Nanorobotics

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Scope of the Project

Nanorobotics is concerned with (1) manipulation of nanoscale objects by using micro or macro devices, and (2) construction and programming of robots with overall dimensions at the nanoscale (or with microscopic dimensions but nanoscopic components) [Requicha 2003]. This project covers both of these aspects. Nanomanipulation is the most effective process developed until now for prototyping of nanosystems, and rapid prototyping is important to validate designs and optimize their parameters. Nanomanipulation is also useful to repair or modify structures built by other means. Nanorobots have dimensions comparable to those of biological cells, and are expected to have remarkable applications in health care and environmental monitoring. For example, they might serve as programmable artificial cells for early detection and destruction of pathogens. The initial research is biased towards nanomanipulation. Work on nanorobot construction has begun at a low level and will increase as the project evolves.

Research at USC's Laboratory for Molecular Robotics (LMR) under a previous NSF grant (EIA-98-71775) has yielded reliable and accurate methods for nanomanipulation by using the tip of a Scanning Probe Microscope (SPM) as a sensory robot, in ambient air or in liquids and at room temperature. These methods involve a human in the loop to compensate for the many spatial uncertainties involved in the manipulation and which are due to such phenomena as thermal drift or piezoelectric creep and hysteresis. Experience at LMR with assembling single-electron transistors, nanowires, nanowaveguides and other nanodevice prototypes has shown that automation is needed if SPM manipulation is to be used for building the complex patterns required by new nanodevices and systems. The current project addresses automation issues across the board, from high-level path planning for the assembly of nanoparticle patterns, to error compensation for SPMs. Nanomanipulation is being studied in the context of concrete tasks such as assembling chemical sensors, or building of 3-D nanostructures by Layered Nanofabrication, a patented process invented in a previous NSF grant to LMR. The theoretical and experimental results of this work will contribute to the understanding of robotics in domains with large spatial uncertainties, and to the development of NEMS (Nanoelectromechanical Systems). The software will be very useful to scientists and engineers involved in nanomanipulation and nanolithography.

Building nanorobots involves sensors, actuators, control, power, communications and interfacing across spatial scales and between organic/inorganic as well as biotic/abiotic systems. The initial focus of the project is on nanoactuators that can be controlled by light or by electrical signals. Techniques for depositing electroactive polymers (EAPs) at the nanoscale and for fabricating various actuators are being investigated. Use of nanomachines as robot grippers for SPM pick-and-place operations will also be studied. Collaboration is envisaged with other groups who are harvesting biomotors or building nanoactuators by self-assembling supramolecular compounds. A simple nanorobot akin to a (non self-reproducing) bacterium will serve as a concrete goal. The robot will be able to swim under very low Reynolds number conditions, but will have essentially no intelligence or sensing. A first-cut design will be based on a rotary motor and a flagellum-like screw or propeller.

Research Results

Nanoassembly by Sintering – Assembly of components, or bulding blocks, into more complex structures is a primary goal of robotics at all scales. It involves positioning the required components, joining them, positioning the resulting subassemblies, joining them with other subassemblies, and so forth, in a hierarchical manner. Previous work at LMR has shown how to position nanoscale components by pushing them on a surface with the tip of an Atomic Force Microscope (AFM). LMR research also has demonstrated joining of positioned components by gluing them chemically, and by electroless deposition of additional material.

Now we have been able to join latex nanoparticles simply by heating (sintering) them. Fig. 1 shows a wire built in this manner [Harel et al. 2003]. The latex particles have diameters of ~ 100 nm. The figure shows the initial structure built by nanomanipulation with an AFM, and the results of sintering it. Note that sintering has a smoothing effect which may be desirable for some applications. Sintering is likely to be applicable to a variety of nanoscale materials besides latex, although this has not been experimentally demonstrated yet. In summary, we have developed another promising tool in the nanomanufacturing arsenal. This new nanoassembly process may be useful in a variety of applications that range from wiring electronic components to building three-dimensional structures by Layered Nanofabrication.

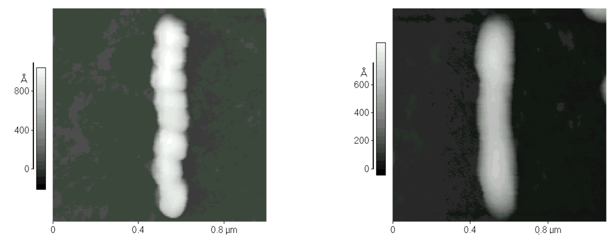

Fig. 1: Latex nanoparticles in a linear array (left) and the "wire" that results from sintering them (right).

Nanowaveguides – Waveguides normally have transversal dimensions commensurate with the wavelength of the radiation being transmitted. The wavelength of visible light is on the order of hundreds of nanometers, which would seem to rule out nanoscale waveguides for the visible spectrum. In colaboration with Professor Harry Atwater's group at Caltech we have shown that nanowaveguides for visible light can be built by exploiting near-field effects [Maier et al. 2003]. Fig. 2 illustrates schematically the experiment. Visible light is injected by means of a Near-Field Scanning Optical Microscope (NSOM) into a structure consisting of several metal nanoparticles with sizes on the order of 30-50 nm and placed at distances approximately equal to their sizes. The injected energy excites plasmon resonances (electronic oscillations) in the particles, and the energy travels down the structure until it reaches a fluorescent end-particle which serves as a reporter, to demonstrate that the energy propagation takes place. The Caltech group developed the basic theory of plasmon nanowaveguides and conducted the NSOM experiments, whereas the LMR team contributed expertise on sample preparation and nanomanipulation, and built many of the structures used in the investigation. Nanowaveguides may find many applications in nanooptics, and are interesting also in other nanotechnology fields. For example, a nanowaveguide may be used to feed energy to individual light-driven artificial molecular machines such as those being developed today at several laboratories. These nanomachines and their successors may provide the means of locomotion needed by future nanorobots.

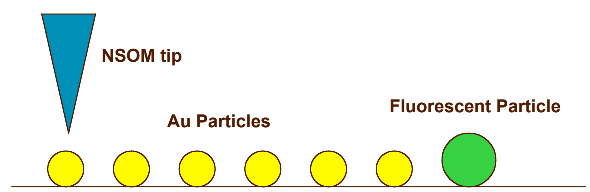

Fig. 2: Schematics of nanowaveguide experiment

Drift Compensation in AFMs - Nanomanipulation with AFMs tends to be labor-intensive because a user is needed in the loop to compensate for the numerous uncertainties associated with AFM operation, especially thermal drift, which is the major cause of errors for AFMs operated in ambient conditions. We have shown that drift can be estimated efficiently by using Kalman filtering techniques [Mokaberi & Requicha 2003]. Preliminary results indicate that drift compensation enables manipulation of groups of particles under program control, without human intervention, in ambient air and at room temperature. This is a first step towards fully automatic nanomanipulation, which would permit assembling, from the bottom up, nanostructures much more complex than those being built today with AFMs.

Active Self-Assembly – Self-assembly is expected to become a dominant fabrication technique for the nanodevices and systems of the future because it is inherently a parallel process. However, traditional, or passive, self-assembly techniques have great difficulty in designing individual components to produce the asymmetric structures needed by many applications. We began to explore self-assembly methods that use active assembly agents (robots). Initial results show that swarms of such robots that communicate only by very simple messages can be programmed to form either wholly or partially specified structures, with the construction process possibly involving sacrificial components or scaffolds [Arbuckle & Requicha 2003]. The assembly agents have small memory and communication requirements, and interact only when they are in contact. They are good models for future nanorobots, which are likely to communicate chemically. Fig. 3 shows sequential steps in the construction by active self-assembly of a wire (or equivalently, determining a collision-free path) between two features in the presence of an obstacle.

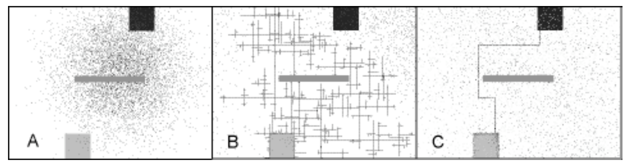

Fig. 3: Road building by self assembly.

Education

The results of the research performed in this project have been incorporated in the regular 1-semester course CS 549, Nanorobotics, taught yearly at USC. The last version of this course was attended by about 30 graduate students from several departments such as Computer Science, Electrical Engineering, Materials Science and Biomedical Engineering. Thus, research is being directly connected to education. Currently, 1 postdoc, 3 graduate students and 2 undergraduates are involved in the project, although not all of them are supported by the grant. Exposing undergraduates to cutting-edge, interdisciplinary research is an important part of their education.

References

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