Nano and Microrobotics

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What is Nanorobotics? {Microrobotics?}

- Programmable assembly of nm-scale (~ 1-100 nm) {μm-scale (~ 100 nm-100 μm)} components either by manipulation with larger devices, or by directed self-assembly.
- Design and fabrication of robots with overall dimensions at or below the μm {mm} range and made of nm-scale {μm-scale} components.
- Programming and coordination of large numbers (swarms) of such nanorobots. (Not covered here.)

- Notes:
  - Nanoelectronics is relevant as well but not covered here.
  - Standard, passive, self-assembly may be viewed as a form of automation but is not robotic. Covered briefly here.
  - Millirobots are larger than microrobots and have critical dimensions at or below the centimeter range.

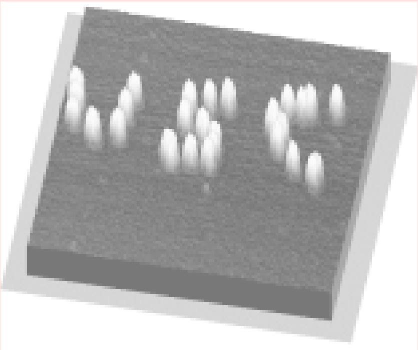
Underlying Science and Technology

- **Macrorobotics traditionally uses principles and tools from information technology, control, mechanics… At small scales, other disciplines need to be included.**
- **Nano:**
  - **Chemistry**
  - **Quantum Physics (not bulk phenomena)**
  - **Biochemistry**
  - **Nanotechnology, mostly chemical processing**
- **Micro:**
  - **Solid State Physics**
  - **MEMS, semiconductor fabrication technology**

Major Labs and Investigators (Nano)

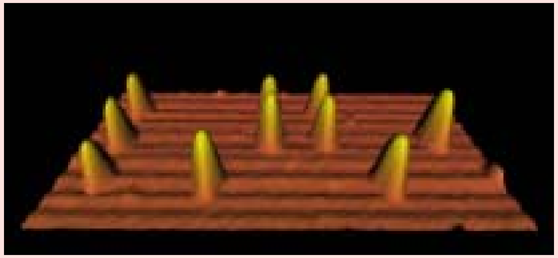
- USC Lab for Molecular Robotics – Requicha, Koel, Thompson, Zhou. Nanomanipulation with AFM; nanosensors; nanoactuators; robotic self-assembly; sensor/actuator networks. Research moving towards building nanorobots and biomedical applications.
- CMU Nanorobotics Lab – Sitti. AFM nanomanipulation. On-going.
- Michigan State University – Xi. AFM nanomanipulation. On-going.
- University of North Carolina at Chapel Hill – Taylor et al. AFM nanomanipulation, especially user interfaces. On-going.
- UCLA – Montemagno. Hybrid systems using biomotors. On-going.
- Self-Assembly of Nanocomponents – Adleman at USC, Reif at Duke, Seeman at NYU, Winfree at Caltech, … Very active area.

Nanorobotics Examples (USC)

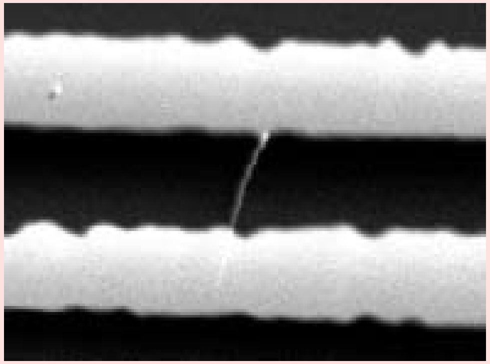


Pattern of 15 nm Au particles built by AFM manipulation (1996)

Line of 100 nm latex particles built by nanomanipulation and sintering



NanoCD: 'LMR' in ASCII encoded in the positions of nanomanipulated 15 nm Au particles



In_2O_3 nanowire sensor for NO_2 built by CVD

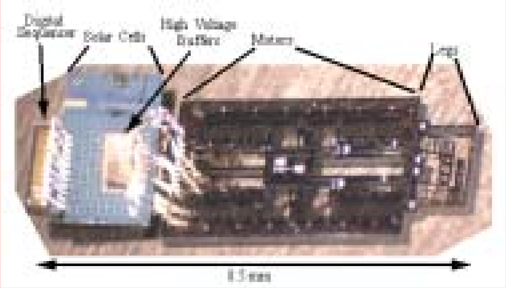
Major Labs and Investigators (Micro)

- RPI Center for Automation Technologies - Akella, Bellouard, Huang, Lee, Popa, Sanderson, Sin, Stephanou. Microgrippers; arrayed micromanipulation; precision placement.
- UC Berkeley - Fearing, Goldberg, Howe, Pister; flying and crawling micro-robots, dextrous micromanipulation, microassembly; fluidic self-assembly.
- Michigan State University- Xi; force controlled microassembly.
- Sandia National Labs - Feddema; precision visually guided microassembly.
- Zyvex - in-SEM micromanipulation.
- Univ. of Minnesota - Nelson, now moved to ETHZ.
- Univ. of Washington- Boehringer; array micromanipulation, self-assembly.

Micro/Millirobotics Examples (UCB)

Flying insect; micromachined C fiber; 100mg weight, 30 mm wing span

Orthotweezers manipulating a strain gage 1000x150x12 μm



Solar powered MEMS leg for crawling robot

Major Accomplishments (Nano)

- Reliable, high-yield manipulation of nanoparticles with sizes ~ 10 nm in air and in liquid, at room temperature.
- Commercial software for nanomanipulation with SPMs.
- Multi-tip SPM arrays.
- Artificial molecular motors.
- Nanotube and nanowire sensors.
- Self-assembly theory and experimental demonstrations using nanoscale DNA components.

Major Accomplishments (Micro)

- Micro-robot components: flexure joints, actuators, structure, MEMS sensors
- Micro-grippers for 100 micron and smaller parts
- Adhesion control for reliable micro-part handling
- Visual servoing for precision handling
- Fluidic self-assembly for low-complexity parts

Influential Papers (Nano)

- J. A. Stroscio and D. M. Eigler, “Atomic and molecular manipulation with the scanning tunneling microscope”, *Science*, Vol. 254, No. 5036, pp. 1319-1326, November 29, 1991.
- R. M. Taylor, W. Robinett, V. L. Chi, F. P. Brooks, W. V. Wright, R. S. Williams and E. J. Snyder, “The nanomanipulator: a virtual reality interface for a scanning tunneling microscope”, Proc. ACM SIGGRAPH '93, Anaheim, CA, pp. 127-134, August 1-6, 1993.
- T. Junno, K. Deppert, L. Montelius and L. Samuelson, “Controlled manipulation of nanoparticles with an atomic force microscope”, *Applied Physics Letters*, Vol. 66, No. 26, pp. 3627-3629, June 26, 1995.
- C. Baur, B. C. Gazen, B. Koel, T. R. Ramachandran, A. A. G. Requicha, and L. Zini, “Robotic nanomanipulation with a scanning probe microscope in a networked computing environment”, *J. Vacuum Science & Technology B*, Vol. 15, No. 4, pp. 1577-1580, July/August 1997.
- R. Resch, A. Bugacov, C. Baur, B. E. Koel, A. Madhukar, A. A. G. Requicha, and P. Will, “Manipulation of nanoparticles using dynamic force microscopy: simulation and experiments”, *Applied Physics A*, Vol. 67, No. 3, pp. 265-271, September 1998.
- C. Montemagno and G. Bachand, “Constructing nanomechanical devices powered by biomolecular motors”, *Nanotechnology*, Vol. 10, No. 3, pp. 225-231, September 1999.
- V. Balzani, A. Credi, F. M. Raymo and J. F. Stoddart, “Artificial molecular machines”, *Angewandte Chimie Int’l Ed.*, Vol. 39, pp. 3348-3391, 2000.
- J. Kong, N. R. Franklin, C. Zhou, M. C. Chapline, S. Peng, K. Cho, and H. Dai, “Nanotube molecular wires as chemical sensors”, *Science*, Vol. 2887, No. 5463, pp. 622-625, 28 January 2000.
- A. A. G. Requicha, “Nanorobots, NEMS and nanoassembly”, *Proc. IEEE*, Vol. 91, No. 11, pp. 1922-1933, November 2003

Influential Papers (Micro)

- A.M. Flynn, "Gnat Robots (and How they will change Robotics)", IEEE Solid State Sensors Workshop, 1987, I*EEE MicroRobots and Teleoperators Workshop*, Hyannis, MA Nov. 9-11, 1987, New York: IEEE, pp. 22/1-5.
- Y-C. Tai, L-S. Fan, and R.S. Muller, "IC Processed Micro-motors: Design, Technology, and Testing", *Proceedings: IEEE Micro Electro Mechanical Systems*, pp. 1-6, Salt Lake City, Utah, 1989.
- R.S. Fearing, "Survey of Sticking Effects for Micro Parts Handling", *Proc. IEEE-RSJ Intelligent Robots and Systems*, Pittsburgh, PA August 3-5, 1995.
- K. F. Böhringer, B. R. Donald, Lydia Kavraki, Florent Lamiraux, "Part Orientation with One or Two Stable Equilibria Using Programmable Vector Fields", IEEE Transactions on Robotics and Automation, 16(2):157-170, April 2000.
- X. Xiong, Y. Hanein, J. Fang, Y. Wang, W. Wang, D. T. Schwartz, K. F. Böhringer, "Controlled Multi-Batch Self-Assembly of Micro Devices", ASME/IEEE Journal of Microelectromechanical Systems 12(2):117-127, April 2003.
- K. F. Böhringer, Ronald S. Fearing, Ken Y. Goldberg, "Microassembly." In Shimon Nof, editor, The Handbook of Industrial Robotics (2nd edition), pp. 1045-1066, John Wiley & Sons, February 1999.
- Dan O. Popa, Harry E. Stephanou, "Micro and Meso Scale Assembly'", to appear in the special issue of SME Journal of Manufacturing Systems, 2004.

Challenges

- High-throughput nano {micro} manipulation. Automatic, massively parallel operations needed.
- High reliability dextrous micromanipulation, force sensing, and joining processes.
- Building nano {micro} robots. Components are beginning to appear or are available but integration is challenging, and so is interfacing to macro and bio systems. Operation of mobile microrobots in outside (real) environments.
- Mass production of nano {micro} robots and other nano {micro} systems by directed self-assembly.
- Issues raised by biomedical applications (which are very promising): biocompatibility, toxicity, interfacing, forming research teams including MDs, …
- Programming and coordination of thousands/millions of nano {micro} robots; robotic self-assembly (related to reconfigurable robotics).

Recommended Funding Areas

- High-throughput nanomanipulation with SPMs.
- High-throughput micromanipulation with parallel microrobot arrays.
- Nanorobot construction.
- Mobile microrobot construction, integration, and operations in real environments, such as medical or exploration.
- Rapid prototyping technology for microrobots as an enabling tool for wider research.
- Non-SPM nanoassembly for mass production.
- *In vivo* sensor/actuator (robot) networks.

Foreign Accomplishments (Nano)

- **Invention of the STM by Binnig and Rohrer at IBM Zurich Lab.**
- **Manipulation of colloidal nanoparticles by AFM, Samuelson group, Lund, Sweden.**
- **Development and characterization of artificial nanomachines by Stoddart at U. Birmingham (now at UCLA), Balzani at U. Bologna, Italy, Feringa at U. Groningen, Holland, …**
- **Direct observation of rotary biomolecular motors, by Noji in Japan**

Foreign Accomplishments (Micro)

Probably > 75% of microrobot work is being done outside the US.

- **Univ. of Toronto, Mills; microrobot microassembly system.**
- **McGill- Martel; nanowalker precise multiple microrobots for nanofabrication.**
- **ETHZ - Nelson; wafer level microassembly; visually guided microassembly; biological micromanipulations.**
- **EPFL- Siegwart; mobile microrobots.**
- **Univ. of Tokyo - Sato; micro and nanomanipulation.**
- **Nagoya University - Fukuda and Arai; mobile microrobots, biological micromanipulation, micro parts handling.**
- **Scuola Superiore Sant'Anna - Dario, medical microrobots, I-Swarm.**

Projects for International Cooperation

- Building mobile nano {micro} robots.
- Biomedical applications.