ensures that the calibration accounts for comparable image distortions.

Firstly, the gripper is moved to the center position. BLOB-detection is used to detect both gripper jaws. From these two objects the gripping point is extracted by calculation of the point between both objects in alignment with the left edge.

Secondly, the gripper is moved to three points in the image; two on the top and bottom left side, one on the right side. The position of each point is measured in pixels by template matching in the image coordination system. The internal sensors of the PI system are used to measure the corresponding position in the robotic coordination system. Next, a transformation matrix is calculated, which allows to transform all positions from the image coordination system to the PI coordination system.

Finally, the z-movement of the PI system is calibrated, since the entire setup is tilted by 5° to the optical axis of the SEM. For this calibration, the gripper is placed in the center position. Template matching is used to determine the x/y-displacement in the uppermost and the lowermost z-position. This value is used for a corrected z-movement, which allows to lower the gripper in z-direction along the optical axis. The drift in the y-direction is about 100 nm/µm.

NanoBit Detachment: The NanoBit detachment sequence starts in the overview pose and with initial SEM conditions; NanoBits and gripper are visible at opposite ends of the image. The NanoBits are detected and their positions determined by template matching.

Secondly, the gripper is moved close to the selected NanoBit, using the global coordinate system. In respect to the NanoBit's and gripper's position, a ROI is activated covering the gripper jaws tips and the handle of the NanoBit. BLOB-detection is used to find all three objects (both jaws and the NanoBit) and relative look-and-move steps are performed in order to achieve an optical alignment of gripper and NanoBit.

Thirdly, the gripper moves in one µm-steps downwards till the jaw shadows the NanoBit's handle significantly, which is indicated by a grayscale drop of at least 20 units. The movement continues until the minimum grayscale is found; the movement is stopped when the grayscale increases back to a fifth of the maximum grayscale drop, in order to guarantee the detection of an actual minimum. This procedure is repeated starting 3 µm underneath the assumed position with maximal shadowing. Now, the gripper moves upwards in 100 nm-steps, until the precise minimum value is found; the NanoBit is presumably in the middle between the jaws. For a proper determination of the grayscale, a scanspeed of 4 and a ten-fold averaging is chosen. Finally, the gripper moves 1.5 µm to grasp the NanoBit at the lowest possible position between the jaws. An overview image of this situation is shown in figure 4.

Fourthly, the gripper closes and wiggles the NanoBit five times with an increasing amplitude in the y-direction in order to break the predetermined breaking point. Finally, the gripper is retracted.

NanoBit Insertion: The NanoBit insertion sequence starts in the overview pose and initial SEM conditions again; reservoir and gripper including the grasp NanoBit are visible at opposite ends of the image. The position of the receiving cavities are determined by template matching.

Firstly, a relative calibration for the NanoBit's tip is performed. A ROI left of the jaws is scanned line by line, in order to determine the tip of the NanoBit (cf. section III-A). Thus, a relative x/y-calibration for the NanoBit is achieved in respect to the gripper jaws. At the same time a template of the NanoBit is acquired.

Secondly, the Nanobit has to be aligned in the x/y-plane above the cavity. The NanoBit is placed 20 pixel beside the detected cavity, in such way that the NanoBit does not mask the cavity. Using a new ROI, a new determination of the

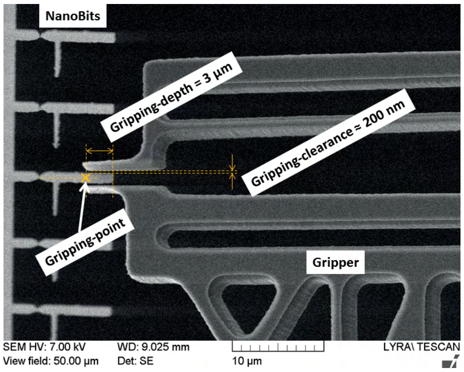

Fig. 4. Gripping procedure: griping point is automatically determined and aligned with the center axis of the NanoBit. Clearance between jaws and NanoBits is about 200 nm. Gripping depth is predetermined with 3 µm.

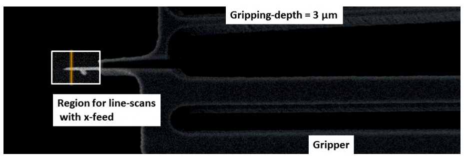

Fig. 5. Scenario after the detachment of the NanoBit: the NanoBit is clamped between the gripper jaws and the tip is fairly visible. The region of interest left of the gripping point is scanned to determine the exact point of the NanoBits tip.

NanoBit's tip and the cavity is performed, which is used for another look-and-move step, aligning the NanoBit exactly above the cavity.

Thirdly, the actual insertion is done. This task is challenging, since a contact-detection failure can lead to the severe damage of all components. A small ROI of a few µm length around the cavity is used to observe the insertion of the NanoBit. Subsequently, the NanoBit is lowered in 100 nm steps. If the NanoBit or the gripper touches the surface of the cartridge, the discharging leads to a significant movement of the image (cf. III-B).

Finally, the gripper is opened and retracted. Since only the actuated, right jaw of the gripper moves, the NanoBit moves to the right side, touches the reservoir, which limits its movement. This reduces the contact surface to the gripper jaw and allows an easy detaching.

IV. RESULTS AND CONCLUSION

The experiments on the automation effort show positive results and build a solid basis for further developments. The combined hardware clearly provides a most suitable setup for micro-automated operations inside the SEM and improved previous setups. Furthermore, the control architecture is most suitable and allows the development of automation script prototypes within a few hours.

Over all, the repeatability of the different steps strongly depends on the quality of the involved microsystem components and the most crucial part is a well fabricated breaking point of the NanoBits. Under the conditions at hand, the breaking point had to be smaller than $\leq$300 nm. This is due to the fact that the most critical process step is the detachment: The NanoBit has to turn inside the gripper jaws properly and the indented breaking point has to collapse fully. All failures during this process result either in a total loss of the NanoBit, or even worse in a situation where the NanoBit fully sticks to one of gripper jaws inaccessibly.

A. NanoBit Detachment

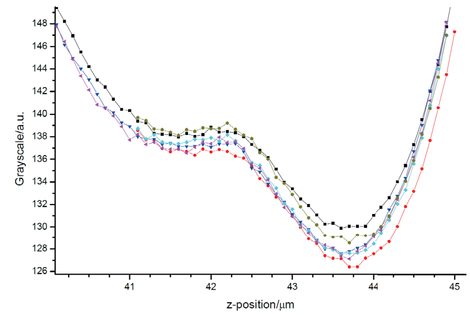

Fig. 6. Comparison of six different z-approaches. The minimum grayscale around 43.7 µm indicated a maximal shadowing of the NanoBit, which corresponds to a fully centered position. Maximal deviation is less than 200 nm.

If the breaking point is well fabricated, the detaching sequence shows a success rate of nearly 100%. The x/y-alignment based on BLOB-detection achieves a high accuracy with only 200 nm clearance between gripper jaws and NanoBit. The z-alignment approach shows a very high repeatability. Figure 6 shows the grayscale values, which are used to determine the optimal gripping position, depending on the z-position of the gripper. The deviation between all measurements is less than 200 nm, which is more than sufficient for all subsequent tasks. A sideview by FIB confirms these results: The deviation of z-positions which are measurable from this perspective is about 100 nm.

The required process time for the detaching sequence (including overview scan and retraction) is between 30 and 50 seconds, mainly depending on the height difference of gripper and NanoBit.

B. NanoBit Insertion

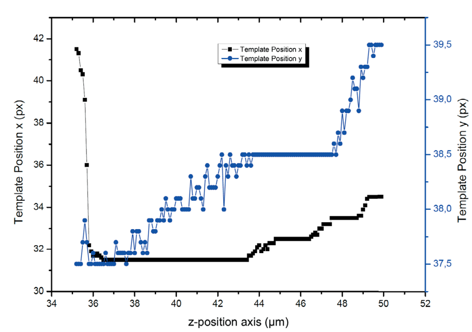

Fig. 7. x and y position of the NanoBit determined by tempate matching during the insertion process. Due to the discharge of the reservoir, the entire image shift significantly along the x axis.

The insertion sequence shows comparable success rates, at which success also includes, that the NanoBit's tip did not touch anything during the assembly sequence. An exemplary measurement of the *touch-detection-by-discharge* approach is shown in figure 7. The absolute movement of the template shows significant chances already on a corresponding z-movement of 100 nm.

Figure 8 shows a series of different insertion attempts. In general, the NanoBits align well with the reservoir: the average deviation is less than 5° in the x/y-plane and less than 7° in the z-direction.

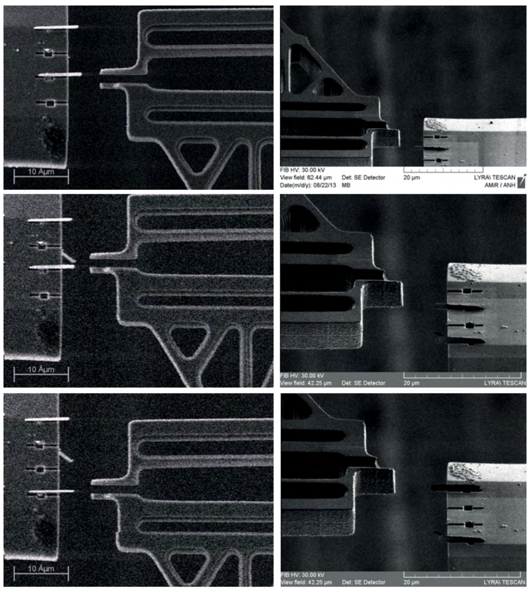

Fig. 8. Top- and corresponding sideview perspective of three exemplary insertion approaches. The NanoBit is successfully inserted to the cavity and is released.

The required process time for the insertion sequence (including overview scan and retraction) is between 24 and 60 seconds, mainly depending in the height difference of gripper, NanoBit and cartridge.

V. CONCLUSION AND OUTLOOK

In conclusion, a successful automation of an assembly process on the microscale has been demonstrated. Success rates are high enough to build a promising basis for further work. The hard- and software design is application proven and guarantees a fast development for upcoming tasks.

Overall, the presented results are an excellent intermediate result and build a promising basis for future developments in the field of micro- and nanorobotic automation.

The next logical perfections and developments in the upcoming work will improve the results significantly: A final after-insertion check of the NanoBit will allow to recognize miss-alignments. In that case a repositioning of the NanoBit can be performed.

Some more important work can be done on the optimization of all image based steps: an optimal scanspeed and averaging will decrease certain process step times.

ACKNOWLEDGMENT

This work is supported by the European Commission in frame of the project NanoBits (257244). The authors especially thank Prof. Peter Bøggild from DTU Denmark for the excellent supply with grippers and NanoBits.

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