Whither Microbots?

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Abstract

In the past few years there has been a great deal of discussion about the feasibility and desirability of developing microminiature robots which could be deployed en masse to do useful tasks. We attempt to examine some of the important issues involved in such a would-be endeavor, including matters of scale and controllability.

Robots require considerable computational resources to be adaptive and flexible. Microscopic robots require no less, and this fact is highly problematic. In lieu of truly small robots, it would seem that the enlistment of naturally occuring or genetically modified organisms or biomolecular approaches would have distinct advantages.

In the near term, and perhaps even very far term, it would seem that improvements in macroscopic-sized micro-motion robots and teleoperation systems which couple humans to such robots will be extremely important. In this regard, for example, scanned probe microscopy has made stunning progress in recent years in the imaging, analysis, and manipulation of mesoscale and atomic scale structures, yet the instruments themselves are very "macroscopic." There appears to be a promising role for MEMS as components for such systems.

In this Keynote Lecture, I present several examples from the research community that illustrate these themes, including work from our own laboratory on miniature modular robots for precision (micron level) assembly and high-fidelity haptic interface devices based on Lorentz magnetic levitation.

1 Background

Ever since the Micro Robots and Teleoperators Workshop was held in Hyannis in 1987, there has been an accelerated mixture of exciting technical advances, progress in scientific understanding of small structures, and rife speculation as to where it may all lead. Predictions that microscopic robots would soon be coursing through our blood streams busily repairing damage, and swarms of intelligent mechanical creatures would soon be collaborating in ant-like fashion assembling new products to revolutionize manufacturing abounded in the popular press. Gnat robots [1] and nano-machinery [2] suddenly became the rage.

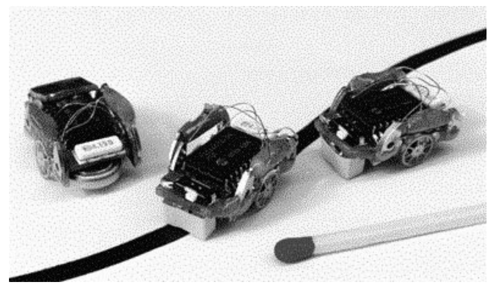

Figure 1: Tiny line-following robots from ETH Zurich.

Funding initiatives began in Japan, Germany, the United States [3]* and other countries, and a number of journals, symposiums, and conferences dealing with the emerging field began popping up.

2 Teensy Tiny Robots†

It is a really neat idea to try to make robots as small as possible, requiring formidable challenges to be overcome. In meeting these challenges, technical progress is made along many dimensions.

Small robots are beginning to appear. Recent examples include ant-like robots at Massachusetts Institute of Technology [4], small line-following machines at ETH Zurich [5] (Fig. 1) and small machines made by Epson and Toyota in Japan. Group behavior of small robots, *e.g.* [6, 7] is under active investigation.

First of all, there are simple laws of scaling [8] to be considered. Actuators and energy storage for an elephant are not appropriate for an ant [9] and *vice-versa*. Second, in the micro world, gravity is no longer the dominant force. Electrostatic, van der Waals, and surface tension forces [10] cause everything to want to stick to everything else.

Beyond these considerations is the observation that robots require considerable computational resources to be adaptive and flexible. Microscopic robots require no less, and this fact is highly problematic. For example, presently the silicon die area of a Pentium processor is considerably larger than

*I was pleased and honored to participate in some of this process.

†Micro robots, or "microbots," for short.

that needed by a micromechanical sensor or actuator. Furthermore, generally speaking, the smaller the sensor or actuator, the higher its bandwidth. This implies higher control rates in the microbot which ultimately translates into additional computational silicon.

Accordingly, this strongly argues for the use of communication and off-board intelligence to bridge the gulf between the micro and macro world (Sec. 4), or else the use of alternative electromechanical, chemical, or biological computation processes.

In lieu of truly small robots, it would seem that the enlistment of naturally occuring or genetically modified organisms or biomolecular approaches would have distinct advantages. Examples in medicine such as leech therapy and maggot debridement therapy [11] are experiencing a resurgence of interest. In wound treatment, for example, the maggots eat away only the dead tissue, leaving behind healthy tissue in a manner pretty difficult to imagine being done by swarms of small robots!

Micro Electro Mechanical Systems (MEMS) technology with its elegant and rapidly advancing silicon, SIO_2, and LIGA processes offer the pathway to ever-smaller components for tiny robots. Many problems remain, including the essentially planar nature of these processes. Interesting developments include folded hinge structures [12] offering greater design flexibilities.

3 Smallish Robots Doing Tiny Jobs

We concern ourselves here with micro-motion robots. In recent years, it has been shown that quite macroscopic-sized machines are capable of exceedingly small (nm and below) motions even in the presence of thermal noise and external vibration. This is done by clever design, high-speed digital control and advances in sensor and actuator materials.

For example, a problem with conventional serial-kinematic industrial robots is their limited resolution and repeatability in automated assembly operations. It was demonstrated that many of these limitations could be overcome by incorporating a fine motion robot at the last link of the robot arm. A direct-drive electromagnetic three degree-of-freedom fine positioner was developed which exhibited large payload capacity, 200 nm (3σ) motion resolution, and 50 Hz position band width [13]. This performance was two orders of magnitude improvement over the robot arm alone, enabling several kinds of precision electronic assembly.

Probably the best examples of micro-motion robots, however, are the scanning tunneling microscope (STM) and its many cousins, including the atomic force microscope (AFM). These devices have opened a fabulous window into the micro world that continues to elucidate the nature of surfaces and quantum interactions at the atomic scale. More recently, they have been used for much more than just looking; they are being used for direct manipulation of microscopic objects including individual atoms.

In 1990, Eigler and his colleagues at the IBM Almaden Research Center succeeded in manipulating Xe atoms on a Ni surface at low temperatures. A famous demonstration was the very tedious job of writing the letters IBM using 35 Xe atoms. More recently, many other atomic species have been used. In Fig. 2, the atoms spell out their name in Kanji for your viewing pleasure (see [14]).

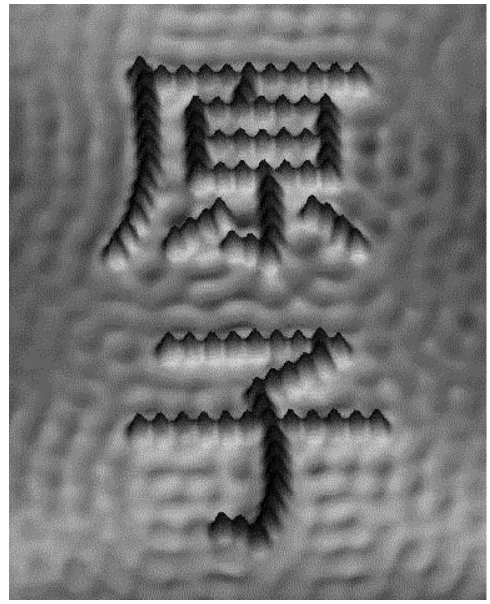

Figure 2: Arrangement of Fe atoms on Cu (Lutz and Eigler).

It has been shown that specially prepared large organic molecules can be manipulated on metal surfaces at room temperature, allowing molecule-by-molecule construction of new compounds [15].

4 Reaching Into the Micro World

A most interesting trend is the strategic incorporation of MEMS structures and devices into small machines, greatly improving all manner of scanned probe microscopies.

Other researchers are building bridges between the macro world and the micro world so that real-time interactivity with human– or machine–supplied intelligence can be brought to bear.

It was demonstrated In 1990 that atomic-scale landscapes could be explored and felt with the hand in real time by interfacing a haptic feedback device with an STM [16]. Figure 3 illustrates this concept: the hand holds a sharp probe which is moved manually over a surface; as the probe is moved laterally by the person, it moves vertically in relation to atomic-scale features. Lateral movements of the hand are scaled down by factors of 10^5 to 10^6 for the STM; vertical motion of the STM tip is scaled up by 10^6 to 10^8 in order to be felt by the hand. Clusters of as small as 10 Au atoms could be reliably felt.

More recently, workers at University of North Carolina have succeeded in feeling individual atoms and in manipulating virus particles [17].

In any such scaled telemanipulation system, there is a part that deals with the micro world, and a part that deals with the macro world, *e.g.* a user's hand. In the Microdynamic Systems Laboratory at

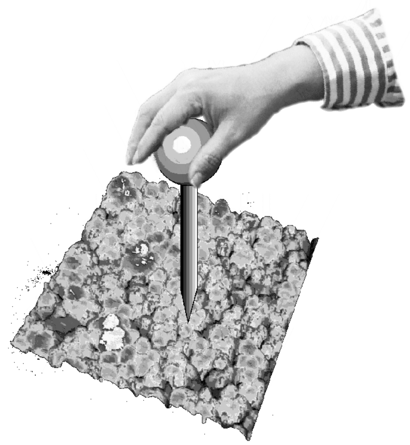

Figure 3: Feeling atomic landscapes by telemanipulation (see text).

Carnegie Mellon University, we are developing high-performance six-degree-of-freedom haptic interface devices based on Lorentz magnetic levitation [18]. Primarily intended for interaction with virtual environments, it is hoped this new device will also be appropriate as a telemanipulation "master," especially in scaled systems, because of its design which uses a single, frictionless moving part with "direct drive" high resolution (3 μm), high frequency ($\sim$90 Hz) response characteristics. Figure 4 is a cutaway view of the device. There is a handle, manipulated by the user, attached to a "flotor" containing coils. The flotor is immersed in strong fields created by permanent magnet circuits in the inner and outer stators. Optical sensors measure the translation and rotation of the flotor over a range matched to the comfortable motion range of the fingertips with the wrist stationary.

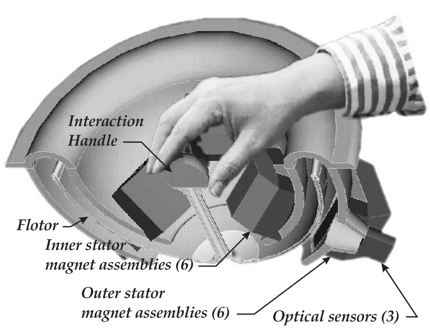

Figure 4: New desktop magnetic levitation haptic interface device (under construction).

5 Miniature Factories

In keeping with the theme of smallness, I would like to finish with one more topic. In recent years, a multitude of products have shrunk in size while vastly increasing in functionality. Examples include magnetic and optical storage devices, palmtop computers, and "mechatronic" subassemblies of larger products.

Parts for these products have become too small to be reliably handled by humans, and conventional automation is having a hard time keeping up. Accordingly, we have asked "why not shrink the factory to a size more appropriate to its mission?"

We are developing an "Architecture for Agile Assembly" (AAA) with goals of drastically reducing factory design, deployment, and programming times; increasing alignment precision from today's 50–100 μm to around 1 μm anywhere within the factory; and reducing factory size by a factor of 10 [19].

To support this framework we are creating families of small, precision two-degree-of-freedom robots that will comprise key elements of miniature factories, or "minifactories" [20]. One type is based on closed-loop planar linear motor "courier" robots that carry subassemblies through the minifactory; another type is a "manipulator/feeder" vertical/rotary motion robot that places parts on the subassemblies. These two types of robots interact cooperatively to form transient four-degree-of-freedom robots emulating the actions of conventional SCARAs. Figure 5 is a thumbnail sketch of a minifactory containing several of these modular, networked robots.

In later stages, these minifactories may serve as *factory-level* platforms for incorporation of MEMS devices such as parts grippers.

6 Conclusion

We began with the question "Whither [**hwi***th*'**ər**] (*adv.* 1. To what place? Where? 2. To what end, point, action or the like? To what?) Microbots [**mī' kro bäts**] (*n.* Very tiny, itsy-bitsy robots)?"—and have run out of space long before finding the answer. Therefore, I will merely conclude by observing that the pace of technological change is so rapid that many things considered unlikely today may well seem plausible tomorrow. In any case, I'm betting that small machines of all types will play important roles in our future.

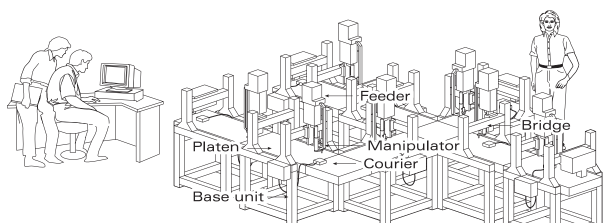

Figure 5: Simplified general view of a minifactory showing modular robotic elements. Seven manipulator/feeders, six couriers, and several overhead processing units are shown.

References

[1] A. M. Flynn, "Gnat robots (and how they will change robotics)," in *Proc. IEEE Micro Robots and Teleoperators Workshop*, (Hyannis, Mass.), November 9-11 1987.

[2] K. E. Drexler, "Nanomachinery: atomically precise gears and bearings," in *Proc. IEEE Micro Robots and Teleoperators Workshop*, (Hyannis, Mass.), November 9-11 1987.

[3] K. Gabriel, J. Jarvis, and W. Trimmer, "Small machines, large opportunities: a report on the emerging field of microdynamics," tech. rep., National Science Foundation Workshop on Microelectromechanical Systems Research, 1988.

[4] J. McLurkin, "The ants: a community of microrobots." World Wide Web http://www.ai.mit.edu/projects/ants/, 1996.

[5] anonymous, "Small robots at ETH, Zurich." World Wide Web http://www.ifr.mavt.ethz.ch/ifrPhoto/, 1996.

[6] N. Mitsumoto and et al., "Micro autonomous robotic system and biologically inspired immune swarm strategy as a multi-agent robotic system," in *Proc. IEEE Int'l. Conf. on Robotics and Automation*, pp. 2187–2192, 1995.

[7] B. B. Werger and M. J. Mataric, "Robotic food chains: externalization of state and program for minimal-agent foraging," in *Proc. From Animals to Animats 4, Fourth Int'l Conf. on Simulation of Adaptive Behavior (SAB-96)*, 1996.

[8] I. Shimoyama, "Scaling in microrobots," in *Proc. IEEE/RSJ Int'l. Conf. on Intelligent Robots and Systems*, vol. 2, (Pittsburgh), pp. 208–211, August 5-9 1995.

[9] J.-D. Nicoud, "Microengineering: when is small too small? Nanoengineering: when is large too large?," in *Proc. 6th Int'l. Symp. on Micro Machine and Human Science*, (Nagoya), pp. 1–6, October 4-6 1995.

[10] R. S. Fearing, "Survey of sticking effects for micro parts handling," in *Proc. IEEE/RSJ Int'l. Conf. on Intelligent Robots and Systems*, vol. 2, (Pittsburgh), pp. 212–217, August 5-9 1995.

[11] R. A. Sherman and E. A. Pechter, "Maggot therapy: A review of the therapeutic applications of fly larvae in human medicine, especially for treating osteomyelitis," *Medical and Veterinary Entomology*, vol. 2, no. 3, pp. 225–30, 1988.

[12] K. S. J. Pister, M. W. Judy, S. Burgett, and R. fearing, "Microfabricated hinges," *Sensors and Actuators A*, vol. 33, pp. 249–256, 1992.

[13] R. L. Hollis and R. Hammer, "The fine positioner: a robotic tool for precise planar motion," *Industrial Robot*, vol. 19, no. 5, pp. 22–25, 1992.

[14] M. F. Crommie, C. P. Lutz, and D. M. Eigler, "Confinement of electrons to quantum corrals on a metal surface," *Science*, vol. 262, pp. 218–220, 1993.

[15] T. A. Jung, R. R. Schlitter, J. K. Gimxewski, H. Tang, and C. Joachim, "Controlled room-temperature positioning of individual molecules: molecular flexure and motion," *Science*, vol. 271, pp. 181–184, 1996.

[16] R. L. Hollis, S. Salcudean, and D. W. Abraham, "Toward a tele-nanorobotic manipulation system with atomic scale force feedback and motion resolution," in *Proc. IEEE Symp. on Micro Electro Mechanical Systems*, (Napa Valley, CA), pp. 115–119, February 11-14 1990.

[17] M. Falvo, R. Superfine, S. Washburn, M. Finch, R. M. Taylor, V. L. Chi, and F. P. B. Jr., "The nanomanipulator: A teleoperator for manipulating materials at the nanometer scale," in *Proc. Int'l. Symp. on the Science and Technology of Atomically Engineered Materials*, (Richmond, VA), World Scientific Publishing, Oct 30 - Nov 4 1995.

[18] P. J. Berkelman, Z. J. Butler, and R. L. Hollis, "Design of a hemispherical magnetic levitation haptic interface device," in *Proc. ASME Symposium on Haptic Interfaces*, (Atlanta), November 17-22 1996. to be published.

[19] R. L. Hollis and A. Quaid, "An architecture for agile assembly," in *Proc. Am. Soc. of Precision Engineering, 10th Annual Mtg.*, (Austin, TX), October 15-19 1995.

[20] A. Quaid and R. L. Hollis, "Cooperative 2-DOF robots for precision assembly," in *Proc. IEEE Int'l Conf. on Robotics and Automation*, (Minneapolis), May 1996.