New Technologies and Applications in Robotics

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Material transfer robots first appeared in the mid-1960s for use in traditional industrial applications. By the 1980s, robots found use in more demanding industrial applications such as welding, assembly, and inspection, with the help of vision and other sensors. It is estimated that 46,000 industrial robots have been installed in the U.S. Japan has six to eight times as many robots.

While the industrial applications of robots will continue to grow, technologies for new applications of robotic systems are emerging. Robots have evolved from relatively simple programmable pick-and-place devices into a new generation of competent robot systems. Robotic sciences are becoming a discipline, and the investment in prior research has yielded a wide range of component technologies which are the foundation for the next generation of robotic systems.

Naturally, the field of robotics is vast—incorporating perception (sensors and transducers), cognition (computation, planning, and learning), and manipulation (mechanisms, kinematics, dynamics, and control). Robotics applications are pervasive, encompassing manufacturing, transport, and exploration, to name just a few. A comprehensive description of interesting robotics technologies and applications would thus fill many volumes. Here, we focus on three new areas which are under investigation at Carnegie-Mellon: autonomous mobile systems for outdoor and hazardous environments, robot-assisted shape deposition manufacturing, and microelectromechanical systems for medical and other applications.

Outdoor Mobile Robots

Removing sensor-based robots from manufactured indoor environments, in which they have traditionally operated, and placing them in outdoor natural environments presents new challenges. Outdoor robots must negotiate rugged terrain, deal with objects of complex shape, and operate with natural lighting conditions. It is difficult to structure a natural environment so that robots can easily interpret its surrounding. Instead, robotic systems must be developed which are robust in the given environment. Several examples are described:

Vision-based autonomous driving. Development of autonomous vision-guided vehicles has attracted much attention throughout the world, and significant progress has been made. Major activities include the Advanced Research Project Agency's Autonomous Land Vehicle (ALV) and the Unmanned Ground Vehicle (UGV) programs in the U.S., Eureka's Prometheus project in Europe, and MITI's Personal Vehicle project in Japan.

Autonomous driving requires all aspects of robotics: perception, planning, mechanisms, computing, and integration. The Navlab, developed at Carnegie-Mellon University (CMU) is a representative system addressing all these aspects [15]. The Navlab I vehicle, shown in Figure 1, was built in 1986 to provide a test bed for vision and navigation experimentation. It is based on a standard commercial van, with a suite of onboard sensors including several video cameras, a scanning laser range finder, a global positioning system, an inertial navigation system, and sonar. It also carries multiple computer systems—currently four Sun 4 computers, as well as a massively parallel processor (MASPAR). Recently, a more capable test-bed vehicle, Navlab II, has been added, which is based on a HMMWV (high-mobility multipurpose wheeled vehicle) ambulance.

The Navlab has demonstrated a range of capabilities for both on-road and off-road autonomous naviga-

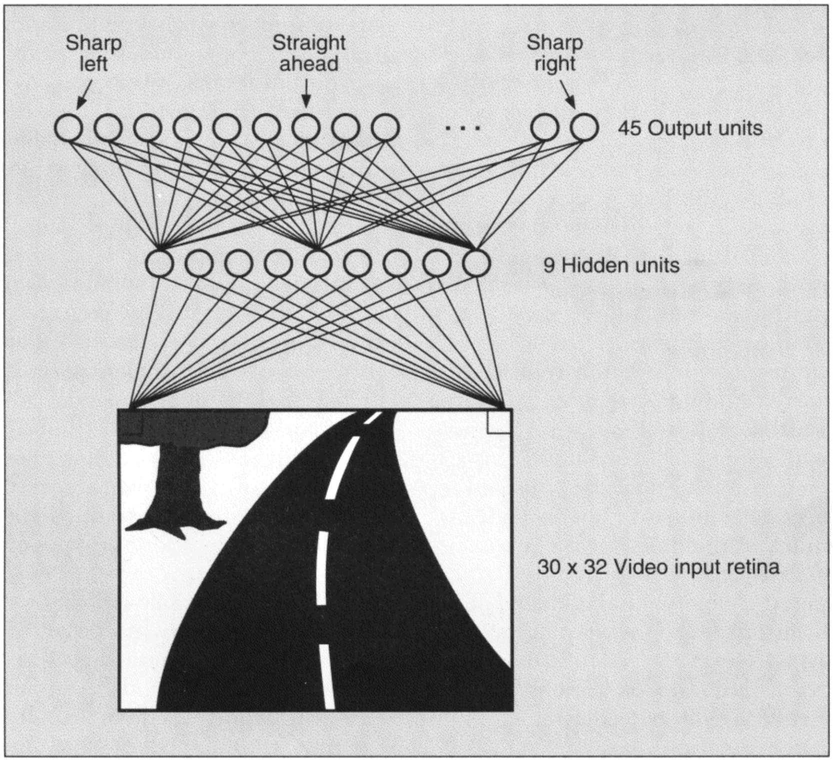


Figure 1. NAVLAB I—An autonomous vehicle, incorporating all aspects of robotics, including perception, planning, mechanisms, computing, and integration.

Figure 2. ALVINN—Autonomous Land Vehicle In a Neural Network

tion. One type is automatic road following (driverless driving) by use of color vision. The ALVINN (Autonomous Land Vehicle In a Neural Net) [13] is a fully connected three-layer backpropagation network, whose input is image information from a video camera and whose output is the vehicle heading required to stay on the road, as shown in Figure 2. The output is updated 15 times per second. The ALVINN network is trained using a unique "on-the-fly" procedure. Road images are processed as the vehicle is driven by a person down a highway. Vehicle heading, as steered by the human

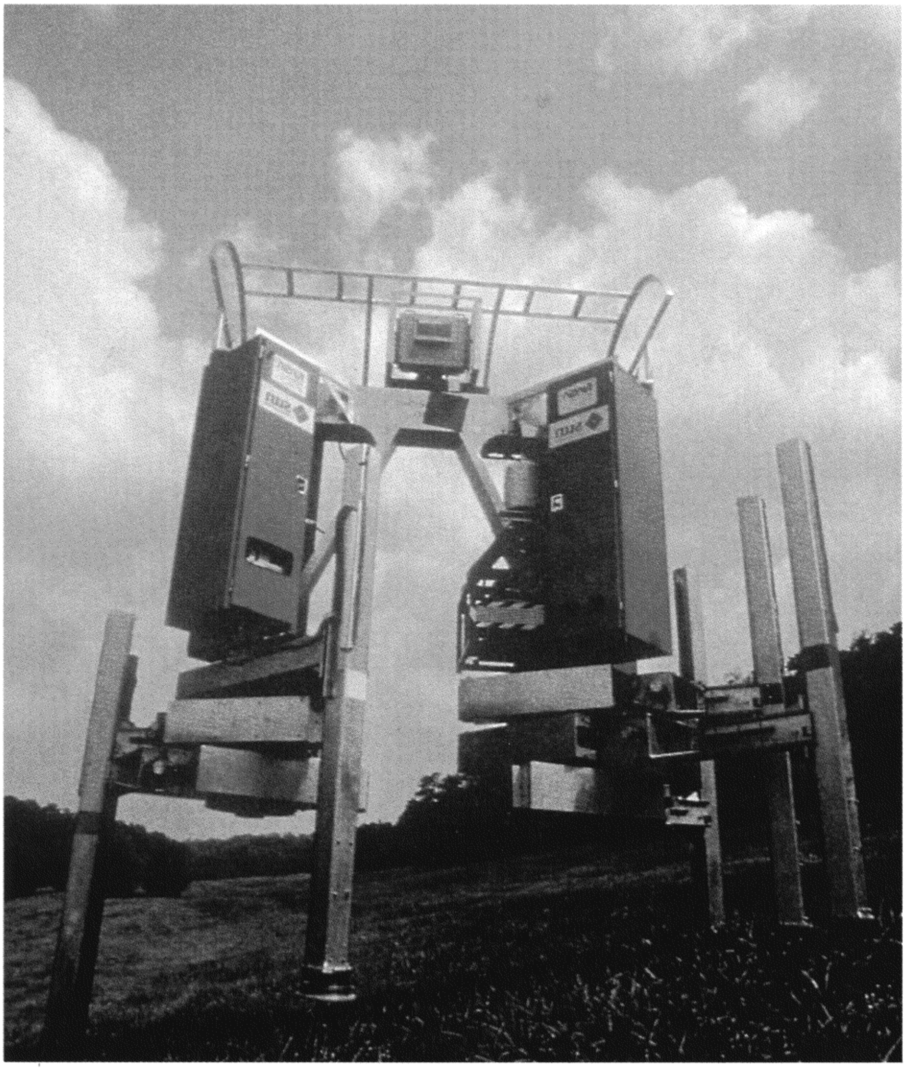


Figure 3. AMBLER—An autonomous, six-legged robot designed to explore the surface of Mars.

driver, provides the feedback necessary for training. Each road image, with its associated vehicle heading, is modified through a series of transformations to simulate a broader class of situations. For example, the raw image is translated laterally to produce a view of the road which would be obtained from a laterally shifted position of the vehicle. The corresponding vehicle heading which is required to stay on the road is also adjusted accordingly. This jogging of the original data is necessary because humans drive "ideally" much of the time, yet for robust operation, the network must be exposed to many misalignments of vehicle heading that may occur. The ALVINN has successfully driven the Navlab vehicles on various types of road (paved, dirt, single-lane, multilane) in various weather conditions. The most recent experiment achieved autonomous driving at the speed of 55mph for a stretch of more than 90 miles on a highway near Pittsburgh.

In addition to road following by color vision, 3D-range images from the laser range finder are processed to detect obstacles, such as trees and rocks, for off-road navigation, and to recognize objects such as cars and mailboxes. An annotated map technique is used for specifying the route and instructions for actions to be taken at various locations on the route. Some of these capabilities will have a direct impact on the intelligent vehicle highway system that will use the vehicle's autonomy, road infrastructure, and communication for increasing safety and throughput of highways.

Robots for hazardous environments. The popular image of robots performing tasks in environments that are too remote or hazardous for humans is becoming the reality. Lunar and Mars missions proposed for this decade and the next include exploration of planetary surfaces by autonomous rovers. Planetary space probe rovers that can cover a much larger area than stationary landing platforms, such as Mars Vikings, require a certain degree of autonomy, since time delays in communication preclude teleoperation over interplanetary distances.

Projects at CMU include the AMBLER [1], a six-legged walker with a unique configuration to traverse challenging terrains autonomously (Figure 3), and DANTE [18], a semiautonomous teleoperated robot which recently attempted an exploration of Mt. Erebus in Antarctica (Figure 4). These mobile, perceptive robots hold the prospect to explore and sample planetary and other hard-to-access surfaces on behalf of humans. Their success motivates a class of robots with unprecedented ability for the autonomous, self-reliant exploration of rugged, barren terrains.

Autonomous mobile robots will also evolve for duty in terrestrial applications such as hazardous waste site characterization and reconnaissance. Successors to these exploratory robots will excavate, mine, and till the Earth and other planets. For example, REX, our robotic research excavator, uses range-based models to help plan interactions with natural materials such as soil and rock. Excavation is an example of a class of 3D tasks that defy preplanning and proceed in an exploratory mode. Significant advances in semiautonomous and teleoperated mobile vehicle control have already provided reliable and safe methods for nuclear damage recovery. The Remote Work Vehicle (RWV), Remote Reconnaissance Vehicle (RRV), and Remote Core Sampler (RCS), developed at CMU's Field Robotics Center, performed years of cleanup duty in the Three Mile Island Unit 2 reactor containment basement. The hazard of radiation exposure and the low productivity of manual service work combine to motivate additional robotic solutions for the nuclear industry for inspection, maintenance, and repair. Further research and development, however, is required to integrate suitable manipulation, locomotion, radiation, and environmental hardening to enable systems which are more self-reliant. The Robotics Institute is currently conducting a research project for the U.S. Department of Energy to develop a new generation of decontamination and decommissioning robotic technologies.

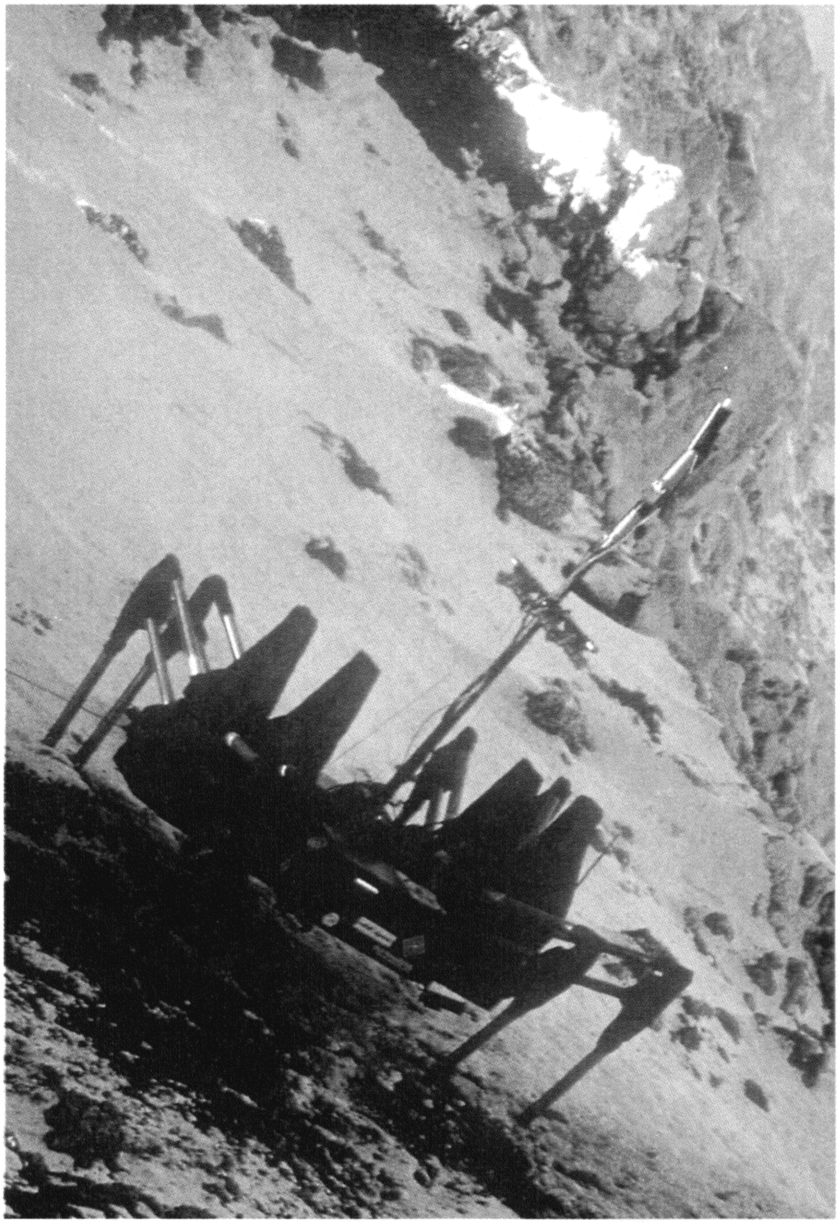
In addition to service for the nuclear industry, there are several other significant needs and opportunities for the next generation of robots. In the next decade we expect to see increased applications to chemical waste remediation and decontamination, site characterization and traversal, emergency response and operations in acute hazards, mining, agriculture, military vehicle and aircraft maintenance, ordinance disposal, security/surveillance, materials handling and combat engineering, and construction activities such as excavation, transport, extraction, and material handling.

Rapid Manufacturing

The ability to rapidly develop and manufacture new products to respond to changing market demands is the key to successfully competing in today's global markets. This requires several innovative manufacturing activities. For example, manufacturers require computer-aided manufacturing (CAM) systems which can quickly produce physical objects directly from computer-aided design (CAD) models with minimal human intervention. Such objects include both prototypes to speed the design process, and custom tooling such as injection molds for mass production.

Shape deposition. Shape deposition is an emerging set of CAD/CAM technologies, which will facilitate the goal of rapid manufacturing. Shape deposition processes build parts by incremental material buildup of thin layers. Each layer is

Figure 4. DANTE—A semiautonomous teleoperated robot, shown here descending into the Mt. Erebus volcano in Antarctica.



fused to the previously deposited layer, and the growing structure may be supported by solid sacrificial layers, in complementary shapes, eliminating the need for custom fixturing. The cross-sectional descriptions are generated by "slicing" a 3D CAD model into sections ("slices") which may vary in thickness [17]. Several alternative deposition materials and processes are available, including stereolithography, selective laser sintering, three-dimensional 3D printing, solid-ground curing, fused-deposition modeling, and recursive masking and deposition [2].

A principal advantage of shape deposition approaches is the ease and speed in going from part design to part fabrication, within a completely automated CAD/CAM environment. In contrast to computer numerically controlled machining, shape deposition processes operate on simple cross-sectional geometries and do not require part-specific fixturing or tooling information. The planning and execution effort for shape deposition is therefore essentially independent of the geometric complexity of a part. Operating the shape deposition apparatus also requires minimal human intervention. Even a part designer or computer programmer without machining skills can operate the equipment.

Robots play an important role in several demonstration shape deposition systems. Robotic thermal spraying integrated into rapid prototyping technology is a new method for fabricating a broad range of custom tooling. Materials, including metals, plastics, and ceramics, are melted in an arc plasma and sprayed onto patterned surfaces by a robot. The robot holds the spray gun and moves it along appropriate trajectories for optimum coverage. On contact, the sprayed material solidifies and forms a surface coating. Spray coatings can be built by depositing multiple fused layers which, when separated from the pattern, form a freestanding shell with the desired shape of the substrate surface. By mounting the shell in a frame and backing it with tooling epoxies, many artifacts can be fabricated, such as injection molds, forming dies, and electric discharge machining electrodes.

Figure 5 shows an example of the cavities of injection molds being fabricated by direct deposition of metal onto plastic stereolithography models of the desired part and then backing the framed shell with epoxy resins. In this application, the robotic spray trajectories are derived directly from the same CAD models used to plan the stereolithography process which produced the plastic model pattern [16].

Another technology developed at CMU is a robotic-assisted approach for directly spraying shapes layer by layer. This method uses iterative masking and deposition steps. The idea is to spray each layer, using a disposable stencil mask with the shape of the current layer cross-section [16]. Masks are produced from paper with a CO_2 laser. Robot trajectory planning for uniform layer deposition is critical [7].

This robotic thermal-spray approach was envisioned to rapidly create functional parts directly from CAD models. It has the potential to go beyond prototyping applications and can create novel structure that would not be feasible with conventional manufacturing processes. For example, composites with complex shapes can be formed; this results from the versatility of thermal spraying in depositing a wide variety of materials including composites and laminates of metals, plastics, and ceramics. Novel assemblies are also feasible, since masking allows selective material deposition within each layer. Therefore, different components can be formed and embedded in a single structure. For example, the fabrication and assembly of encapsulated electronic and mechanical structures, such as wearable computers, can be integrated into a single process [4]. Components such as heat pipes, heat sinks, electromagnetic interference shields, wires, and sensors can be sprayed in place while other components, such as integrated circuits and connectors, can be embedded in the sprayed structure. This technology allows for a packing density which is significantly greater than conventional hybrid assembly methods.

In the future, R&D efforts will focus on deposition processes to make available a wider range of materials with improved properties, and with greater deposition resolution. In the longer term we envision a complete manufacturing facility, which would include multiple deposition sources, as well as several conventional intermediate material-processing and inspection stations. For example, inspection is simplified in this scheme, since it is straightforward to continually measure and interpret the flat-top geometry of growing structures. Robotic transport systems, which move the growing shapes from station to station, and intelligent robotic deposition cells, will play an important role in robust and flexible automation.

Microelectromechanical Systems

The emerging technology of microelectromechanical systems, or MEMS, is likely to bring robotics and applications of robotics into an entirely new realm: the world of Lilliput.

Miniature actuators and sensors. Broadly speaking, we can say that MEMS are devices and systems whose physical dimensions are on the order of one mm or less, and whose operating principles depend in some way on mechanical properties, rather than strictly electronic properties. The origin of MEMS was the realization, many years ago, that the same techniques used to make the now ubiquitous integrated circuit could be applied to fabricate tiny mechanical elements. The techniques of silicon micromachining were developed to make miniaturized sensors and transducers, which are now used in many products. For example, a tiny mass on a cantilevered beam will deflect when accelerated. By detecting the change in piezoresistance arising from the stress in the beam, one can construct a miniature accelerometer; such devices are used to trigger air bags and seat belt tensioners in automobiles. This sensor technology has been the foundation for expanding the range of functions that can be performed in the microdomain. In addition to sensing their environment, MEMS have the ability to change and control the space around them.

Figure 5. Robotic thermal-spray deposition. a. CAD model of a fan blade, b. pattern built with stereolithography, c. robot spraying metal onto framed pattern, d. resulting injection mold tooling

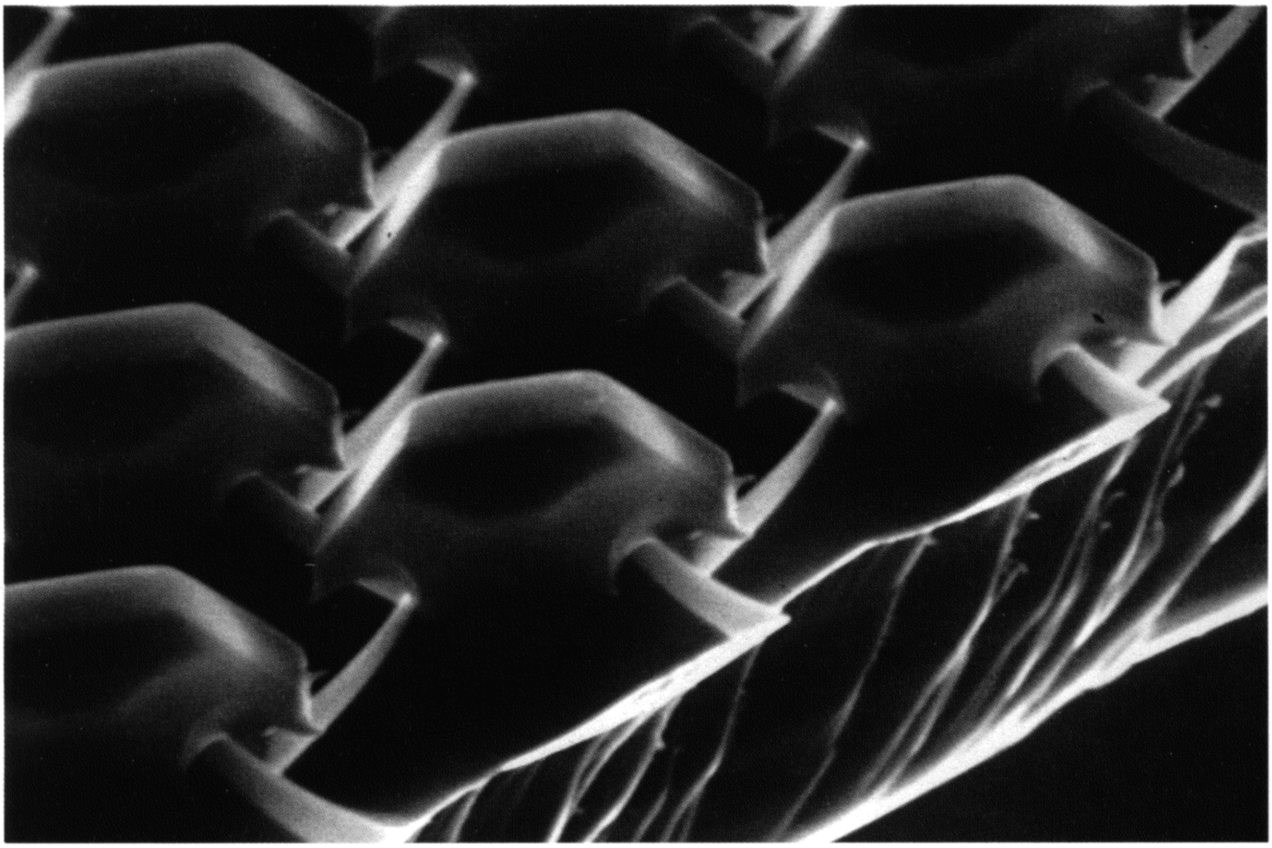


Figure 6. Micromechanical velcro structures formed by bulk micromachining [10]. These silicon and SiO_2 microstructures mate with like structures, forming a strong surface bond.

Two key developments are the development of miniature actuators, which convert electrical signals into mechanical motion, and the ability to merge both mechanical sensors and actuators with electronic control circuitry. These have the combined effect of making MEMS technology useful for complicated functions, rather than being just one component of a larger system. For example, it is possible to build tiny electrostatic motors, with rotors less than 50 μm in diameter, and electrostatically driven resonators which act as linear-drive oscillators. These devices could be integrated with sensors and sophisticated electronics so that the actuators can be controlled in real time, and thus perform useful functions.

Micromachining techniques. Although MEMS can be constructed with many different techniques, those based on silicon fabrication technology are among the most advanced. "Silicon micromachining" is the term applied to a broad array of fabrication methods that result in mechanical microstructures. This technique differs from conventional machining in that many devices are fabricated at once, in batches, and both additive and subtractive processes are common. There are two further categories: bulk and surface. In bulk micromachining, the final microstructures are formed by dissolving away large fractions of the thickness of a crystalline silicon wafer—which is about 200 to 600 μm thick. One can form pyramids, frustums, and cavities with dimensions from less than 1 μm up to a few millimeters. Typically, a bulk micromachined MEMS will undergo the following steps: an oxidation process to form an SiO_2 masking layer; one or more photolithographic steps to pattern the oxide mask; and a crystallographic silicon etch which defines the final structure. These steps are in addition to those forming any electronic devices or circuitry. (The micromechanical velcro structures shown in Figure 6 were fabricated with a bulk micromachining process.)

In surface micromachining, the silicon wafer is not etched, but instead acts as a substrate for the microdynamic elements, which are fashioned from thin films. Surface

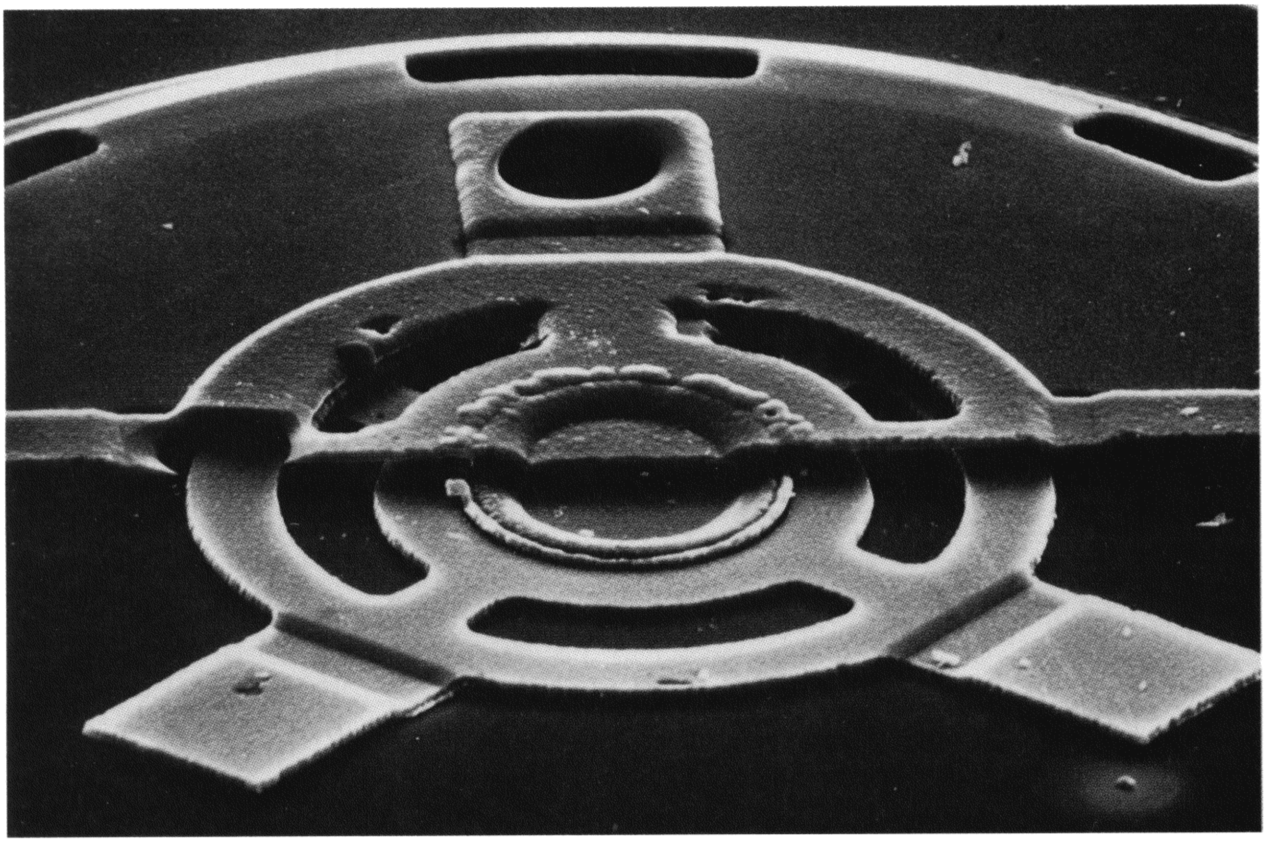


Figure 7. Micromechanical rotor, fabricated from three levels of polysilicon using a surface micromachining process. The rotor is about 300 μm across.

processes use multiple thin films of a structural material, generally polycrystalline silicon ("poly"), interspersed with a sacrificial layer, usually SiO_2. The idea is to pattern the various structural films into the desired shapes using photolithography, and then, as a final step, to dissolve away the sacrificial layers to "release" the structures. The films forming the structural elements are generally limited by the fabrication equipment to about 5 μm in thickness, but can be arbitrary sizes and shapes in the other two dimensions. Figure 7 shows a rotor fabricated by surface micromachining.

A distinguishing feature of MEMS is that the fabrication technology—be it bulk micromachining, surface micromachining, or nonsilicon techniques like LIGA or stereolithography—is inherently a parallel process and results in assembled systems. For example, precision machining tools can turn out thousands of sub-mm-scale gears and springs, but wristwatches are not considered MEMS, since the manufacturing process involves discrete assembly steps. The distinction between precision machining and MEMS technology is not always clear, but is a useful one to make because different economies of scale result for integrated systems. Viewed in this light, MEMS technology represents a new approach to manufacturing systems; MEMS are not simply macroscopic robotic systems made small.

Issues important to the field include: system applications, expansion of the user base, control of distributed systems, 3D structures, nonsilicon technology, and CAD. Several of these issues are interrelated. We consider each briefly in the following paragraphs.

Applications. A key issue in the field is the demonstration of appropriate applications. It is likely that some of the earliest applications will be in the area of invasive medical devices, since in medicine it is often necessary to have tools capable of operations at the cellular scale. Trends in surgery point toward laparoscopy, which requires innovative approaches to even simple problems. For example, in suturing tissues together, a common task is tying a knot. However, this simple operation

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takes on an unexpected complexity if the procedure is performed inside a laproscopic trocar, where it is very difficult to manipulate objects in three dimensions. MEMS technology holds the promise for microengineered tissue fasteners and specialized tools. The benefits would be tremendous [14].

One way to accelerate the use of MEMS technology in real applications is to expand the number of potential users. Today, a sizable fraction of MEMS technologists have come to the field by way of an interest or training in integrated circuits. While this kind of background is appropriate for appreciating the finer points of microfabrication, it does little to bring the potential of this technology to a wide audience. The clear demarcation between "design" and "process" in integrated-circuit manufacture has done much to popularize that technology. There exists an army of IC designers that need to know little about the actual process of microfabrication.

An analogous situation does not yet exist in MEMS. One idea is to establish regional centers, housing fabrication lines, design tools, and local expertise, to which users could come and build MEMS to solve their problems. Another idea is to provide a foundry service, patterned after the MOSIS custom IC service, which would take designs from many sites and merge them into a multiproject run. One difficulty with this is that the process/design paradigm is nowhere near as clearcut as is the case with ICs.

Distributed and 3D MEMS. Many of the current efforts in MEMS are focused on the design and development of single-actuator elements. Individual micron-scale actuators cannot provide sufficient forces, torques, or mechanical throws for many applications. For example, a potentially far-reaching niche for microrobotic actuators is in positioning the read/write head on a magnetic disk drive storage unit. The current generation of electrostatic actuators are not well suited to this task due to the relatively large head inertia. This and other applications need actuators capable of macroscopic motion at the mm scale. One way to create forces and throws at this scale is to design systems in which many actuation and sensing elements are integrated. Arrays of microelectromechanical elements, forming a distributed MEMS, are thus of considerable interest.

In much the same way an IC chip synergistically combines individual information storage elements, one can obtain higher-order functionality in a MEMS when large numbers of microscopic components are massed together. The central problems of distributed MEMS involve integration and control. For example, how does one integrate the information from individual sensor elements, in a system consisting of thousands or millions of such elements, into a coherent whole? Or, how is a global, macroscopic end effect broken down into the individual instructions for each actuator element? Many such problems exist in a distributed MEMS. These problems are not merely scaled-up versions of individual actuator issues, but are fundamentally different in character.

A key technological challenge in MEMS is the ability to fabricate true 3D structures of arbitrary shape [5, 6, 8, 9]. For historical reasons, many microfabrication tools are optimized for the particular requirements of IC manufacturing, where the driving force is to make structures thinner, and thus more two-dimensional. Conventional photolithographic tools offer a nearly unlimited range of pattern scales in the plane of the substrate, but have very limited range in the orthogonal direction. This drawback has fueled research in alternative fabrication technologies more suited to MEMS.

Nonsilicon technology. Related opportunities exist in nonsilicon technology. A considerable amount of micromachining work has been based on silicon substrates, for several reasons, including the following: silicon is inherently a good mechanical material [12]; anisotropic etching techniques offer much latitude in producing complex and precise shapes [3, 11]; and microelectronic systems can be integrated on the same substrate. However, there is no reason to strictly limit MEMS to what can be fabricated in silicon. To take again the example of medical applications, one can imagine reasons why another material would be more appropriate. For instance, something more yielding than silicon might be needed to be compatible with pulsating blood vessels. Or, it might be advantageous to construct a device from a biodegradable polymer that slowly dissolves over time. MEMS fabricated using processes other than standard planar silicon technology are likely to become important in the future.

Tools. Finally, there is a need for CAD and manufacturing tools geared specifically to MEMS. For this technology to gain a foothold in a larger user community, it is important to automate the more onerous design and visualization tasks. For example, it is possible to use CAD tools to lay out the patterns for an integrated circuit from a high-level description of the system function and then use the layouts to extract performance simulations. The same level of sophistication should be possible for MEMS, since both the electrical and the mechanical responses are important. The availability of such tools would enable designers to short-circuit the design/fabricate/test/redesign iteration sequence.

Summary

The popular vision of robots as androids with the physical power, dexterity, and intellect of humans is far from realization. New technologies, only a few of which have been touched on here, are needed to approach this goal. Smaller and more powerful actuators, stronger and lighter materials, vastly increased processing power, sensors with higher bandwidth and resolution, and manufacturing and control strategies for reliably integrating all of these will be forthcoming as robotics moves into the next millennium. C

References

1. Bares, J. Configuration of autonomous walkers for extreme terrain. Ph.D. dissertation, Civil Engineering Dept., Carnegie-Mellon Univ., Pittsburgh, Pa., 1991.
2. Beaman, J.J., Marcus, H.L., Bourell, D.L. and Barlow, J.W., Eds. In *Proceedings of The Solid Freeform Fabrication Symposia.* The University of Texas at Austin, 1990–1992.
3. Bean, K.E. Anisotropic etching of silicon. *IEEE Trans. Electr. Dev. ED-25,* 10 (1978), 1185–1193.
4. Beck, J.E., Prinz, F.B., Siewiorek, D.P. and Weiss, L.E. Manufacturing mechatronics using thermal spray shape deposition. In the *Solid Freeform Fabrication Symposium.* The University of Texas at Austin, 1992.
5. Bloomstein, T.M. and Ehrlich, D.J. Laser-chemical three-dimensional writing of multimaterial structures for microelectromechanics. In the *IEEE Workshop on Micro Electro Mechanical Systems (MEMS-91),* (Nara, Japan). IEEE, New York, 1991, pp. 202–203.
6. Ehrfeld, W., Bley, P., Götz, F., Hagmann, P., Maner, A., Mohr, J., Moser, H.O., Münchmeyer, D., Schelb, W., Schmidt, D. and Becker, E.W. Fabrication of microstructures using the LIGA process. In the *IEEE Micro Robots and Teleoperators Workshop* (Hyannis, Mass.). IEEE, New York, 1987.
7. Fasching, M.M., Weiss, L.E. and Prinz, F.B. Optimization of robotic trajectories for thermal spray shape deposition. EDRC 24-74-91, The Engineering Design Res. Center of Carnegie-Mellon University, Pittsburgh, Pa., 1991.
8. Frazier, A.B., Allen, M.G. High aspect ratio electroplated microstructures using a photosensitive polyimide process. In the *IEEE Workshop on Micro Electro Mechanical Systems (MEMS-92),* (Travemünde, Germany). IEEE, New York, 1992, pp. 87–92.
9. Guckel, H., Skrobis, K.J., Christenson, T.R., Klein, J., Han, S., Choi, B. and Lovell, E.G. Fabrication of assembled micromechanical components via deep X-ray lithography. In the *IEEE Workshop on Micro Electro Mechanical Systems (MEMS-91),* (Nara, Japan). IEEE, New York, 1991, pp. 74–79.
10. Han, H., Weiss, L.E. and Reed, M.L. Micromechanical velcro. *IEEE J. Microelectromech. Syst. 1,* 1 (1992), 37–43.
11. Lee, D.B. Anisotropic etching of silicon. *J. Appl. Phys. 40,* 1 (1969), 4569–4574.
12. Petersen, K.E. Silicon as a mechanical material. In *Proceedings of IEEE 70,* 5 (1982), 420–457.
13. Pomerleau, D.A. Neural network based autonomous navigation. In *Vision and Navigation: The CMU Navlab.* Kluwer Academic Publishers, Boston, 1990.
14. Reed, M.L., Han, H. and Weiss, L.E. Silicon micro-velcro. *Adv. Mater. 4* (1992), 48–51.
15. Thorpe, C., Herbert, M., Kanade, T. and Shafer, S. Vision and navigation for the Carnegie-Mellon NAVLAB. In *Annual Review of Computer Science. Vol. II.* Annual Reviews Inc., Palo Alto, Calif., 1987.
16. Weiss, L.E., Prinz, F.B., Adams, D.A. and Siewiorek, D.P. Thermal spray shape deposition. *J. Therm. Spray Tech. 1,* 3 (Sept. 1992), 231–237.
17. Weiss, L.E., Prinz, F.B. and Gursoz, E.L. A rapid tool manufacturing system based on stereolithography and thermal spraying. *ASME Manuf. Rev.* (March 1990), 40–48.
18. Wettergreen, D., Thorpe, C., and Whittaker, W. Exploring Mount Erebus by walking robot. In *Proceedings of the International Conference on Autonomous Intelligent Systems* (Pittsburgh, Pa., 1993). pp. 172–81.

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