Integrated 3-D manipulation of nanoscale objects in the Scanning Electron Microscope

Application to the Additional Appointments Scheme of the Isaac Newton Trust

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Summary: This project will involve the application of advanced visualisation, software and hardware technologies to advance the state-of-the-art in precise manipulation of nanoscale objects for assembly and test of prototype nanotechnology devices.

1. Introduction

Nano-assembly and manipulation is becoming an increasingly important tool for characterisation of objects and also in building prototype devices. Nanotechnology devices such as carbon nanotubes (CNTs) and nanofibres are regarded as key technologies, with ramifications in medicine, sensors, security and many other applications. However, to achieve the necessary level of precision to achieve repeatable high quality results calls for an environment in which the requisite complex sequences of sub-micron scale operations can be planned and monitored. We propose an environment based on a scanning electron microscope to develop an integrated system to accomplish manipulations of complexity and accuracy not achievable hitherto. Outputs are expected to be research papers and a facility available for use by researchers in nanotechnology.

The scanning electron microscope (SEM) is arguably the most important advance in scientific instrumentation since the Second World War. From 1948 to the present day, the Department of Engineering has been at the forefront in the evolution of this instrument in all aspects of its development, its instrumentation and its applications. [2, 3, 4]

Carbon nanotube technologies and nano-manipulation are under active investigation in the Department of Engineering by Dr Ken Teo and colleagues [1]; projects are under way to develop carbon nanotube technology (both multiwall and single wall) for a variety of applications that include electron guns, displays, vacuum and solid state electronic applications. This also extends to semiconducting nanowires. A range of assemblies for use in nano-manipulation have been developed, including thermal actuators, microspring actuators, mechanical locks, microtweezers and microcages.

The proposed project will build upon this existing foundation, in partnership with Carl Zeiss SMT Ltd who have committed substantial support in the form of a high performance scanning electron microscope that will be available for this work, plus a contribution towards the costs of the research.

2. Objectives of Research

Nanotechnology devices promise enormous benefits including more powerful computers, miniaturised sensors to improve security, monitor health or track pollutants in the environment, and clinical drugs that target specific parts of the body. The ability to carry out precise manipulation of nano-samples and to assemble elements on a nanometre scale is in consequence of rapidly increasing importance, both for characterisation of objects and also in building prototype devices. For example, nano-manipulation can be used to pick up small objects (organic nanowires, cells, laminar slices) and place them precisely onto electrodes or grids as part of an assembly procedure, or for measurement of their characteristics.

We propose a novel system, based upon a scanning electron microscope, in which to carry out nano-manipulation and measurement of material characteristics. The SEM is an ideal environment for such a development. The versatile stage driven by user-friendly software, facilitates easy location and inspection of the specimen, and the availability of real-time high-magnification images and electronic signals opens up the possibility of carrying out manipulations on an automated basis. Some experience is being gained in the use of the SEM on a manual basis for this purpose [5], and...
confirms the potential of the instrument as an imaging environment for this kind of work. However, it has proved immensely tedious to carry out anything more than extremely simple manipulations on an ad-hoc basis, for reasons discussed below. Further research needs to be undertaken to develop a system capable of executing complex sequences of operations reliably and repeatably.

Nano-manipulators can take a number of forms (for example, a cantilever, a gripper or a probe), according to the experiment being undertaken. Simply matching the exact location of the nano-manipulator and the object being picked up calls for extreme accuracy in positioning. While the specimen stage and control software provided with the standard SEM nowadays are highly advanced and user-friendly, offering a versatile environment for moving a specimen within a field of view, they do not support the kind of coordinated motion called for in the application considered here. Additional hardware is required to control the manipulator incrementally, in accordance with the intended sequence of operations. Further, there is a need to calibrate the manipulator movement to the coordinates of the SEM, and to measure the position of any part of the specimen or manipulator to high accuracy. These kinds of measurement, using stereometry, automatic focusing and 3-D modelling techniques, have been under study in the Department over many years. Finally, there is a requirement to develop an accurate 3-D model of the environment (manipulator and target object) in the SEM, which may be used for the detailed planning of plan manipulation experiments prior to their execution. Such a model could be used to prepare sequences of manipulations of a complexity simply not achievable hitherto, by identifying the precise locations for the manipulator to go, and the exact sequence of manipulations required.

In order to achieve these objectives of precise nano-manipulation within the SEM in an integrated fashion, four main areas of research are required:

2.1 Visualisation of the environment

Techniques for building up a 3-D model of the nanomanipulator and the target object will be explored. These will involve use of direct stereophotogrammetry in the SEM to determine the spatial coordinates of the object and target location. Since its inception, the scanning electron microscope has been recognised as an exceedingly powerful tool for the inspection of three-dimensional objects. The techniques of stereo imagery and stereometry offer a powerful means of extracting qualitative and quantitative information from the topography of a specimen.

It is proposed to investigate a new and promising stereo technique which can be employed with any microscope design, and to apply a knowledge-based approach to simplify the task of achieving usable stereo images and making accurate measurements from them. Direct dynamic 3D measurements will be made using stereometry or automatic focusing, to determine the time-varying position of the manipulator, including its altitude above the substrate, and to feed back information about the deformation and other operating conditions of the manipulator. In this way, it will be possible to carry out automated manipulations and measurements quickly and conveniently.

2.2 Hardware development

A 3-D nanomanipulator will be designed and built using a suitable 3-axis piezo micro-translator system, under computer control, by means of which a manipulator or cantilever can be swept accurately across the surface under controlled conditions. The manipulator may be a silicon-micromachined flat cantilever, etched tungsten tip or even grippers. The nanomanipulator will be integrated into the stage of the SEM, and its capabilities will complement those of the existing specimen stage.

2.3 Software development

The 3-D model will form the basis of the interface to the operator, and will have a broad range of functions. Firstly, it will be required to communicate with the SEM in order to perform imaging, so that accurate parameters can be determined for the model, according to the manipulator and samples in use. The interface will contain calibration algorithms, and will use computer visualisation techniques as well as direct measurements of manipulator movements in order to build the 3-D model. In addition, it will link with the micro-translator system to control movement of the stage mechanism as well as the dedicated micro-translator. The 3-D model may then be used by the operator to move and engage objects in a virtual environment, planning entire experiments in their
entirety, facilitating the simulation of complex manipulative or nano-assembly tasks in the model before committing to the tasks themselves, many of which will be executed in a fully automatic way.

2.4 Virtual Microscopy and Training

Despite automation, many of the procedures in the system envisaged for nano-manipulation in the scanning electron microscope are too complicated for the average user, who may not have the experience to judge which to use, or how effective might be the results. Training is the answer; however, such a system may not easily be made available for training purposes. The objective of this part of the project is to develop a novel approach to training in the operation of the system through the creation of a Virtual Environment, which will build on previous developments in developing a Virtual SEM. The aim is to provide a realistic environment in which trainees can undertake structured learning exercises and carry out complex manipulation operations indefinitely, in order to understand them, without causing damage to specimens or manipulators, or unnecessary wear and tear to the instrument itself. It is intended that this package will serve as a teaching tool to educate inexperienced users in the use of the system.

3. Project Resources and Outputs

The project is projected as a three year programme of research involving one Research Associate, who will focus on one or more key areas, and, with the Proposer, will co-ordinate the remaining work and oversee Research Students who will undertake parts of the project under studentships funded by EPSRC or other sources; additional support tools are likely to be developed by final-year Engineering Masters’ students as part of their project work. The work is expected to result in a facility that could be used by nanotechnology researchers for carrying out advanced experiments; the outputs are also expected to include scientific research papers in nanotechnology and other journals.

Carl Zeiss SMT have donated a high performance scanning electron microscope for use in the work, and in addition are providing a second instrument for general purpose use (on the basis of a five year loan), plus maintenance for both instruments. They have also committed to make a financial contribution towards the Research Associate post itself, and an additional sum for travel and consumables. IP resulting from the project is covered by an agreement already concluded between the University and Carl Zeiss SMT. IP resulting from the project will be vested in the University; for any outputs representing enhancements to the SEM, and which are regarded as worthy of exploitation, Carl Zeiss SMT will be eligible to negotiate with the University for a licence to do so.

The Isaac Newton Trust’s assistance is therefore requested to provide a supplementary sum under the Additional Appointments Scheme for the applicant at the Research Associate scale.

4. References


(2) Caldwell, N.H.M., Breton B.C., Holburn, D.M., & Young, T.C.W., "Particle Analysis using Neural Networks and Image Processing in the SEM", in Microscopy and Microanalysis 2003, Vol. 9, Supplement 2, pp 738-739.

