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Combined Nanorobotic AFM/SEM System as Novel Toolbox for Automated Hybrid Analysis and Manipulation of Nanoscale Objects

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Abstract— **In this paper, the concept and first results of a novel toolbox for nanoscale characterization are presented. A nanorobotic AFM system is being developed and integrated into a high resolution SEM/FIB system allowing nanoanalysis, -manipulation and -structuring. The compact and modular AFM setup enables probe- as well as sample-scanning and uses self-sensing AFM cantilevers. Image fusion algorithms are developed to merge SEM and AFM information for hybrid analysis of nanoscale objects. A commercial AFM controller is embedded into a special control system architecture that allows for automation of nanomanipulation sequences.**

I. INTRODUCTION

The development of a novel toolbox for nanoscale characterization combining atomic force microscopy (AFM), scanning electron microscopy (SEM), and focused ion beam (FIB) technology and several additional nanoanalysis techniques such as energy dispersive x-ray diffraction (EDX), time-of-flight mass spectrometry (TOFMS), and electron back-scattered diffraction (EBSD) is carried out in the scope of the European research project "FIBLYS". In this paper we describe the development of a compact and modular nanorobotic AFM setup that will be integrated into a high-resolution field emission SEM/FIB system at the end of the project. The final system will offer unique nanomanipulation capability but will also be able to perform standard AFM measurements as well as special AFM techniques such as electron beam-induced current (EBIC) and cathodoluminescence (CL) measurements. As a first step, we present the integration of the AFM setup into a traditional SEM system and show first results.

The SEM is a powerful tool to perform online observation of objects across several orders of magnitude from the millimeter range down to the nanoscale. Furthermore, it provides the opportunity to integrate robot-based systems for manipulation and characterization of nanoscale objects [1]. On the other hand, the AFM provides cantilever-based force feedback. The combination of both systems will thus enable the analysis and manipulation of nanoscale objects having both, direct visual feedback provided by the SEM and force feedback obtained by the AFM. The first AFM/SEM system has been proposed by [2]. In this system, the deflection of the AFM probe was measured using the SEM's secondary electron detector signal. Disadvantages of this approach are that the electron beam is not available for visual feedback during AFM scanning and that electron beam-induced deposition might cause an additional mass on backside of the cantilever leading to a drift of the cantilever's resonance frequency. Another AFM/SEM system was reported by [3]. The system uses self-sensing piezoresistive cantilevers as force feedback without the need of integrating additional equipment for measuring the AFM probe deflection. However, the piezoresistive AFM probe only enables detecting the normal cantilever deflection so that lateral forces cannot be determined. An optical beam deflection AFM system was firstly integrated into an SEM by [4], realizing topographic as well as lateral force measurements. However, the working range of the AFM scanner was limited to 8 µm in x,y-direction and 1.6 µm in z-direction. The development of another optical AFM/SEM system was presented by [5]. Visual SEM feedback during AFM scan operation was realized by tilting the whole setup. No quantitative AFM scans have been shown. [6] reported another optical beam deflection system allowing both AFM and SEM operation at the same time, but the relative bulky setup prevents the use of additional techniques such as EBSD or EDX detectors. A very compact and finger-like AFM setup was introduced by [7]. The system has been used to perform in-situ testing of electron beam-induced deposition of tungsten structures inside the SEM. An advanced AFM/SEM system has been developed by [8]. The setup combines a commercial AFM and SEM system and provides nanomanipulation capabilities with haptic force feedback. Unfortunately, the utilized AFM system is no longer available on the market.

Any of the technological solutions developed until today has been designed with specific tasks in mind and has to compromise with regard to its architecture. Often, these setups are limited to the use of special sensors, limited scan areas, access to single samples and certain modes of operation. One of the goals within the FIBLYS project is the development of a versatile compact and modular nanorobotic AFM system that will allow for a variety of operation modes and the usage of different sensors in a modular fashion. The system will enable choosing a variety of probes and actuators and offer both probe scanning and sample scanning mode according to the specific need of the tasks at hand. Thus, special AFM techniques such as EBIC and CL measurements that profit most from a sample scanning configuration can be performed whereas the special needs of nanomanipulation and robotic automation can benefit from fixed samples and mobile endeffectors. Furthermore, the envisioned system will

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allow for the fast exchange of several samples and the quick selection of sample sites to be inspected. Additionally it will be integrated into a microrobotic control environment that facilitates the automation of considerable repetitive tasks or standard procedures.

The paper is structured as follows: In section II, the intention of the FIBLYS project is described in detail. Section III is dealing with the development of the nanorobotic AFM setup and its integration into an SEM system. Image registration algorithms for merging AFM and SEM image information are proposed in section IV. In section V, a control system architecture for automation of nanomanipulation and nanoanalysis tasks is presented. Finally, a conclusion and an outlook of upcoming work are given in section VI.

II. UNIQUE TOOLBOX FOR NANOSCALE CHARACTERIZATION

The idea of the FIBLYS project is to provide a unique toolbox for nanoscale characterization. This competitive tool is based on a dual beam SEM/FIB system with analytical capabilities such as EDX and extended 3D EBSD. In addition, a TOFMS will be integrated to carry out FIB-based secondary ion mass spectroscopy (SIMS). A novel scanning probe/nanomanipulation capability is developed (described in this paper) to exploit tip-sample interactions and to probe different electron-matter interactions such as EBIC and CL directly at the surface with nanoscale resolution by using cantilever-based sensors. This variety of techniques will also enable a 3D tomography approach based on sequential FIB slicing followed by analysis such as EBSD and subsequent data-processing to create 3D objects with analytical information. A closed-loop vision-control of cantilever and sample position via real-time SEM image processing will allow for performing new types of automated nanomanipulation experiments. Finally, the system will offer the possibility to deposit material using an integrated gas injection system in order to create 3D nanopatterns for diverse applications in photonics or plasmonics.

To that end, it is clear that scanning electron microscopes with more than just one detector are already representing a great improvement, but the implementation of nanoscale manipulation, surface modification, imaging and analysis capabilities in one single instrument will represent a real breakthrough and provide a unique toolbox allowing for operations in nanotechnology that are currently problematic or impossible. Complementary use of SEM/FIB/AFM and several analytical techniques will enable the analysis of nanostructures just after their preparation or even during their production. Such an in-situ measurement in the same apparatus is not degraded by contamination and oxidation as in case of separated production and control lines. Possible production defects are detected early and in some cases may even be corrected. The outcome of FIBLYS will be a unique toolbox for nanoscale characterization interconnecting production, analysis and control.

III. COMBINED AFM/SEM SYSTEM

A crucial task of the FIBLYS project is the development of a compact AFM setup with nanopositioning and scanning capabilities.

The prototype setup for initial testing purposes and proof of concept investigations, as they are presented in this paper, has been realized by utilizing readily available scanners and positioning components. It was integrated into a Zeiss Leo 1450 SEM already available at the beginning of the FIBLYS project.

The nanoscanning and -manipulation setup is designed as a rigid, compact instrument that can be mounted on a standard SEM stage. The prototype has been set up on the standard motorized sample stage and all measurements presented hereafter have been realized with this setup. During the further progress of the FIBLYS project this setup - with minimal adaptations to the base plate - will be transferred into the SEM/FIB analytical tool system that will be integrated and commercialized by the project partner TESCAN s.r.o.. The motorized SEM sample stage will enable the user to observe the sample from normal viewing incidence up to any tilting angle that is permitted by the SEM stage. At almost parallel incidence of the electron beam to the sample surface even the tip sample interaction can be directly monitored via the SEM.

The AFM system consists of a fine positioning unit with scanning capabilities and a coarse positioning unit. Both are fixed to a common base plate. Fig. 1 shows the setup mounted on the stage of the Zeiss Leo 1450 SEM.

The piezo driven fine positioning unit is equipped with capacitive sensors for closed-loop movement control and high accuracy positioning. For the prototype, a PI-Hera scanner from Physikinstrumente GmbH (PI) is used, which provides a lateral scanning range of up to 100 µm and a z-range of 50 µm. Its integrated capacitive position sensors facilitate a closed-loop AFM operation that automatically compensates for piezo drift and creep. A nanoscale positioning accuracy and repeatability for the tasks of nanomanipulation and nanorobotic control is also enabled by this integrated position sensor feedback.

The coarse positioning unit uses positioners made by SmarAct GmbH, a partner in the FIBLYS consortium. These positioners are equipped with optical positioning sensors allowing for travel ranges of several centimeters with a repositioning accuracy up to 50 nm. The coarse positioning unit enables the user to select areas on a sample for inspection or even to quickly select and swap different samples.

In the course of the FIBLYS project, these two positioning solutions are thought to be modular entities that each will allow for the mounting of a sample carrier that can hold two or more standard SEM stubs as well as the mounting of an exchangeable sensor head that can carry a variety of probe sensors or even nanomanipulation devices such as microgrippers. The exchangeable sensor head is designed in such a fashion that it enables fully shielded local electronics to be integrated close to the sensor.

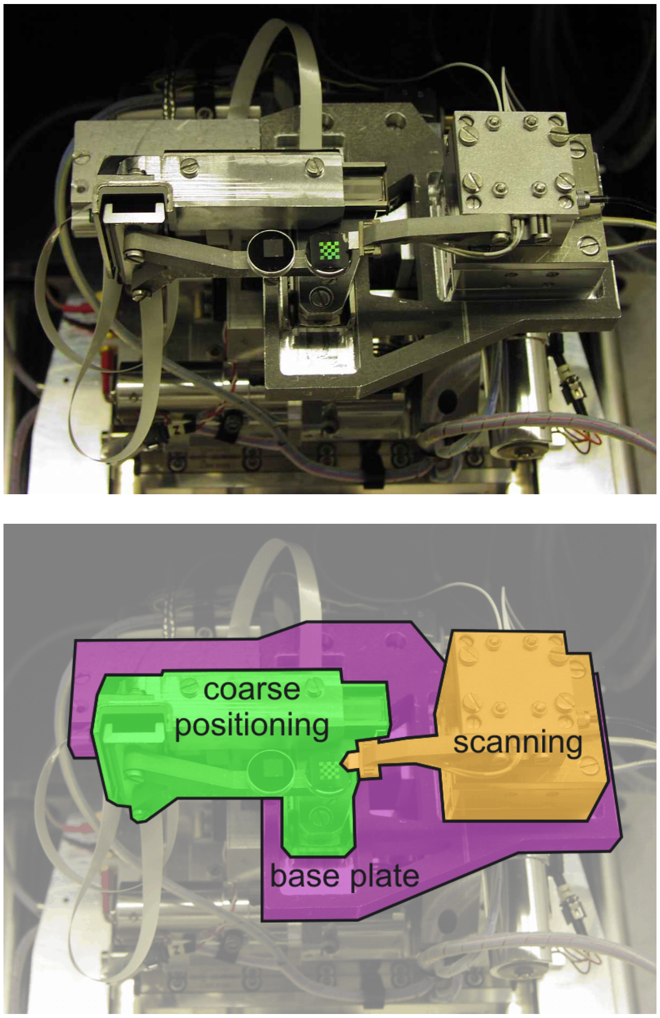

Fig. 1. Photograph of the AFM setup mounted on a Zeiss Leo 1450 stage (top). In the schematic representation (bottom) the functional units are encircled (and color graded) for better distinguishability. The scanning unit on the right side has a protruding arm to the left, on which the probe cantilever is mounted. The coarse positioning stage carrying two stubs with samples can be seen on the left hand side. Both are mounted on a common base plate.

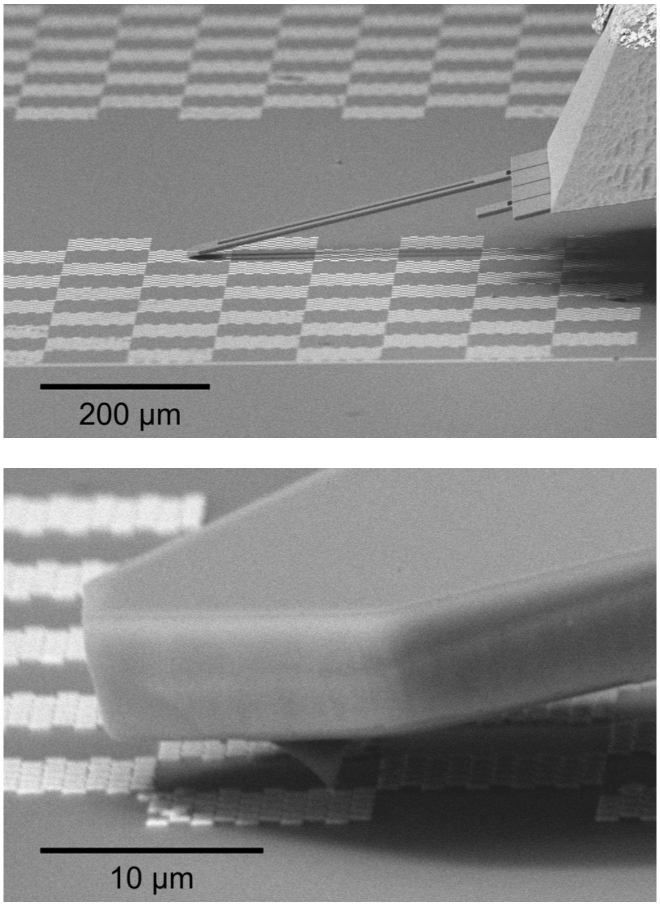

Fig. 2. Piezoresistive cantilevers from SII-NT have been used to perform the AFM measurements and are shown here as observed in situ with the SEM. The sample is a chessboard test pattern.

The prototype setup presented here has been selected to operate with the configuration of a scanning probe. This configuration was chosen with the predominant needs of nanomanipulation and robotic automation in mind. It facilitates keeping the working volume of the fine-positioned scanning probe under constant observation by the SEM while it also provides the opportunity to quickly change sample locations in a fully automated fashion by the sensor equipped coarse positioning stage.

The final configuration for the FIBLYS project shall enable the user to select which way of operation - a scanning probe with a fixed sample or a scanning sample with fixed probe - is most suitable. E.g. for the task of nano-CL or nano-EBIC analysis, a fixed probe in relation to the electron beam can be desirable while the sample is to be scanned.

For the AFM operation in these initial experiments presented here a piezoresistive cantilever from Seiko-Instruments Nanotechnology Inc. (SII-NT) has been used as a sensor. Based on noise limitations from the current electronics a force resolution of approximately 10 nN can be achieved in contact mode. Alternatively a tuning fork based Akiyama style probe sensor [9] can also be employed for tapping mode AFM operation. Both sensor types have the advantage that they are self-sensing and do not need additional equipment above the cantilever to detect the force induced deflection. A first stage signal amplification is performed by an OpAmp integrated on a small electronics board mere centimeters away from the cantilever.

SEM images of the cantilever interacting with the sample can be seen in Fig. 2 as they have been observed by the SEM at a tilting angle of about 80°. In this configuration the user can directly observe the interaction between tip and sample. A corresponging AFM image taken in situ inside the SEM is depicted in Fig. 3 as a pseudo 3D rendering. The test pattern shown in the SEM images as well as in the AFM images is a standard SEM chessboard test pattern consisting of 300 nm thick consecutive gold chessboard patterns across several orders of magnitude. The smallest structures are 1 µm gold squares.

Additionally, a very compact proprietary beam deflection sensor head is currently under development. With the

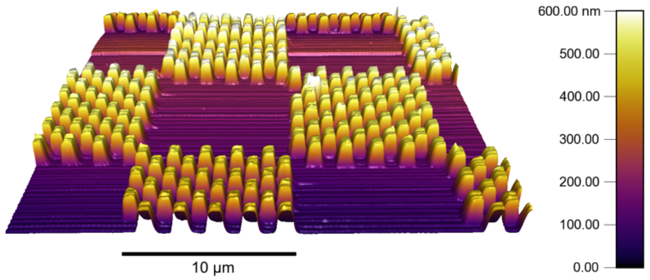

Fig. 3. Pseudo-3D rendering of a standard SEM chessboard test pattern as observed by the AFM in situ within the SEM. The pattern features 1 µm gold squares with a height of about 300 nm that are depostited onto a silicon sample.

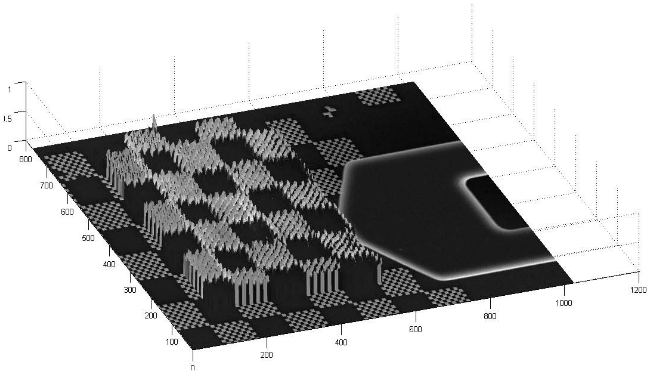

Fig. 4. Fused representation of SEM overview scan and AFM topography scan of a calibration pattern. Each square is 1 µm^2. SEM scanning has been performed perpendicular to the sample surface. The overview scan also shows the AFM cantilever after scanning.

FIBLYS project completed, it should allow for using all modes of AFM operation with commercially available cantilever types to unlock the full potential of the combined AFM/SEM/FIB system for analytical purposes.

IV. MERGING OF HYBRID IMAGE INFORMATION

For interpretation of the results, a meaningful representation of the AFM and SEM image data is necessary. This problem is referred to as image fusion. A good fusion scheme does not remove image detail relevant to the interpretation, does not introduce image artifacts or inconsistencies and is tolerant to noise and other imperfections. There have been earlier investigations on the fusion of AFM and SEM scans with a focus on correct surface reconstruction [10]. A more general approach has been presented in [11].

All fusion schemes require a proper spatial alignment (image registration) of the two or more image sources. The registration method is defined by a transformation model, which describes the spatial interrelationship between AFM and SEM scan. Although far more complex models have been proposed [12], we found a linear conformal transform $T\left(\mathbf{x}\right)$ sufficient for this application:

$$T\left(\mathbf{x}\right) = \mathbf{S} \cdot \mathbf{R} \cdot \mathbf{x} + \mathbf{t}\ , \tag{1}$$

where $\mathbf{S}$ and $\mathbf{R}$ denote matrices for scaling and rotation and $\mathbf{t}$ the vector of translation. These parameters are estimated from a set of manually labelled landmark points, which must be identified in the AFM and SEM source images.

Once an estimate of $T\left(\mathbf{x}\right)$ is known, a fused image may be computed. Three methods were considered here:

- *Color space fusion:* The aligned one-channel source scans are mixed in the channels of a color image. Several variants are possible with the result of a flat color image.
- *Multiresolution fusion:* Both scans are transformed into a multiresolution representation (pyramid) and fused at each level of resolution. This requires the selection of a fusion rule resulting in a flat monochrome image.
- *Surface rendering:* Because the AFM can provide scans based on surface topography, it is a natural choice to visualize them in a three-dimensional representation. The rendered surface might be textured by the SEM scan using OpenGL [13], which will end up in a perspective surface view.

In the special, but most common case, the SEM viewing direction is perpendicular to the specimen surface. A result of surface rendering based fusion for the perpendicular case can be seen in Fig. 4. The surface is textured by the SEM scan, which also shows the AFM cantilever after scanning. Areas not covered by the AFM scan remain flat. This fused representation is useful for the planning of subsequent AFM scans. It may be rotated and zoomed for identifying new regions of interest.

In a special but common case, where the SEM viewing direction is in a flat angle to the specimen surface, the SEM scan is a perspective projection of the specimen surface. From this projection, the perpendicular view can usually not be reconstructed. Therefore, the fusion is performed between the SEM scan and a specially generated surface view of the AFM scan, using multiresolution fusion. A fusion result with a tilt angle of 84° can be seen in Fig. 5. This view is useful for cantilever navigation, as it exposes the cantilever tip. As compared to the perpendicular view, a drawback is the loss of surface detail in the SEM scan.

V. AUTOMATION ARCHITECTURE

To enable full automation of the tasks described above, an efficient control architecture is needed [14]. The employed architecture separates control tasks into low-level control and high-level control and additionally provides flexible integration of different sensors, including image processing software. The architecture acts as distributed system where every element can easily be moved to a different computer, thus making the architecture scalable. Fig. 6 shows the used architecture which is divided into a generic system base architecture and a project specific setup. The generic part consists of three main components: The graphical user interface ”Frontend“, the scripted automation server ”HiLeC“, and the image processing system ”OlVis2“. Each of these components implements a specific part needed to achieve full automation on the nanoscale.

The Frontend is the graphical user interface (GUI) for manual project control and automation development as well as image processing control and observation. The frontend can be used for different tasks, from early project stages, where all parts are controlled manually, through the whole project lifetime to automatic execution of complex automation tasks. Together with the HiLeC, telecontrol of every actuator and tool can be easily done by the user. For image processing development, the frontend includes interfaces for creating and executing dynamic image processing pipelines inside OlVis2, providing full observation of every data or image inside the pipelines. To develop automation sequences, the frontend includes a script language editor and interfaces for the debugger included in the automation server.

The HiLeC software is the scripted automation server, where semi- and fully automated handling can be executed. The HiLeC executes a scripting language that has been extended to allow easy control of the connected low-level controllers and sensor programs which can be dynamically connected. During script development, a debugger is attached to the executed automation sequences, enabling fast automation prototyping.

The OlVis2 image processing software is a versatile computer vision system with dynamic pipeline support. Multiple inputs such as SEM, camera or AFM can be combined with different image processing algorithms [15].

The project specific low-level controllers (LoLeCs) and sensor programs (SePros) for the different automation tasks have to be connected to the generic architecture. As shown in Fig. 6, there are three dedicated software parts for each system component:

- The stage controller controls the positioning of the coarse positioning stage and can be controlled by the automation server.
- The SEM/FIB acts on the one hand as a sensor providing image data to the computer vision system. On the other hand it can also be used as tool for nanostructuring (FIB) and is therefore connected to the image processing system as well as to the automation server.
- The AFM is, similar to the SEM/FIB, for some tasks used as a sensor providing data to the image processing system and for other tasks used as a manipulator. It can, like the SEM/FIB, transmit data to the computer vision system and accepts manipulation commands from the automation server.

The project specific low-level controllers implement a set of basic operations that can be executed by the automation server. The stage controller for example implements operations to get the current position or move to a specific position. These basic operations can be used inside automation scripts. Combining those basic operations together with programming constructs enables complex open-loop control automation.

To perform closed-loop control automation, visual feedback is crucial. For this purpose, uhe used computer vision system acquires images from the SEM/FIB and merges them with depth maps from the AFM by using the techniques described in section IV. Additionally, other algorithms such as template matching or tracking techniques can be used to provide visual position feedback to the automation server.

VI. CONCLUSIONS AND UPCOMING WORKS

A. *Conclusions*

A modular and compact nanorobotic AFM setup has been developed and at a first stage integrated into a scanning electron microscope. The system can be used to perform standard AFM methods as well as manipulation of nanoscale objects. The whole setup can be tilted by using the SEM stage allowing for direct visual feedback of AFM operation provided by the SEM. In-situ observation of AFM scans of a chessboard test pattern have been performed.

Special image fusion algorithms have been proposed to merge the resulting AFM and SEM image information. First

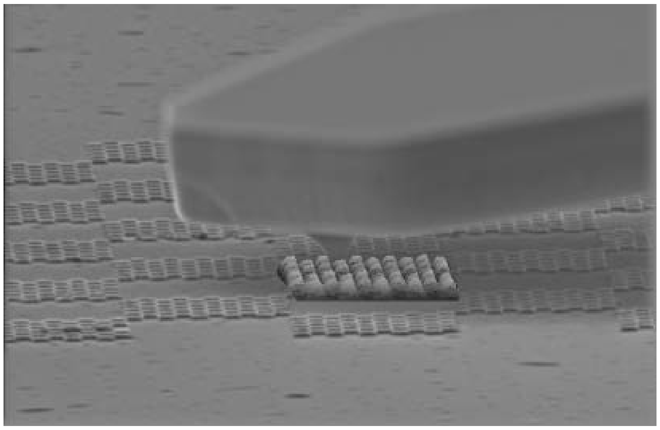

Fig. 5. Fused representation of tilted SEM overview scan and AFM topography scan. The tilt angle is 84°. This view exposes the AFM cantilever tip and allows for cantilever navigation having regard to previous AFM scanning results.

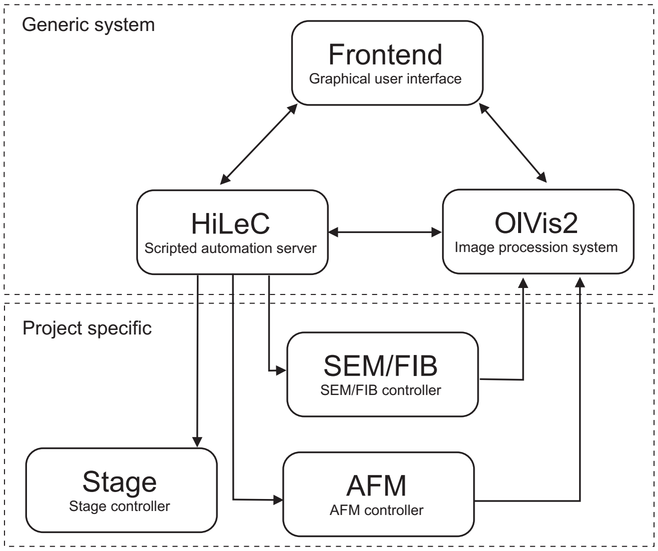

Fig. 6. Automation architecture for the foreseen AFM/SEM/FIB system. The architecture consists of a generic system and project specific low level controllers for the applied hardware devices.

results are presented that show fused AFM/SEM images taking advantage of both analytical methods.

The developed and described control architecture will enable the automation of nanomanipulation and -analysis tasks. For this purpose, project specific low-level controllers of all integrated hardware devices are being developed and must be integrated with the generic software architecture components.

B. Upcoming Work

Upcoming activities will focus on further development of the presented AFM system. A novel compact optical beam deflection system will be integrated giving the opportunity to apply most types of commercial available AFM probes and thus enabling specialized AFM techniques such as EBIC and CL measurements. In addition, a haptic device will be connected to the system facilitating force feedback and haptic control of the AFM. The next steps towards fully automated nanohandling and -analysis will be the identification of necessary image processing algorithms for position feedback as well as the development of nanohandling sequences. Key challenges will be the automated positioning and approach of the AFM cantilever onto selected sample locations as well as the AFM-based manipulation of nanoscale objects based on SEM image data. Furthermore, the developed image registration procedure will be fully automated and evaluated on AFM and SEM image data at the nanoscale.

VII. ACKNOWLEDGMENTS

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