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纳米操纵机器人及其自动化设计

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摘要：在纳米技术和纳米材料领域，纳米操纵机器人已经成为一种用于分析和制作原型纳米器件的使能技术。这类纳米操纵机器人拾放操作灵活，可将单个纳米器件集成到现有的微器件中来提高微器件的总体性能和灵敏度。如今这种被称作微纳米集成装配的自动化装置不再局限于实验室使用，还需要应用于工业领域。本文综述了纳米微操作机器人的产生、集成装配和自动化等方面的基础技术，同时探讨了不同种类原子力显微镜超级探针的装配方案。

关　键　词：纳米操作手；纳米机器人；自动化；碳纳米管；原子力显微镜
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Nanorobotics and automation

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Abstract：Nanohandling robots have become an enabling technology for analysis and prototyping in the field of nanotechnology and nanomaterials. Nanorobotic pick-and-place operations facilitate the flexible integration of individual nanostructures into existing micro devices increasing their overall performance and sensitivity. The automation of this so-called robotic micro-nano-integration is required to establish the technology not only in research labs，but also in industrial areas. In this paper，basic technologies for the development，integration and automation of nanohandling robots are presented. In addition，special handling strategies for the assembly of different kinds of Atomic Force Microscope（AFM）supertips are discussed.

Key words：nanohandling；nanorobotics；automation；carbon nanotubes；AFM

1　Introduction

Nanoobjects such as Carbon Nano Tubes（CNTs）and other nanowires have become of significant interest for both the research community and industrial applications. In order to characterize these structures and in order to build

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nanocomponent-based devices, nanorobotic systems have been successfully applied[1-4]. For simplicity, such systems are called nanohandling robots or nanorobots throughout this paper as they can move and manipulate objects with nanometer precision. The size of the nanorobots themselves however is a few cm^3. Sensory feedback is a major challenge on the way to high throughput industrial application, as the exact relative position of tools and nanoobjects is hard to measure. In this paper, an overview on robot based nanohandling automation on the nanoscale is given. In section 2, the state of the art technologies of mobile robots and in section 3, applications of robot-based nanohandling are presented. Finally, the paper is concluded in section 4.

2 Automated Nanorobots

Mobile robots for nanohandling can be used as flexible key components for conducting a variety of nanohandling tasks such as the manipulation of specimen. Key applications include the handling of Carbon Nano Tubes (CNTs)[5], biological cell investigation[6] and the positioning of metrology tools[7]. In comparison to stationary robotics, which mostly consists of linear actuators combined to systems with Cartesian Degrees of Freedom (DoF), mobile robots offer several benefits. They combine multiple degrees of freedom in a compact design; have a theoretically unlimited working range and virtually no infrastructure requirements. A mobile robot can be easily integrated into practically any handling setup by simply providing a flat operating surface. Their compact design makes it easily possible to use mobile robots inside the vacuum chamber of a Scanning Electron Microscope (SEM) or under a light microscope.

As the current mobile robots (shown in Fig. 1, top) do not feature internal position sensors, their position needs to be determined by external sensors. Cameras or microscopes with suitable tracking algorithms are commonly used as external sensors. If such imaging devices are employed as feedback sensors in a control loop, the closed-loop positioning is also called visual servoing. For micro- and nanorobotics, two imaging systems are usually combined for positioning. Cameras are used to determine the position coarsely by tracking macro-features of the robot, e. g. LEDs mounted to the robot. With such cameras, the end-effector of the robot can be moved into the working range of the employed microscope system. This system can then track the end-effector′s position with high resolution and facilitate fine positioning.

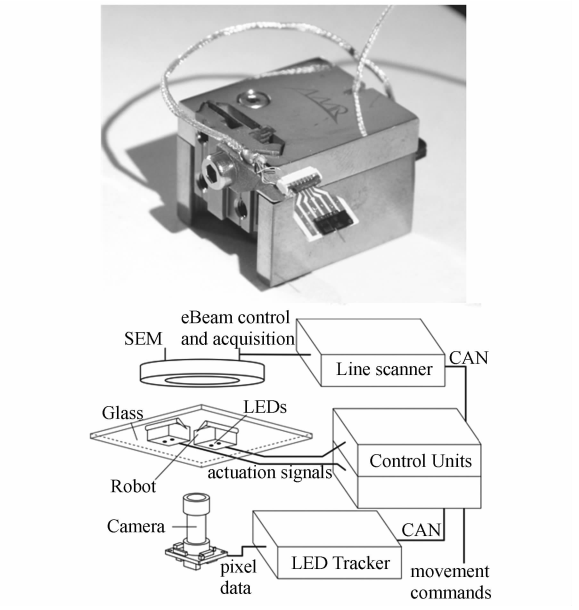
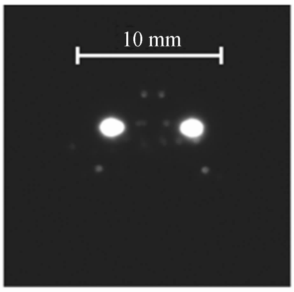


Fig. 1 Top: Picture of a mobile robot with four degrees of freedom (x, y, z, φ). The robot has a size of 20 mm×23 mm×15 mm and a mass of 40 g. It can carry different tools, e. g. micro- or nanogrippers. Bottom: Example setup of a nanohandling cell with multiple mobile robots in a scanning electron microscope chamber. The robot has a camera-based tracking as coarse-positioning unit. The fine positioning is done using a special developed algorithm that controls the electron beam for high-speed tracking.

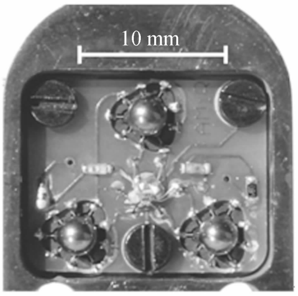
There are suitable sensor systems that can be used for highly efficient visual servoing for both coarse and fine positioning (see Fig. 1, bottom)[8], implemented the visual servoing control loop for coarse positioning of a mobile robot in an embedded control system. With the embedded control system, a sensor update rate >100 Hz could be used with a low and predictable latency. Thus, the downsides of visual servoing executed using computer-based image processing are de facto eliminated. A similar position tracking and visual servoing is in the process of being applied to the end-effector tracking under optical microscopes. In scanning electron microscopes, the end-effector tracking can also be done quickly and predictably using line scan-based tracking[9].

The crucial steps during visual servoing are image acquisition and image processing. Image acquisition requires a camera to read all pixel sensors and transfer the obtained data into the memory of a computer. The computer then performs image processing operations to calculate the pose information of the tracked robot. Both operations consume a considerable amount of time leading to latency in the control loop. Furthermore, if the involved computers and communication protocols are not real-time capable, there is an unpredictable jitter on the update rate. Lastly, due to the amount of transferred data and the required processing time, there is a limit on the achievable update rate of such a system. This is a severe limitation, especially for high-speed cameras that can deliver more than 50 images per second.

The robot features two infrared LEDs mounted at its bottom (see Fig. 2). The two infrared LEDs are observed by a CMOS camera leading to two bright regions. The robot's position can be extracted precisely by calculating the weighted center of gravity of the two LED regions. In [10], the LED regions are detected using a flood-fill algorithm. This is a so called offline algorithm which requires the entire image to be available in memory. Instead, for the hardware implementation, a stream algorithm is used that processes each pixel directly after reception from the camera[11-12]. The algorithm can track the robot with predictable latency virtually jitter-free. It has a positioning accuracy below 2 μm and a working range of 80 mm × 120 mm.



(a) Image acquired by the coarse positioning camera



(b) Picture of the robot's bottom side

Fig. 2　Robot features

Efficient SEM-based control is not possible using software-based image processing[12]. Thus, a novel position tracking approach is used that can determine the position of an object with high precision using only a number of line scans (see Fig. 3). In [13], a successful position tracking in x, y and rotation was shown with an update rate of up to 1 kHz and resolutions down to less than 5 nm.

For the control of the robot, rotational position tracking is not necessary on the small scale. If the robot moves only a few micrometers, the rotational deviation is entirely negligible. If the robot needs to be brought to the working area from another angle, the rotation itself has to be done via coarse positioning and coarse position sensing as also lateral movement of several mm or even cm is required. Thus, a simplified pattern, i. e. a single point-shaped pattern, can be used. Such a pattern can easily be created using electron beam-induced deposition[14].

As the same mobile robot is controlled by visual servoing based on different sensor system, however, the robot′s controller does not initially know the characteristics and configuration of the sensor. The characteristics include static properties such as orientation, scale and resolution as well as dynamic properties such as update rate and latency. All of these characteristics are important control parameters when designing a controller for high-speed positioning[8].

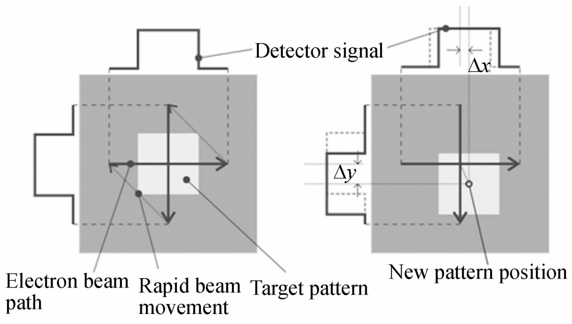


Fig. 3 Basic approach of the line tracking presented in [13]. Instead of acquiring a full SEM image, only two lines are scanned over a known pattern. The movement in x and y direction can be calculated from the offset of the pattern in consecutive images.

The effortless integration of a mobile robot into a micro- or nanorobotic setup can be extended to visual servoing and thus automation by means of an automated self-characterization and auto-configuration sequence. Key properties of the sensor and the motion behavior of the robot can be determined automatically and with a high resolution. Sensor properties include orientation, scale update rate and latency. Determining these properties is crucial to implement high-speed visual servoing as described by [12]. With the described approaches, microrobots can be employed and automated in handling cells in a plug-and-play-like fashion[15].

3 Nanorobotic Applications

The above described automated nanorobots can be applied in different areas. Industries in micro- and nanotechnology produce devices that are supposed to have well-defined properties in order to guarantee their performance. To achieve and keep these properties, various metrology steps for process control are required and especially measurements at critical dimensions become more and more important. For example, the production and development of integrated photonic devices with optical waveguides and complex photonic systems are crucial tasks in micro- and nanosystem technology.

Atomic Force Microscopy (AFM) has become a standard and widely spread instrument in industry and research for the characterization of such nanoscale devices due to its unique ability to analyze nanomaterials in ambient, liquid, and vacuum environments. The quality of information strongly depends on the size and shape of the atomic force microscope probes used. Commercially available AFM probes are usually made of micro-machined silicon or silicon nitride cantilevers with integrated pyramidal tips. Such AFM probes have a typical tip radius of about 10 nm and a typical cone angle of 30°. This large cone angle limits the usability of the tips in imaging deep and narrow structures. Super sharp silicon tips with radii of 5 nm and cone angles of 10° are available. However, their mechanical stability is limited and they are quickly worn down due to brittleness of the sharp silicon tip. In general, conventional AFM probes are unable to penetrate high aspect ratio structures, to touch every point on the sample surface and to exactly profile surfaces with a complex topography, which contributes significantly to the distortion of AFM images.

Several works have shown that the refinement or decoration of AFM probe tips can improve the imaging quality, especially with respect to the aspect-ratio, by orders of magnitudes[16-18]. For this reason, one-dimensional nanomaterials such as carbon nanotubes[19] and nanowires[20] made of different materials are used as ultra-sharp tips for AFM probes[21]. In addition, especially fabricated two-dimensional flakes of silicon nitride, so-called NanoBits are a promising approach to provide exchangeable and customizable tips in AFM technology[22].

Various approaches exist to attach CNTs to the tip of an AFM probe. The first technique developed by [21] uses a polymeric adhesive to attach a bundle of multiwalled carbon nanotubes (MWCNTs) to the tip of a silicon AFM probe. Nanotube probes of various lengths were fabricated by [23] and [24] using a combination of electrophoresis, robotic nanomanipulation, and Electron Beam-induced Deposition (EBiD). Dielectrophoresis was used for rapid and reproducible fabrication of carbon nanotube AFM probes. The carbon nanotube AFM probes showed an angle distribution up to 12° and were used to image an epoxy-based SU8 negative photoresist with deep trenches fabricated by photolithography[25]. A novel arc discharge technique for attaching MWCNTs by applying a DC field between the CNT sample and the AFM probe tip was developed by [26]. Furthermore, CNTs can be grown directly onto the AFM probe tip by Chemical Vapor Deposition (CVD)[27]. The direct growth of CNT tips by CVD techniques offers the most promising approach for producing CNT-enhanced AFM probes which by the nature of the CVD process can be scaled up for mass production[28].

NanoBits are a completely new generation of exchangeable and customizable AFM probes. In previous work, NanoBits have been prepared by Electron Beam Lithography (EBL) and standard silicon processing. In this way, NanoBits could be produced suspended on a tiny contact and free lying above the substrate. The dimensions are 2 ～5μm long and 120～150 nm thick, while the length of the handle is user-definable[22]. In latest work, Focused Ion Beam (FIB) milling is used for rapid fabrication of custom-made NanoBits AFM tips with a very short turn-around time. The end-user can then easily prepare own tips with an application-specific shape in less than half an hour, without access to a cleanroom[29].

However, a reliable direct growth process for different nanotube length, diameter, and orientation as well as a direct integration of NanoBits is not available yet. Therefore, the automated nanorobotic assembly of CNT-and NanoBits-enhanced AFM probes is a versatile alternative and pre-stage to mass production. In this section, different nanorobotic assembly strategies for CNT-enhanced AFM probes are presented that can be supported by FIB processing. The FIB-processing can either be used to support the nanorobotic pick-and place process itself or to initially fabricate NanoBits and finally to shape and shorten the CNT-enhanced AFM probes[30] facilitating the fabrication of AFM probes that are customized for special applications such as the imaging of high aspect ratio structures and the measurement of sidewall roughness. The International Technology Roadmap for Semiconductors (ITRS) identified the metrology of high aspect ratio critical dimensions as an important issue in the field of 3D interconnects[31].

Different nanorobotic assembly strategies have been developed for mounting CNTs and NanoBits onto AFM probes. A microgripper-based pick-and-place strategy that only makes use of the acting gripping and adhesion forces can be used without the need of additional joining techniques. In addition, EBiD can be applied to mechanically fix the CNT or NanoBit to the AFM probe and to overcome the adhesion forces between gripper jaw and object for the placement. Furthermore, FIB milling can be used to create a corresponding connector in the target AFM probe. For CNTs, this can be a circular hole in the AFM cantilever while for planar NanoBits a slit structure can be used to realize a form closure-based placing process. Fig. 4 shows SEM images of resulting CNT- and NanoBit-enhanced AFM probes that have been manufactured by using the different assembly strategies.

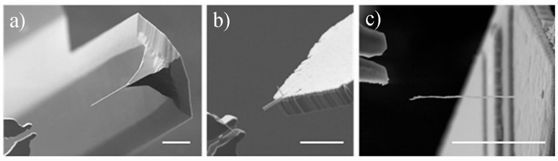


Fig. 4 SEM images of assembled AFM supertips. a) Microgripper-based assembly of CNT-enhanced AFM probes using EBiD. b) Form closure-supported assembly of a NanoBit-enhanced AFM probe using FIB milling to create a slit in the AFM cantilever. c) Form closure-supported assembly of a CNT-enhanced AFM probe using FIB milling to create a circular hole in the AFM cantilever. The scale bar in all images is 10 μm

4 Conclusions

The presented nanorobot handling cell and tracking technique facilitates the fully automated control of nanorobots. Together with specially developed handling strategies this nanorobotic enabling technology allows for the flexible but reliable assembly and prototyping of nanomaterial-based devices. As an example, different types of AFM supertips are presented. Future work will focus on the automation and optimization of graphene flake handling and their mechanical characterization. High-throughput and automated measurement protocols will help to obtain more systematic and reproducible results compared to manually performed experiments.

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References:

[1] ABBOTT J J, NAGY Z, BEYELER F, *et al.*. Robotics in the Small, Part I: Microrobotics [J]. *IEEE Robotics & Automation Magazine*, 2007, 14(2):92-103.

[2] DONG L, NELSON B J. Robotics in the Small, Part II: Nanorobotics [J]. *IEEE Robotics & Automation Magazine*, 2007, 14(3):111-121.

[3] FUKUDA T, NAKAJIMA M, LIU P, *et al.*. Nanofabrication, nanoinstrumentation and nanoassembly by nanorobotic manipulation [J]. *Journal of Robotics Research*, 2009, 28(4):537-547.

[4] NELSON B J, DONG L X, SUBRAMANIAN A, *et al.*. Hybrid nanorobotic approaches to NEMS [J]. *Robotics Research*, *ser. Springer Tracts in Advanced Robotics* (STAR), *Springer*, 2007, 28: 163-174.

[5] EICHHORN V, FATIKOW S, DAHMEN C, *et al.*. Automated microfactory inside a scanning electron microscope [J]. *Proceedings of the 6th International Workshop on Microfactories* (IWMF), 2008,207-212.

[6] TAGLIARENI F, NIERLICH M, STEINMETZ O, *et al.*. Manipulating biological cells with a micro-robot cluster [J]. *Proceedings of the IEEE/RSJ International Conference on Intelligent Robots and Systems* (IROS), 2005,1414-1419.

[7] MARTEL S, SHERWOOD M, HELM C, *et al.*. Three-legged wireless miniature robots for mass-scale operations at the sub-atomic scale[J]. *Proceedings of the IEEE International Conference on*

Robotics and Automation (ICRA), 2001, 3423-3428.

[8] JASPER D, DIEDERICHS D, FATIKOW S. Hardware-based trajectory-controlled visual servoing of mobile microrobots [J]. *Proceedings of IFAC Symposium on Mechatronic Systems*, 2010, 565-570.

[9] JASPER D, FATIKOW S. Line scan-based high-speed position tracking inside the SEM [J]. *International Journal of Optomechatronics*, 2010, 4(2): 115-135.

[10] EICHHORN V, FATIKOW S, WICH T, *et al.*. Depth-detection methods for microgripper based CNT manipulation in a scanning electron microscope [J]. *Journal of Micro-Nano Mechatronics*, 2008, 4(1): 27-36.

[11] DIEDERICHS C. Hardware-software co-design tracking system for predictable high-speed mobile microrobot position control [C]. *Proceedings of IFAC Symposium on Mechatronic Systems*, 2010, 14636-14641.

[12] JASPER D, EDELER C, DIEDERICHS C, *et al.*. High-speed nanorobot position control inside a scanning electron microscope [C]. *Proceedings of Electrical Engineering/Electronics, Computer, Telecommunications and Information Technology Conference*, 2010, 542-546.

[13] JASPER D. High-speed position tracking for nanohandling inside scanning electron microscopes [C]. *Proceedings of the IEEE International Conference on Robotics and Automation* (ICRA), 2009, 508-513.

[14] LUTTERMANN T, WICH T, STOLLE C, *et al.*. Development of an automated desktop station for EBiD-based nano-assembly [C]. *Proceedings of the 2nd International Conference on Micro-Manufacturing* (ICOMM), 2007, 284-288.

[15] FATIKOW S, STOLLE C, DIEDERICHS C, *et al.*. Auto-configuration and self-calibration in flexible robot-based micro-/nanohandling cells [C]. *Proceedings of the 18th IFAC World Congress*, 2011, 14630-14635.

[16] BRUGGER J, BUSER R A, DE ROOIJ N F. Silicon cantilevers and tips for scanning force microscopy [J]. *Sensors and Actuators* A, 1992, 34(3): 193-200.

[17] RASMUSSEN P A, THAYSEN J, BOUWSTRA S, *et al.*. Modular design of AFM probe with sputtered silicon tip [J]. *Sensors and Actuators* A: *Physical*, 2001, 92(1-3): 96-101.

[18] WANG Y, VAN DER WEIDE D W. Microfabrication and application of high-aspect-ratio silicon tips [J]. *Journal of Vacuum Science & Technology B: Microelectronics and Nanometer Structures*, 2009, 23: 1582-1584.

[19] IIJIMA S. Helical microtubules of graphitic carbon [J]. Nature, 1991, 354: 56-58.

[20] LI Y, QIAN F, XIANG J, *et al.*. Nanowire electronic and optoelectronic devices [J]. *Materials Today*, 2006, 9(10): 18-27.

[21] DAI H, HAFNER J H, RINZLER A G, *et al.*. Nanotubes as nanoprobes in scanning probe microscopy [J]. *Nature*, 1996, 384: 147-150.

[22] RAJENDRA KUMAR R T, HASSAN S U, SARDAN SUKAS O, *et al.*. Nanobits: customizable scanning probe tips [J]. *Nanotechnology*, 2009, 20(39): 395703.

[23] NAKAYAMA Y. Scanning probe microscopy installed with nanotube probes and nanotube tweezers [J]. *Ultramicroscopy*, 2002, 91: 49-56.

[24] FAHLBUSCH S, MAZEROLLE S, BREGUET J M, *et al.*. Nanomanipulation in a scanning electron microscope [J]. *Journal of Materials Processing Technology*, 2005, 167(2-3): 371-382.

[25] TANG J, YANG G, ZHANG Q, *et al.*. Rapid and reproducible fabrication of carbon nanotube AFM probes by dielectrophoresis [J]. *Nano Letters*, 2005, 5(5): 11-14.

[26] STEVENS R M D, FREDERICK N A, SMITH B L, *et al.*. Carbon nanotubes as probes for atomic force microscopy [J]. *Nanotechnology*, 2000, 11: 1-5.

[27] HAFNER J H, CHEUNG C L, LIEBER C M. Growth of nanotubes for probe microscopy tips [J]. *Nature*, 1999, 398: 761-762.

[28] YE Q, CASSELL A M, LIU H, *et al.*. Large-scale fabrication of carbon nanotube probe tips for atomic force microscopy critical dimension imaging applications [J]. *Nano Letters*, 2004, 4(7): 1301-1308.

[29] BARTENWERFER M, EICHHORN V, JASPER D, *et al.*. Automated handling and assembly of customizable AFM-tips [C]. *Proceedings of the IEEE International Symposium on Assembly and Manufacturing* (ISAM), 2011, 1-6.

[30] RNEICHHO V, BARTENWERFER M, FATIKOW S. Nanorobotic assembly and focused ion beam processing of nanotube-enhanced AFM probes [J]. *IEEE Transactions on Automation Science and Engineering*, 2012, 9(4):679-685.

[31] International Technology Roadmap for Semiconductors (ITRS 2011)[Online]. Available: http://www.itrs.net

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