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CameraMan: A Multirobot System For Nanohandling In A Scanning Electron Microscope

S. Fatikow, D. Jasper, C. Edeler, C. Dahmen

Abstract— **This paper presents the detailed design of a nanohandling robot cell that can work inside an SEM's vacuum chamber and incorporates miniature video microscopes in order to enable fully automated nanohandling and -assembly. The geometrical and mechanical requirements are defined and addressed in a modular implementation. Image processing techniques can be used to recognize and track objects and three dimensional information can be obtained by stereo vision as well as the microscope's focus. To control this highly heterogeneous system, different low-level controllers are used, challenges for cooperatively controlling the multi-robot system are outlined, and high-level automation is discussed.**

I. INTRODUCTION

Visual feedback is of great importance for both automated and teleoperated nanohandling tasks [1]. This information is usually gathered using scanning electron microscopes (SEMs), because the necessary resolution can be achieved and the vacuum chamber provides sufficient space for nanohandling robots. Since especially mobile nanohandling robots do not have internal pose sensors that could be used to determine their exact position in the world's coordinate system, it has to be derived from the SEM's visual feedback [2]. While an SEM can provide high resolution images, parts of each nanohandling robot and the specimen have to stay in the SEM's scanning region and working distance in order to extract pose information while performing an automated task. Furthermore, most SEMs have a fixed perspective, which makes it difficult to track overlapping objects or to measure distances in depth.

The *CameraMan* concept (short for Camera-assisted Manipulation) tries to overcome these limitations by integrating CameraMan robots with miniature video microscopes to gather additional visual information into the SEM. A robot cell thus consists of nanohandling systems that carry out specific tasks and CameraMan robots that, if combined with the SEM's image, provide excellent visual data to control the task and bridge the gap between the micro- and the nanoworld.

A CameraMan robot can assist at nanohandling tasks in several ways. It can provide visual feedback to move objects that are outside the SEM's current scanning range. Furthermore, for SEM images, a compromise between fast scanning speed and good image quality has to be made. If a very high resolution is not necessary, video microscopes can deliver high quality images without the drawback of a low update rate. The CameraMan also provides an easy way to measure distances of arbitrary objects up to a certain precision. If objects are not strictly aligned on a plane orthogonal to the electron beam or are located beneath other objects, it is practically impossible to measure their correct distance using the SEM. The miniature video microscopes can be moved to a position where both objects can be seen and their distance can be measured correctly.

This paper describes the detailed design of a CameraMan implementation as well as its applicability for different micro- and nanohandling tasks. At first, the mechanical construction of the rail system and the CameraMan robots is illustrated. Next, several aspects and possibilities for processing visual feedback such as object recognition, object tracking and deriving depth information are discussed. Furthermore, the problem of control and automation is analyzed. Finally, the benefit of employing CameraMan in different automation scenarios is analyzed.

II. THE MICROROBOT CELL

The CameraMan system needs to fulfill certain requirements which are precisely defined in the following section. The CameraMan concept uses miniature microscopes that can be positioned within the SEM's vacuum chamber. The necessary geometric positions of these microscopes are described, as they strongly influence the system's design, the system has to support sufficient degrees of freedom. In order to make good use of the available space, a rail-based positioning system was chosen, on which multiple autonomous CameraMan robots consisting of a carriage and a camera module can operate. Finally, strategies to minimize interference with nanohandling robots or other equipment such as the SEM's electron detector are discussed.

A. Requirements

As the CameraMan system has to work together with other nanomanipulation equipment, it must be flexible in terms of the SEM's mechanical environment. Firstly, the CameraMan should be mechanically compatible to the SEM's stage, which is used to position specimens under the electron beam. Ideally, CameraMan features similar degrees of freedom to track the specimen's positions. Secondly, trivial to mention, CameraMan must be able to be mounted into the SEM's chamber. It is impossible to mount the CameraMan parts directly into the chamber because of the danger to damage the sensitive SEM. In the current setup, the SEM's door including the stage can be completely demounted. This

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All authors are with the Division Microrobotics and Control Engineering, University of Oldenburg, 26111 Oldenburg, Germany. fatikow@uni-oldenburg.de

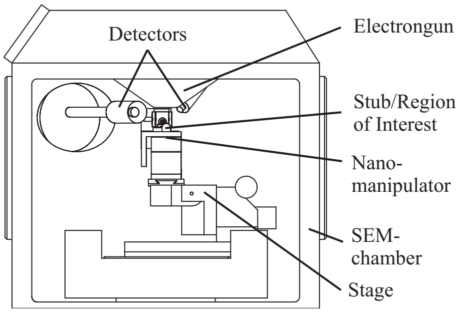

Fig. 1. Available Space in the vacuum chamber

allows an easier design of CameraMan. Another important requirement is, not to block necessary space for other robotic systems. As the CameraMan concept also supports a SEM-stage free scenario with mobile microrobots, space close to the SEM's focus point must not be used. Additionally, the possibility to use diverse carriage robots implicates properly defined working spaces as well as mechanically and electrically defined interfaces.

These requirements lead to a design, where the CameraMan system mostly uses previously unused space. Particularly the vertical chamber corners around the SEM stage and the space under the chamber's ceiling are available (see Fig. 1). As the detectors are mounted in the back chamber wall, they do not impede CameraMan's mounting, but limit the possible working range. The electrongun geometrically defines the working distance or focus point, further called Region of Interest (RoI). Depending on the SEM conditions, the RoI is located 10-20 mm under the electrongun. Any handling task viewed with the SEM must remain inside this region. Typically, some special tasks are performed with the specimen using the nanomanipulator, which includes additional degrees of freedom. For the design of the CameraMan it is adequate to regard the SEM stage and the nanomanipulator as one standalone positioning system.

The RoI implies some evident viewing positions which need to be supported by the system. Fig. 2 shows the most important positions for the miniature microscope. Position 1 is the position with the highest possible viewing angle. The microscope is it aligned to the electrongun and at the chamber ceiling. Due to its size, the RoI has to be about 20 mm under the electron gun. This distance is not ideal for the SEM image generation, but it is still usable. Position 2 shows a compromise between SEM working distance and viewing angle. The working distance for the SEM is more attractive and the miniature microscope can still monitor the task. Position 3 is a vertical aligned view, important for measurements along the SEM's electron beam. As the SEM cannot deliver any information about depth, measuring distances in depth is a great challenge. Position 4 serves as a parking position, where the miniature microscope can be left without disturbing other systems or blocking space of other robotics.

B. CameraMan Design

The first approach of the CameraMan design is shown in Fig. 3. Virtually all operations of a nanohandling task are performed in the center of the SEM's vacuum chamber. Thus, working on a circular rail enables the CameraMan robots to observe the scene from any angle while keeping the working distance constant. Two degrees of freedom are realized through the height-adjustable rail and the carriage, whereas the remaining three degrees of freedom are implemented by the camera module. Thus, the miniature microscope can be moved with 5 degrees of freedom (5-DoF). Rotating the microscope along the optical axis is not necessary as it would only rotate the resulting image. Usually, the rail cannot be implemented as a full circle, because this would interfere with the SEM's electron detector. Thus, a 270 degree circular arc is used as rail (see Fig. 3). As a mechanical requirement, there is a need for a rigid construction. Because of the different miniature microscope positions, the resulting forces and torques in the attachment vary. The system must be rigid enough to tolerate these load changes with comparatively low deflections.

C. Rail drive module

In Fig. 4 one of the two rail drive modules is presented. The rail drive modules carry the rail, implementing one degree of freedom. One rail drive module consists of two linear bearings, a step motor with threaded spindle, a sensor with linear scale, electronics on a circuit board and mounting components. The height of the rail is adjusted using the step motor, which can perform 200 steps per revolution and thus elevate the rail with a 3.5 μm resolution. In combination with the height sensor, half or micro-stepping can further enhance the resolution. The optical sensor has a 1 μm accuracy and a 50 nm resolution. The alignment of the linear scale to the sensor is critical and must be handled with care. A variety of set screws ensures the proper adjustment. Another important issue is the attachment of the bearing rods. As all linear bearings must be aligned parallel to each other, the fabrication of the rod connectors is done by wire-based Electrical Discharge Machining (EDM). EDM enables parallel alignment and mounting of the bearing rods, so the drive runs easily and with low friction. Movements parallel to the linear bearings are created by the threaded spindle

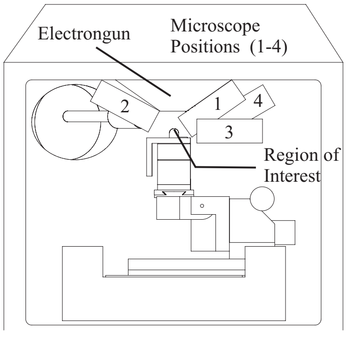

Fig. 2. Important positions for the microscope

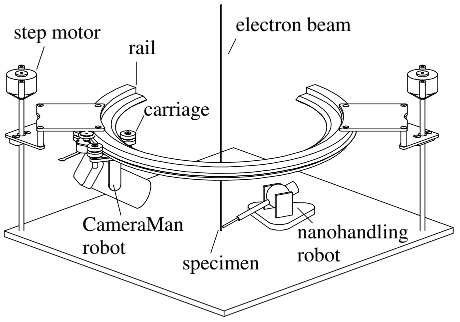

Fig. 3. CameraMan robot cell

and the step motor. Behind the linear scale in Fig. 4, a circuit board with control electronics is located implementing motor control and sensor evaluation. Hence, only a supply voltage has to be connected to operate the complete rail drive module. The high level control runs via wireless communication. Since the two rail drive modules can theoretically be driven independently, synchronous position control has to be ensured to avoid mechanical damage.

D. Carriage Module

As visible in Fig. 3, a carriage on the rail implements the second degree of freedom. A rotational motion around the electron beam alters the perspective without significantly changing the working distance. The carriage module consists of actuator, sensor and mounting parts.

The carriage is actuated by a miniature brushless DC-motor. A control strategy was developed that can use this motor in two different modes. The speed mode operates the motor with constant speed using the integrated hall sensors whereas the step mode treats the motor like a step motor in a half-step pattern. The smallest achievable step length with the integrated 270:1 gearbox is 3 μm and the maximum speed is >20 mm/s. The gearbox has the downside of a considerable backlash, which needs to be compensated using the sensors.

The position of the carriage is measured with two photo interrupters. A two-channel photo interrupter acts as a relative encoder with a period of 550 μm. Using sine/cosine interpolation a sub-μm resolution can be achieved. A second photo interrupter reads a barcode like code. This barcode is aligned with the relative encoder an thus single bits can be read. After moving 5 mm into any direction, 10 consecutive bits are read and the absolute position of the carriage is known.

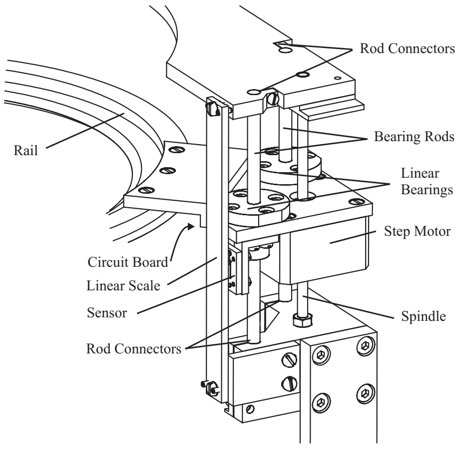

Fig. 4. Rail drive module

The carriage receives energy from the rail by means of sliding contacts. A single 10 V power source is converted up to 150 V to power the piezo-based actuators of the camera module and converted down to 3.3 V to power all other electronic equipment. The communication with the carriage is implemented by a 2.4 GHz wireless transceiver which enables high-speed data exchange without interfering with the SEM's image generation. Furthermore, the wireless chip allows up to six nodes to communicate with each other. This leads to an autonomous carriage design.

E. Camera Module

The camera module consists of a miniature video microscope along with actuators for rotating and focusing. This is achieved by one linear and two rotary axes as can be seen in Fig. 5.

These axes provide the rest of the necessary degrees of freedom. All actuators use piezo stacks in a slip-stick actuation approach with sub-nm resolution. The driving signals for the actuators are generated by an integrated circuit board using a DC-DC converter to generate the necessary high voltage and a switching amplifier to generate a sawtooth signal. The linear actuator controlling the focus has an integrated optical sensor with a 1 μm accuracy. This sensor is very important as it will later be used for measuring depth information when focusing on different objects. The rotary actuators are equipped with encoders that have a 0.001 degree resolution.

The 60 mm-long microscope used in the current setup features a 60-fold magnification at 22 mm working distance, which has shown to be useful for a variety of different tasks. The microscope is sensitive to infrared light, which does not impair the SEM's image generation. The light is generated by infrared LEDs.

F. Integrating the CameraMan into an SEM

There are several issues to be considered when integrating the CameraMan setup into an SEM. The most important aspect is the vacuum compatibility of all devices and materials. Heat is a major problem as components are not cooled by air. There is only a slow heat transfer from the components

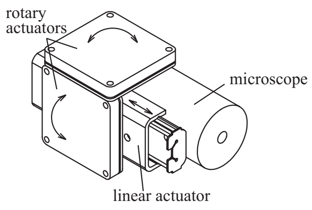

Fig. 5. Camera module

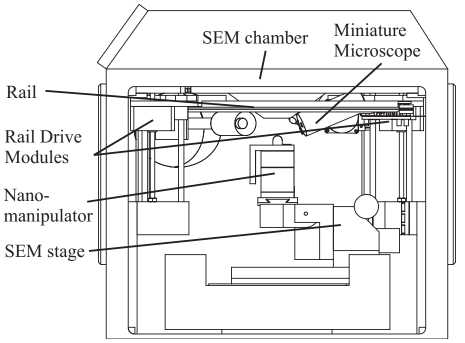

Fig. 6. Complete CameraMan system in LEO 1450 SEM

to the vacuum chamber's hull. For some components such as the miniature microscope, it might not be possible to reduce the heat generation sufficiently. This problem can be solved by reducing the active time of those devices. If the devices are not needed or reach a critical temperature, they are shut down for cooling. A further issue is the impact of the different systems on the SEM's image generation process. Several factors such as vibrations, electric fields, magnetic fields, wireless communication and infrared light do all not severely impair the SEM image but might all lead to a small decrease in image quality. Thus, if very high resolution and quality images are required, each of the problematic systems can be suspended. The system is designed in a way that it will hold its position when the actuators are turned off. Once the acquisition of the high resolution SEM image is complete, the devices can resume without any need for recalibration or homing. However, the system is designed in such a way, that the impact on the SEM image is very small. The electric motors are located as far as possible from the electron beam, infrared light is used for illumination and wireless communication is implemented in the 2.4 GHz band. Therefore, it is hardly necessary to suspend devices in a common nanohandling task. Fig. 6 shows the CameraMan system in the vacuum chamber of a LEO 1450 SEM device.

III. VISUAL FEEDBACK

The CameraMan concept permits an approach also known as *Active Vision* or *Active Perception* (see e.g. [3], [4]). The visual system can actively decide from where images should be taken. Being able to control the viewpoint and the view direction helps to solve different problems concerning recognition, measurement and tracking in complex settings.

A. Illumination

Illumination turned out to be a critical issue for aquiring suitable images with the CameraMan robot. Due to the placement in the SEM, infrared light is the only viable choice for illuminating objects. We used an infrared LED array consisting of 28 LEDs for this purpose.

Tests have shown that the position of the LED array has a great influence on the obtained images, depending on the position of the CameraMan robot (see Fig. 7). Under certain conditions, reflections from the SEM walls, tools and objects can interfere with image processing, or objects cannot be easily distinguished because of insufficient illumination. Depending on the task it could be useful to have a mobile, and thus adjustable, illumination.

B. Object Recognition

In a nanohandling setup, unambiguous recognition and classification of objects in the image is not always possible, due to effects such as occlusion or an imperfect viewpoint. The CameraMan concept allows to deal with these problems.

Active object recognition strategies (see e.g. [5], [6]) can resolve ambiguities which may exist in single images. A new viewpoint will be calculated, from which the CameraMan is able to deliver the missing information or at least part of it. Fully utilizing the possibilities of the CameraMan concept increases the reliability of object recognition in automation tasks.

C. Orthogonal Distance Measurements

Distance measurements are most exact when carried out in the image plane, i.e. orthogonal to the camera view. In fixed-perspective image acquisition of complex setups this can only be achieved in specific cases, with constraints on flexibility. CameraMan gives within certain bounds the opportunity to optimize the viewpoint for planned measurements. This will decrease measurement errors caused by projection of the object onto the camera plane.

D. Depth Estimation

With the CameraMan concept, the position of objects in line of sight can be estimated using different methods.

1) Depth from Focus: Taking advantage of the limited depth of focus of the microscope camera, measurements in view direction can be made using depth from focus methods (see e.g. [7], [8]). The camera has a fixed focal length. By varying the position of the camera with the linear actuator the point of maximal object sharpness can be determined. Since the position of the camera is known, the object's position in the world coordinate system can be calculated.

Sharpness measures which can be used include image variance and entropy. While a focused image should yield the maximum value for variance because its grey levels contain the most fluctuation, entropy should be minimal, due to the sharp edges resulting in relatively discrete values in the histogram. Blurry edges would create intermediate values,

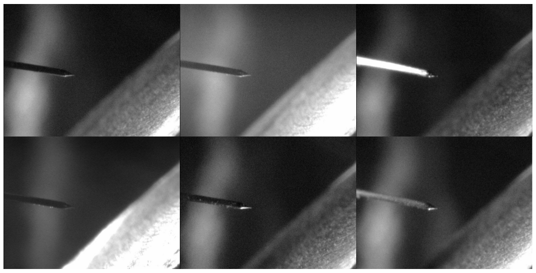

Fig. 7. Illumination examples

therefore increasing image entropy. First experiments showed that this approach has high potential within the CameraMan concept.

2) Depth from Stereo: An additional method which can be used is depth from stereo (see e.g. [9]), assuming that a second CameraMan robot is present. From the two images, disparities can be calculated, which are a measure for depth. An advantage is the possibility to dynamically vary the baseline, by moving the CameraMan modules.

3) Depth from Motion: Within the CameraMan concept the depth from motion approach (see e.g. [10]) can also be used. The position and line of sight of the CameraMan is known at any time. Moving the CameraMan displaces image features depending on their distance. While tracking these features, depth can be recovered by triangulation. Due to the nature of this method results will get more exact the further the camera moves.

E. Autofocus

The same techniques used for depth from focus are also applied to implement autofocus. After determining sharpness values for a few images with different focus, an estimate for the object's location can be calculated. The focus is then iteratively varied to approach the point of maximal sharpness.

Performance considerations, as well as the densely packed environment rule out the approach of sweeping through the whole working range. Collisions with objects in the manipulation setup would be the result. Instead, the autofocus implementation determines the required movement direction by executing trial steps and evaluating the sharpness gradient. After the direction has been found, the axis is moved towards the focus point until the gradient of the sharpness measure sequence gets negative. Subsequently, the point of optimal sharpness is approached with decreasing speed. If the observed object moves out of the focus plane, a loss in sharpness is detected and the algorithm triggers refocusing. The sharpness measure used is the variance of an arbitrary region of interest in the image.

In Fig. 8, an STM tip has been used as observed object. The object is moved three times using a highly accurate linear axis to perform 1 mm steps. The duration of the autofocus movement was 1.36 s, 0.88 s, 0.76 s and 0.88 s respectively. The deviations in positioning for the separate refocusing steps were 54 μm, 36 μm, 6 μm and -96 μm.

Autofocus for the CameraMan robot has shown to be working and relatively stable. The determined focus positions are usable (see Fig. 9), though they may be subjected to errors of up to 100 μm. A source for this error is the tip itself, which is not aligned parallel to the image plane, making an optimal focus of the whole tip impossible. This leads to a broad peak in the sharpness measure and multiple points of maximal sharpness. If higher accuracy is required, a smaller region of interest can be specified.

F. Object Tracking

In the Division Microrobotics and Control Engineering, algorithms for real-time tracking of objects in an SEM based on active contours have been developed (see [11]). These algorithms have the advantage of being robust against partial occlusions. However, two limitations exist up to now.

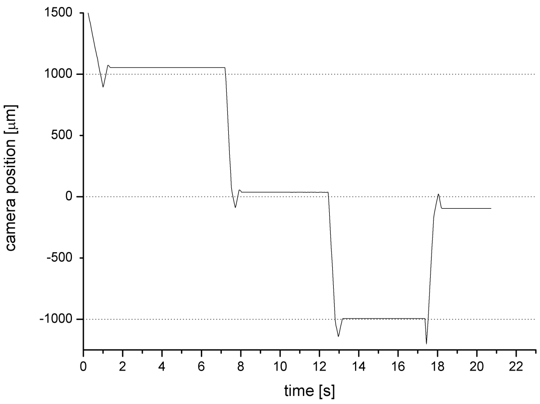

Fig. 8. Autofocus measurement

First, the existing tracking algorithms have to be initialized manually. This is disadvantageous for automation tasks, but can be resolved with the help of object recognition. Second, the tracking algorithms are currently limited to 2D-tracking, e.g. using Euclidean transformations. There are possible solutions for this in the literature (e.g. [12], [13]), extending tracking algorithms based on active contours to the 3D space.

The CameraMan concept allows to dynamically change viewpoint and line of sight to optimize the tracking performance. This enables tracking in high magnification over long distances, avoiding occlusion and disturbance by objects which may potentially be in the line of sight.

A useful application of the camera tracking for teleoperated tasks will be the continuous tracking of tools or workpieces. This avoids manual change of camera parameters during manipulation tasks.

IV. CONTROL AND AUTOMATION

The control of the CameraMan microrobot-cell can be divided into two tasks. The *low-level control* is responsible for moving CameraMan robots to certain global pose. Based

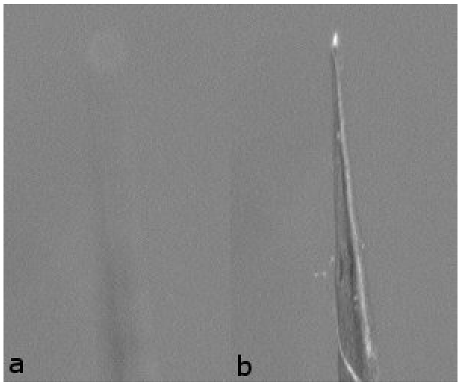

Fig. 9. Image of tip in (a) beginning and (b) end of focusing

on a low-level controller, the microrobot-cell can easily be used for teleoperated or fully *automated* nanohandling.

A. Low-Level Control

The low-level control of the CameraMan system uses different algorithms for the different actuators. Each actuator group has its own low-level controller that translates target movements to actuation parameters.

The step motors for adjusting the height are used in a full-step commutation scheme in order to drive to a target position. Meanwhile, the linear encoders can detect a stalling of the step motors and take appropriate measures. The brushless DC-motor of a carriage is driven analogously using a full-step commutation scheme with hall sensor feedback. If the carriage gets close to a target position, it is decelerated and finally driven as close as possible to the target position using a half-stepping pattern. Both actuator systems are stable and the step mode enables them to quickly reach a target position without overshooting.

The camera module features three degrees of freedom using slip-stick actuators. These actuators show strongly non-linear, time-variant and load-dependent behavior and thus are hard to control accurately. Due to the fast and accurate internal sensors of each actuator, however, the employed control algorithm can quickly adapt to those changes during operation. The input parameters to the actuators are signal amplitude and frequency. In the current implementation the actuators are only used performing full slip-stick steps.

A very important feature for the CameraMan robot is the ability to automatically focus on an object. Due to the microscope's fixed working distance, focusing is controlled with the linear actuator and lies within the low-level controller's responsibility. The low-level controller gathers input from the actuator's internal position sensor as well as the autofocus information (see section III-E) and calculates appropriate actuation parameters.

B. Automation Scenarios for CameraMan

In a partly automated process, the CameraMan robots can be used to automatically observe the handling. E.g. a miniature microscope can be set to follow a specific object. If the object is moved through teleoperation, the position of the camera will automatically be adjusted to keep the object in focus and in the center of the image. Furthermore, a CameraMan robot can store and return to arbitrary positions. CameraMan can continuously analyze the recorded images, extracting data such as positions and distances.

In a fully automated nanohandling process, the CameraMan robots can additionally be used to measure positions and distances that cannot easily be extracted from the SEM image. Furthermore, an important measure for the efficiency of a automated nanohandling are the so called zoom and center (ZAC) steps. In order to get nm-sized objects into a high resolution scanning region of an SEM, the magnification has to be iteratively increased, centering the specimen and nanomanipulator after every step. The CameraMan robots can reduce the number of required ZAC steps by constantly providing lower magnification images and thus considerably increase the speed of an automated process.

V. CONCLUSIONS AND FUTURE WORKS

This paper describes the CameraMan concept along with the successful implementation of a prototypic nanohandling robot cell. A flexible rail-based robot system for operating inside the SEM's vacuum chamber was developed featuring high accuracy, fast actuation speed, five degrees of freedom, and a large working range. The robot system does not interfere with other equipment of the nanohandling station because it mostly uses otherwise unused space. The mechanical construction of the prototype can be enhanced in several ways. Firstly, a hybrid actuation combining the brushless motor with a piezo stack can boost the carriages positioning accuracy and resolution. Furthermore, a newly available optical sensor could measure the carriages position with higher resolution and accuracy.

The CameraMan concept provides additional possibilities for already employed image processing algorithms such as object recognition, object tracking and depth from focus. Furthermore, other algorithms such as depth from motion can be used that were not previously available for micro- and nanohandling stations.

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