Robotic Assembly of Functional Nanostructures

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This project's goals are to develop nanorobotic principles and techniques for building nanostructures, and to demonstrate that these techniques can be applied to nanodevice prototype fabrication. Nanorobotics denotes (i) the construction of robots with overal dimensions on the nanometer range, or of robots at the microscale but whose components are nanoscopic, or (ii) the manipulation of nanoscale objects with micro or macro devices—which has been the focus of our work.

We are pursuing a nanofabrication paradigm which we call *programmable assembly*. We begin with building blocks or with scaffolds that are produced by chemical means. Then, we assemble the building blocks by using robotic nanomanipulation with the tip of a Scanning Probe Microscope (SPM). Single-tip SPM assembly is suitable primarily for device prototyping and small-batch fabrication, because of its sequential nature and low throughput. Large-batch fabrication requires manipulation with multi-tip SPM arrays, which are currrently being developed at several labs. Mass production is best approached by programmed self-assembly, using scaffolds designed by algorithmic methods. Self-assembly is outside the scope of this project, but our lab is collaborating with Len Adleman's group at USC, who is studying the computational foundations of self-assembly.

Robotic nanoassembly, much like its macroscopic counterpart, involves positioning and joining of components. We position nanocomponents by using the SPM as a robot, essentially by pushing the components mechanically. We join (i.e. glue) them chemically, by using linkers such as di-thiols (for gold nanoparticle components) or DNA complementary strands, or by depositing additional material over the templates defined by the nanocomponents.

An SPM tip manipulating nanoobjects on a substrate surface is analogous to a helicopter that must construct a map of the terrain over which it flies, and then must navigate with such a map, being equipped only with altitude radar and dead reckoning capabilities. Spatial uncertainty is a fundamental issue both in mobile robotics and in SPM manipulation. For SPMs it is due to thermal drift and other phenomena, and must be combated for successful manipulation.

We have developed several protocols, implemented in custom software, for manipulating nanoobjects with an Atomic Force Microscope (AFM), which is a specific type of SPM. Our primary protocol is as follows. First we image the sample by using the AFM in dynamic, non-contact mode, with a vibrating cantilever. Then we select an object to be manipulated and approach it still in non-contact mode, but with the feedback turned off. Extensive investigations in our lab revealed the basic phenomena involved in this procedure. When the AFM tip approaches a nanoparticle, the amplitude of the cantilever vibration begins to decrease and becomes zero when the tip contacts the object. Then, the cantilever begins to bend, and climbs the nanoparticle until sufficient force is exerted for the particle to move. Motion continues as long as the feedback is off. There is a definite threshold for manipulation: if the cantilever deflection is not sufficiently large, the particle does not move. A naïve approach to manipulation often fails, because at manipulation time the particle is no longer at the position where it was imaged. We use tracking techniques to follow the particles and ensure a very high yield for positioning operations. We work in air, at room temperature, without sophisticated environmental controls. We also have demonstrated nanomanipulation in water and other liquids. Operation in liquids opens new application areas in the biosciences.

Our research has been focused on the construction of nanoparticle patterns. These are interesting for several reasons: (i) many kinds of nanoparticles are available (metalic, semiconducting, magnetic, etc.); (ii) they are typically smaller and more uniform than similar objects built by e-beam lithography; and (iii) arbitrary (planar) structures can be constructed by nanomanipulation using our techniques. The potential applications of nanoparticle pattern include (i) high density data storage; (ii) wires and circuits; (iii) tunneling structures such as SETs (single-electron transistors); (iv) NEMS (Nano Electro Mechanical Systems) components; (v) molds or dies, e.g., for nanoimprinting, (vi) templates for growth, e.g. by material deposition; and (vii) nanowaveguides. We are investigating several of these applications.

Figures 1-4 depict examples of this work. Figure 1 illustrates the storage of ASCI-encoded data in the positions of nanoparticles, and the single-line SPM signal obtained by scanning the second row of the data (which is read as "M"). The particle size is 15 nm and the separation 100 nm. Fig. 2 shows several subassemblies that can potentially be used to construct mechanical nanocomponents. They were obtained by SPM manipulation of 27 nm gold nanoparticles followed by chemical linking with di-thiols. Each of these subassemblies can be further moved as a whole. Figure 3 illustrates the construction of an SET by pushing two gold nanoparticles between the source and drain electrodes of a transistor. These electrodes were built by e-beam lithography, in collaboration with Pierre Echternach at the Jet Propulsion Laboratory. The electrodes are shown on the left, and the two particles positioned between the electrodes are shown in the magnified image on the right. Figure 4 shows how to fabricate a wire of arbitrary geometry. First we build a template by SPM manipulation of gold nanoparticles (left). After manipulation these particles do not touch; the interparticle distance is on the order of the particles' radius. We then use electroless deposition to add more gold to the structure (right). The result is a nanowire that can be moved as a whole. We are also investigating other applications. For example, in collaboration with Harry Atwater's group at Caltech, we are developing prototypes for optical nanowaveguides.

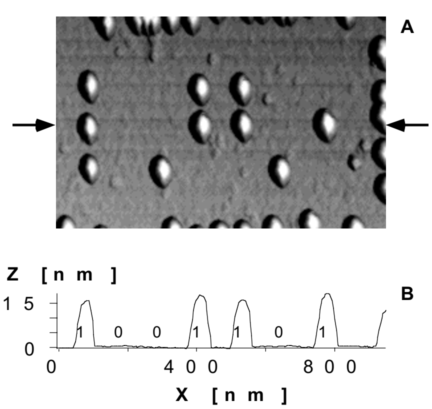

Figure 1

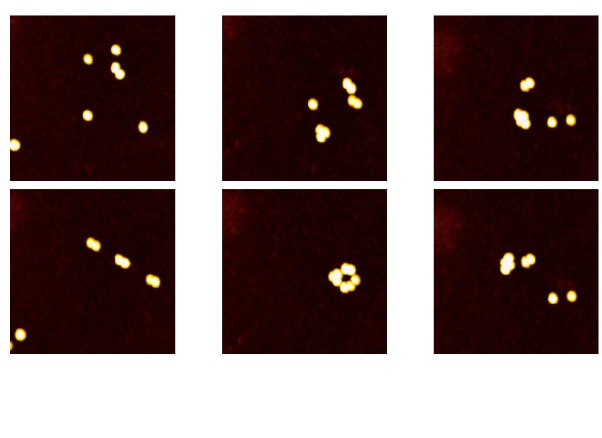

Figure 2

We envisage continuation of this research along several directions: (i) networks of nanoscale sensors and actuators (“physically-embedded nanowebs”) for such applications as environmental monitoring and medicine; (ii) nanorobots, and more general NEMS; (iii) open-architecture, “ultra-programmable” SPM control and manipulation software with a high degree of automation; and (iv) layered nanofabrication of 3-D objects by a process analogous to macroscopic rapid prototyping (or solid freeform fabrication). Nanorobot construction is an especially interesting and challenging problem, since it involves issues of sensors, actuators, control, communications and power, all at the nanoscale.

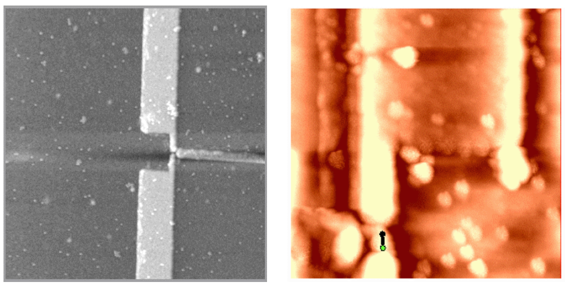

Figure 3

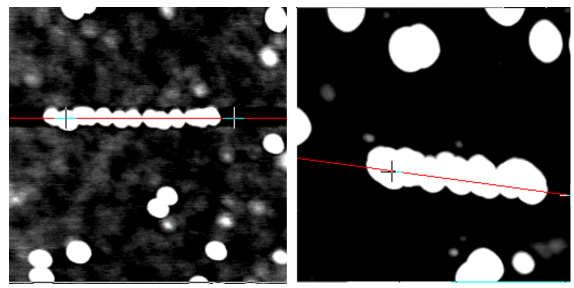

Figure 4

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