Technology Innovations, LLC and Innovation On Demand, Inc.
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"Wireless technique for microactivation" patent: Technical Backgrounder

For "Breakthrough enables world's smallest robots;
nanobots capable of manipulating large molecules and cells" press release
(innovation-on-demand.com/microactuators.pdf)

One of the major goals of current nanotechnology research is to develop tools for manipulating or constructing nanoscale[1] objects. There are basically two approaches to this:

- **Molecular assembly** one atom or molecule at a time (bottom-up)
- **Micropositioners** that can move and control objects in the near-molecular sub-micron[2] arena.

Molecular assembly

There are several tools for measuring and moving nanoscale objects, such as the scanning tunneling microscope[3] (STM) and atomic force microscope (AFM). These devices are capable of sensing and positioning individual atoms or molecules at the low end (down to a few tenths of nanometers[4]) and IBM and others have created impressive images[5].

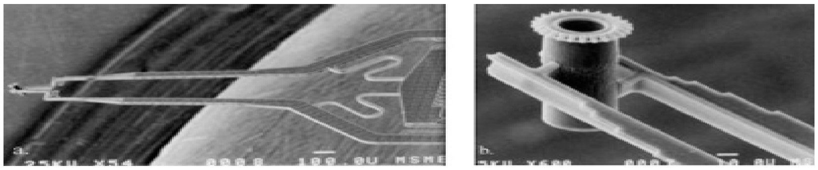
But these tools are extremely slow and the small tips are unable to move larger molecules. Until automated molecular assembly can be developed in the future, this approach is not a practical solution.

Micropositioners

The top-down approach is based on building a hierarchy of increasingly smaller devices with modular molecular blocks (a.k.a. "Legos") until you get down to the desired nanoscale device size[6]. Each of these devices must be built by a larger device that serves as a tool for constructing the smaller device.

At the high end, there are devices such as piezoelectric actuators that can move larger objects around and construct smaller devices. However, for manipulation of sub-micron size objects, micron-size actuators are required.

Conventional micropositioners (based mainly on electromagnetic and piezoelectric devices), with their space-consuming baggage of chips, batteries, actuator "muscles," and wires, do not scale well down to micron size; they're limited in miniaturization to a few millimeters.



Example of millimeter-scale microtweezers. These HexSil tweezers are removed from the wafer they were made on and then mounted on conventional positioning systems (such as the one shown on the left, which is part of an X-Y-Z tilt stage the size of your hand). They are suitable for handling parts from a few microns to 1000 microns in size and must be held about 5 cm away from the parts.[7]

So there's currently a huge gap between nanoscale and microscale tools in the nanotechnology field. This gap is currently of intense research interest because this is the size range of molecules of DNA, nanotubes, crystalline building blocks, and other important substances.

Heat-actuated shape memory actuators

One of the most promising solutions to filling this gap is heat-actuated shape memory alloy (SMA) actuators[8], which allow for miniaturizing actuators down to the micron range. These devices are based on a property of certain alloys of titanium and nickel: they can be bent, stretched, or compressed (using a spring, for example, or the action of an opposing SMA device) when cool to a specific shape, but when heated above the phase transformation temperature, they will snap back to their original ("memory") shape.

The TiNi Alloy Company[9] has pioneered the development of such devices, specifically using thin film. The advantage of these thin-film SMA actuators is that they can produce large forces and displacements within small spaces at voltages compatible with electronics. Specifically, they can produce 10 joules per cubic centimeter per cycle -- at least ten times higher energy density than other microactuator mechanisms.

Prototype SMA actuators are fabricated by sputter deposition of titanium-nickel thin film (about 100 nm. thick) on silicon substrates, which are then micromachined using photolithography patterns and selective etching techniques to create a specific device, eventually in volume quantities

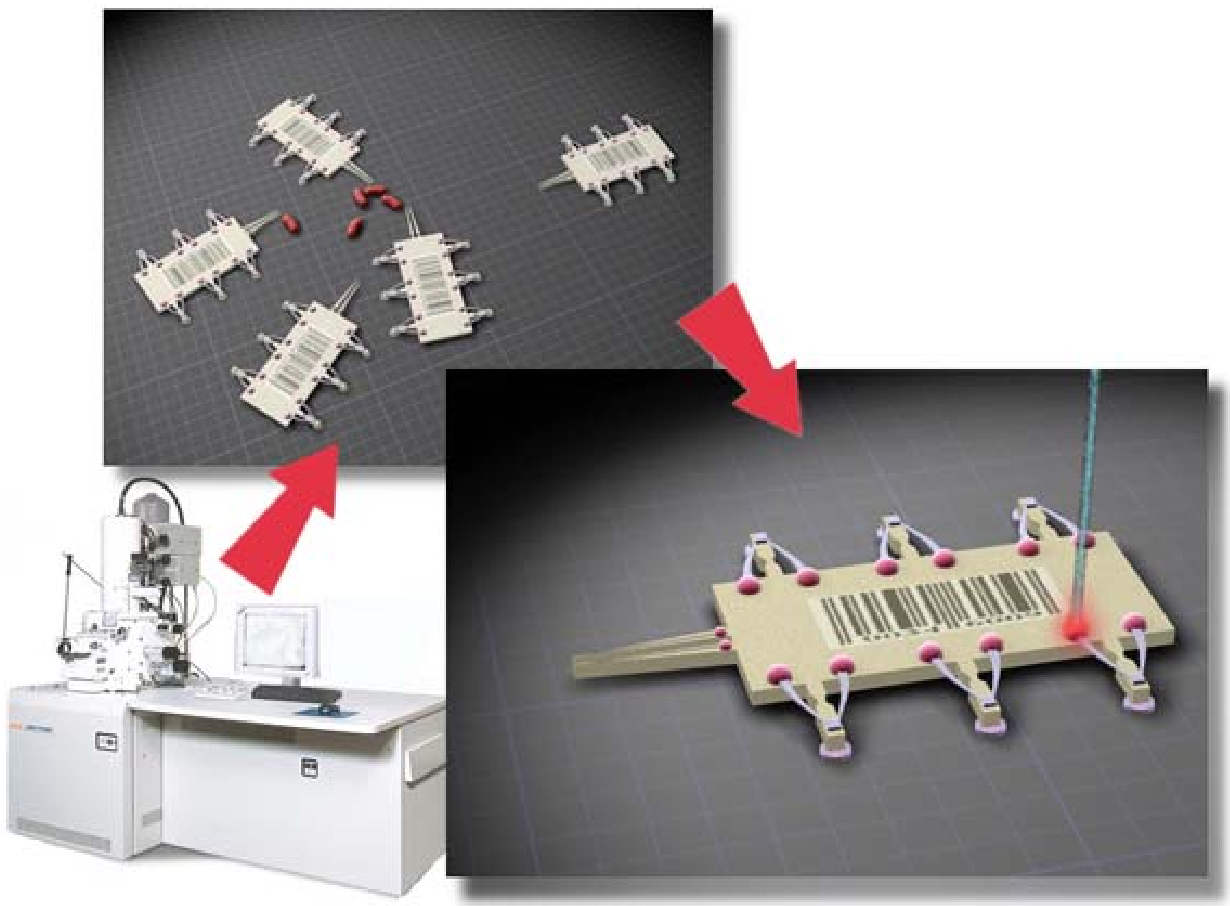
However, these devices are still limited to .1 mm (100 microns) at the low end. This limitation is caused by the need to use wires or tubes delivering energy for microscope heating. For devices in the sub-micron range (under 100 microns), there is currently no practical way to fabricate wires or tubes that are thin enough and strong enough to create a reliable electrical connection, especially for devices that move.

The breakthrough: Wireless shape-memory microactuators

Inventor Ken Clements, working with Technology Innovations, developed a breakthrough solution to this impasse: using an electron beam (a photon beam such as a laser or a phonon or sound beam can also be used) instead of wires to deliver the precise heat energy needed to trigger a heat-based SMA microactuator[10], as confirmed by research at TiNi Alloy[11]. An electron beam can be precisely focused down to tenths of a nanometer and the beam can be rapidly moved to an exact location to activate the desired SMA device.

This landmark invention is described in United States Patent #6,588,208, "Wireless technique for microactivation[12]," issued July 8, 2003.

Using an electron beam (e-beam) from a scanning electron microscope (SEM), a micro-robot created from an SMA thin film can now be sized as small as 2 microns wide by 10 microns long. That's 50 times smaller than what's feasible with current microactuator technology.



Click image for full-size illustration

Artist concept of wireless heat-based SMA* micro-robot *with gripper for 100 nm objects and "legs" for mobility. Purple dots are targets heated by the e-beam; they then

conduct the heat to the SMA "muscles" in the legs and gripper to generate the programmed movement.

Such a micro-robot, positioned on an electron microscope stage, can have grippers capable of grasping and moving objects as small as 100 nm, such as a DNA molecule or a crystalized building-block molecule.

Here's how: The grippers grip the object when cool. If you heat the microtweezer arms with a precisely timed series of e-beam pulses, it bends outward and releases the object.

You can also move the microbot in any direction. If you heat one of the two SMA "muscles" on the micro-robot's "legs" while simultaneously letting the other muscle cool, and do the same on the other side of the micro-robot, you can make the micro-robot "walk" in a chosen direction – similar to how a rowing team moves a boat[13].

The action and movement of the micro-robot can be precisely controlled by CAD (computer aided design) software in a PC that is connected to the e-beam device. The software will direct the e-beam to send a series of pulses.

The same e-beam microscope will also be used to image the micro-robot, so the experimenter can have continuous feedback on a CRT of the microbot's position and actions.

Uses of micro-robots

There are many important applications for micro-robots. Here are a few:

- Building medical devices such as valves and stents that are 100 times smaller than current technology

- Building tinier remotely controlled microsurgical instruments that can progress through the bloodstream and do noninvasive surgery such as in vivo catheterization for endovascular deposition of thrombogenic materials or microbiopsy of vessel walls (brings the "Incredible Voyage" scenario one step closer)

- Fabricating biochips for security uses

- Fabricating miniaturized molds that can turn out parts in a microfactory

- Manipulating proteins and genetic components

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[1] "Nanoscale" generally refers to objects less than 100 nanometers in size. A nanometer is one billionth of a meter.

[2] Micron = 1 millionth of meter.

[3] Principle of Scanning probe microscopy, http://www.physics.leidenuniv.nl/sections/cm/ip/group/Principle_of_SPM.htm

[4] Nanometer (nm) = 1 billionth of a meter. 1000 nm = 1 micron. Millimeter (mm) = 1,000th of a meter. A human hair is around 100,000 to 300,000 nm (.1 to .3 mm).

[5] Scanning Tunneling Microscopy, IBM Almaden Research Center Visualization Lab, http://www.almaden.ibm.com/vis/stm/

[6] Richard Feynman first articulated this principle in "There's Plenty of Room at the Bottom," http://www.resonancepub.com/feynmann.htm:

"Now, I want to build much the same device---a master-slave system which operates electrically. But I want the slaves to be made especially carefully by modern large-scale machinists so that they are one-fourth the scale of the ``hands" that you ordinarily maneuver. So you have a scheme by which you can do things at one- quarter scale anyway---the little servo motors with little hands play with little nuts and bolts; they drill little holes; they are four times smaller. Aha! So I manufacture a quarter-size lathe; I manufacture quarter-size tools; and I make, at the one-quarter scale, still another set of hands again relatively one-quarter size! This is one-sixteenth size, from my point of view. And after I finish doing this I wire directly from my large-scale system, through transformers perhaps, to the one-sixteenth-size servo motors. Thus I can now manipulate the one-sixteenth size hands.

"Well, you get the principle from there on. It is rather a difficult program, but it is a possibility. You might say that one can go much farther in one step than from one to four. Of course, this has all to be designed very carefully and it is not necessary simply to make it like hands. If you thought of it very carefully, you could probably arrive at a much better system for doing such things."

[7] Michael B. Cohn, Karl F. Böhringer, J. Mark Noworolski, Angad Singh, Chris G. Keller, Ken Y. Goldberg, and Roger T. Howe. Microassembly Technologies for MEMS. http://citeseer.nj.nec.com/rd/84820478%2C293432%2C1%2C0.25%2CDownload/http://citeseer.nj.nec.com/cache/papers/cs/14545/http:zSzzSzwww.ee.washington.eduzSzfacultyzSzkarlzSzPublicationszSzspie98.pdf/cohn98microassembly.pdf

[8] A. D. Johnson, "Vacuum-Deposited TiNi Shape memory Film: Characterization and Applications in Micro-Devices," J. Micromech. Microeng. 1(1991) 34-41.

[9] http://www.sma-mems.com

[10] The estimated energy required to actuate a TiNi specimen measuring 4 x 10 x 100 microns by heating it from the room temperature to the transition point is about 1.3×10^{-5} joules. The power available from the electron beam is 2×10^{-3} watt (for

accelerating voltage ~20 KV and beam current ~10^{-7} A), so the estimated heating time is ~6×10^{-3} sec.

[11] *A. D. Johnson, M. Fanucchi, V. Gupta, V. Martynov, V.Galhotra, K. Clements.* "TiNi as a nano-actuator: experimental verification of excitation by electron-beam heating." Presented at NanoSpace 2000 - Advancing the Human Frontier.
http://www.nanospace.systems.org/ns_2000/NS00_agenda.htm
http://www.innovation-on-demand.com/Papers/Nanoactuation_Paper.htm

[12] innovation-on-demand.com/nano.pdf

[13] This is functionally similar to a much larger (15x5 mm) micro-robot described in Thorbjörn Ebefors*, Johan Ulfstedt Mattsson, Edvard Kälvesten and Göran Stemme. "A WALKING SILICON MICRO-ROBOT." Presented at The 10th Int Conference on Solid-State Sensors and Actuators (Transducers'99), Sendai, Japan, June 7-10, 1999, pp 1202-1205. http://www.s3.kth.se/mst/research/publications/1999/tetrans_99pp1202_1205.html