Design for a Millimeter-Scale Walking Robot

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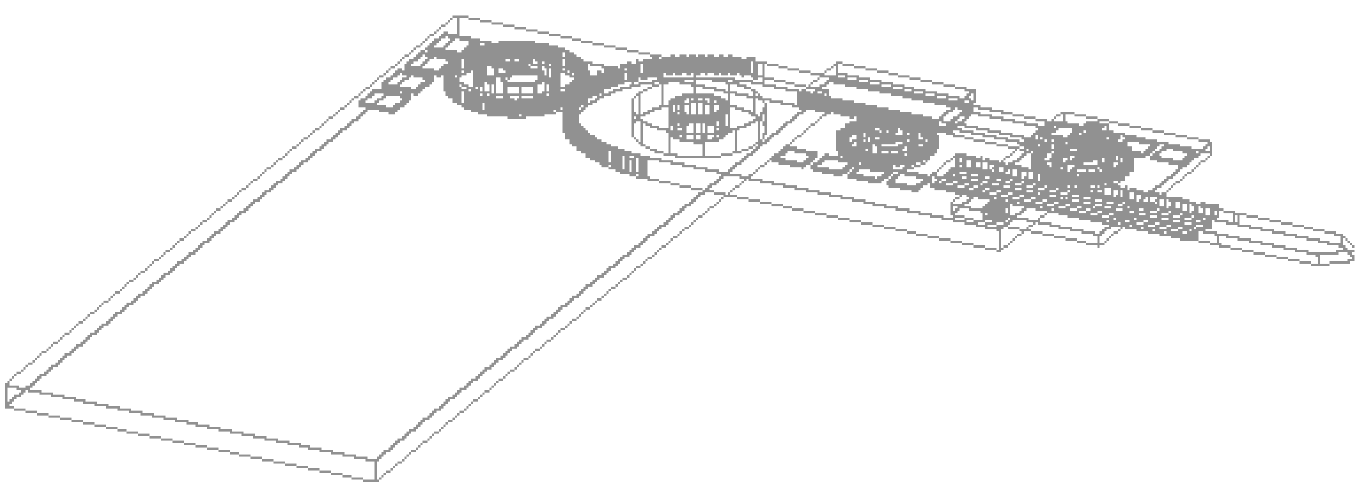

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MITRE Nanosystems Group

e-mail: nanotech@mitre.org
WWW: http://www.mitre.org/technology/nanotech

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ABSTRACT

A design is presented for a millimeter-scale walking robot. The five-millimeter-long robot would be fabricated using micro-lithographic techniques. The design specifies six identical legs, each of which is a discrete microelectromechanical system (MEMS), and for which detailed design drawings already have been developed. Each of the legs incorporates and integrates only motors and drive mechanisms that previously have been fabricated and demonstrated elsewhere, in other types of MEMS devices.

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I. INTRODUCTION

This article gives a brief overview of recent efforts at the MITRE Corporation toward the development of a detailed mechanical design for a millimeter-scale walking robot. An overall view of the design is shown in Figure 1. As is detailed below, construction of such a millirobot according to this design would utilize existing micro fabrication techniques to produce a system that also might be scaled down into the microcosm as fabrication techniques continue to improve.

Key elements of the system's design, as displayed in Figure 1, are as follows:

- Mechanical structures of the mobility system
- Micro-scale power supply
- Hybrid nanoelectronic / microelectronic controllers for mobility and power system

This article focuses primarily on the description of the mechanical systems and the power supply.

II. BACKGROUND

The design developed here for a walking millirobot benefits from prior technological advances in the general area of microelectromechancial systems (MEMS), as well as in the specific technologies for building small robots. Some discussion of these two topics is helpful in explaining the millirobot design set forth here.

A. MEMS

As the miniaturization of microelectronic circuits continues, there has been a similar movement in the development of small mechanical devices. The result of these efforts is the birth of a relatively new field of engineering called micromachining. Devices produced by these techniques range in size from several millimeters down to a few tens of micrometers and are termed micromachines or MEMS (microelectromechanical systems). Many different types of miniature machines have been fabricated, although there has been a particular concentration in the areas of micro-sensors and microactuators [1].

Micromachining sprung out of the integrated circuit (IC) industry. Therefore, it relies on the same techniques used to fabricate transistors in integrated circuits. As in the IC industry, MEMS designers have adopted silicon as the material of choice because of its excellent mechanical properties, as well as the availability of fabrication processes for use with the material [1,2]. There are a number of different processes by which MEMS can be fabricated. However, almost all of them rely on some type of photolithography.

There are three "M-words" typically used when describing the advantages of MEMS fabrication: miniaturization, multiplicity, and microelectronics [1,3]. The first and most obvious of these advantages, miniaturization, is an important characteristic of MEMS. It is not difficult to imagine the benefits of tiny machines, which could be placed unobtrusively in a variety of industrial or medical settings. For example, microsensors are being developed that can be placed under the skin to monitor body functions without disturbing patients. Decreasing the size of a device is not always advantageous, though. For example, reducing the size of an accelerometer, one common MEMS device, can make the detection of small accelerations more difficult, even though it makes manufacturing the device easier [1].

Considering the second "M" word, the inherent multiplicity of MEMS fabrication is what makes MEMS such a unique and promising field. Because of the batch processes involved in photolithography, it becomes just as easy to fabricate 10,000 copies of a component as to make a single one [1,3]. Another benefit of multiplicity is the opportunity to design massively parallel systems. Like the components that make up a microprocessor, simple mechanical components can be combined by the thousands to form complex systems. One such system is a cascaded microactuator [4] consisting of many identical microactuators linked to form a large array. The actuators in this array can act together to provide macro-scale forces and motion like the individual fibers of a muscle.

The third "M" in MEMS technology is microelectronics. Since micromachines are fabricated using the same processes as microelectronics, both can be designed and produced in the same foundries [2], and even together, as a single unit. Also, because MEMS and IC's share a common history, the development of MEMS technology has occurred very rapidly.

The common bond with microelectronics is what has made MEMS technology desirable and attainable. However, microelectronics also may be keeping MEMS from reaching their full potential. This is because they provide circuitry as large as a micromachine, and these circuits often comsume more power than the micromachines that they control. If one were to make an analogous macro-scale machine, such as a robot arm, it would be undesirable to use a processor that was as large as

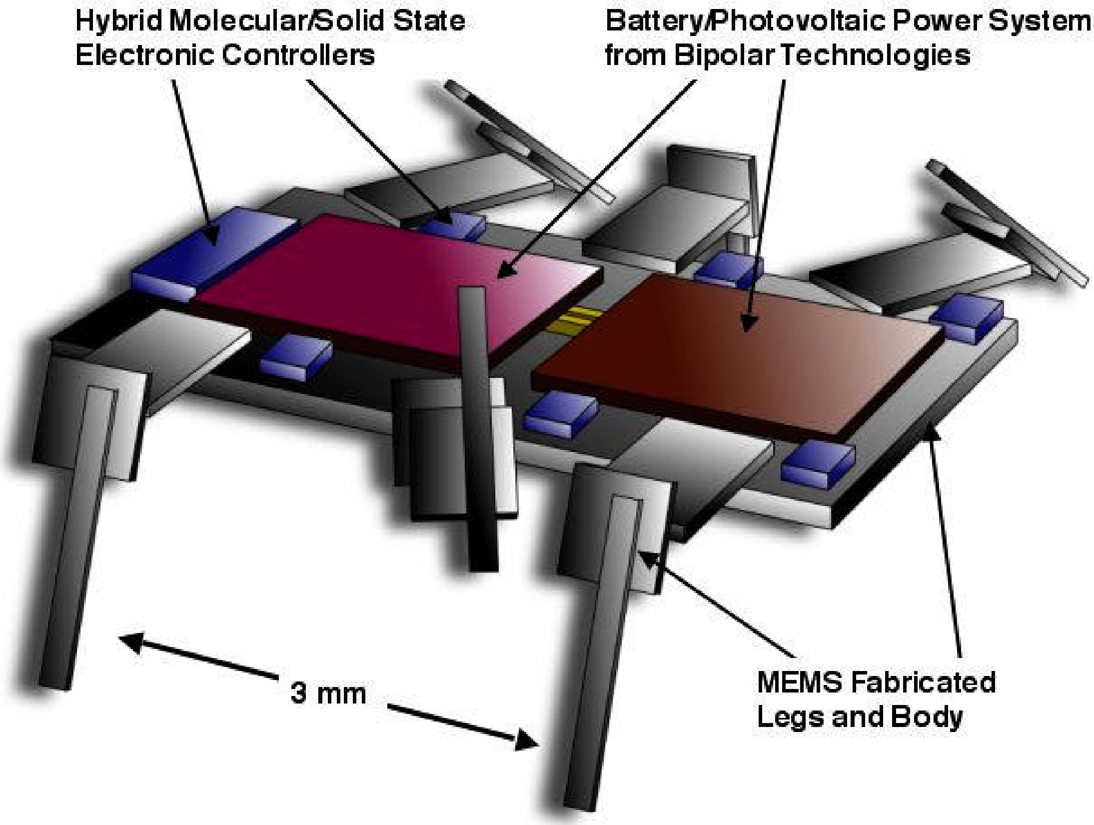


Figure 1

High-Level Design of Microrobot

the entire arm. Therefore, if one is to build micro-scale machines and systems, it is not necessarily desirable to use micro-scale processors. As yet, microprocessors are the smallest computers available, but as the development of nanometer-scale computers progresses, such "nanocomputers" are likely to be the logical choice for controlling microsystems because of their small size and the likelihood of their much lower electrical power requirements [5-7].

B. Microrobotics

Producing a robot on the millimeter scale has been the goal of many scientists and engineers throughout the last decade, because robotic systems are often considered a pinnacle of engineering achievement. Further, microrobots could have numerous practical uses, from intelligence gathering to the manipulation of tiny objects.

Many of the components necessary for assembling such a robot have been constructed and tested at various institutions around the world. Also, several operational robotic systems have been constructed on the millimeter scale and demonstrated to be functional [8-11].

One such system, developed by Ebefors *et. al* [10,11] at the Department of Signals, Sensors, and Systems, Stockholm, Sweden, is a millimeter-scale walking platform that can carry up to forty times its own weight. This millirobotic system uses polyimide joint thermal actuators to walk at a speed of five mm/s. However, due to the nature of thermal actuators, it is difficult to control the robot with a high degree of precision. At 15 mm by 5 mm, the robot is still rather large, and the ability to scale the design to smaller dimensions is undetermined.

A very different millirobotic system is in development at the University of California at Berkeley under the direction of Professor Kris Pister. Unlike the simple, one-degree-of-freedom legs demonstrated by Ebefors, Pister's robot will have complex, jointed legs capable of moving with three degrees of freedom [8,9]. The legs, which are several millimeters long, are composed of 3 hollow triangular beams, each of which is fabricated flat and then folded into a triangular prism. These legs are extremely strong. They do require a complicated hinge and latch system, though, which could be quite difficult to scale down to a still smaller size [8,9]. The hinged legs of this robot have been constructed and operated using electrostatic actuators, but they have not yet been integrated with control circuitry to form a complete operational robotic system.

Microrobotics is the next frontier of microengineering. The last decade has been spent developing component technologies that can be integrated to create autonomous machines smaller than ants, and, eventually, machines that are invisible to the eye. However, as yet, there are no complete microrobotic systems with the ability to perform complex tasks proficiently. Thus, in this effort we attempt to further develop the design and integration for an entire scalable millirobotic system.

III. DESIGN GOALS AND OBSTACLES FOR MILLIMETER-SCALE ROBOT

Design Goals for the millirobot were divided into two types: (A) fixed goals and (B) flexible goals. The fixed goals were those, of which immediate achievement was deemed essential to the success of the design efforts. Immediate achievement of the flexible goals would not be critical to the success of the design, but would be highly desirable for the system. Thus, one might refine the design to work toward the flexible goals in stages.

A. Fixed Goals

1. Millimeter Scale

The robot must be no larger than five millimeters on a side and must be composed of micron-scale mechanical components. These components will be fabricated using the presently available MEMS technology and should be scalable to smaller dimensions as fabrication technology is developed further.

2. Self-contained Power Supply

It is necessary for an un-tethered millirobot to carry a millimeter to micron scale power supply. Presently, MEMS are usually powered and controlled by large external systems [12]. However, this would necessitate a tethered robot that would be useless in the field. Nonetheless, initial prototypes of the millirobot described here may rely on external power sources and controls for testing purposes.

3. Arbitrary Two-dimensional Motion

The robot must be capable of arbitrary motion to any location on a horizontal plane.

B. Flexible Goals

1. Movement Over Uneven Terrain

Ideally, the robot should be able to move over uneven terrain and obstacles. This would be important to its successful operation in the field, since very few surfaces actually are flat and smooth.

2. Integrated Sensors

The design would ideally provide a walking platform for micro-sensors, such as optical sensors. It would also be useful to integrate sensors such as strain gauges into the design to give feedback to the control system.

3. Autonomous Control

Ultimately, autonomous control would be highly desirable in the field. Artificially intelligent robots would be programmed to react to a number of situations and would learn to react to others.

C. Design Obstacles

Certain obstacles and operational constraints are intrinsic to any robotic system of the general description given above. Among these obstacles, two are particularly significant, as follows:

1. Planar Construction

MEMS fabrication technologies require that all structures be planar or at least have a very low aspect ratio [1-3]. Thus, out-of-plane structures on the robot must be unfolded for use [13-15].

2. Dominant Forces

At the micron scale, the importance of gravity as a dominant force is severely lessened. Surface attractions take on gravity's role as the dominant forces [16,17]. Electrostatic forces are the main source of these surface attractions. The significance of inertia is lessened as well, and friction becomes the greatest resistive force [12,17].

IV. STRUCTURAL AND MECHANICAL DESIGN FOR MOBILITY SYSTEM

A. High-Level Considerations for the Design of the Mobility System

1. Desirable Properties from Macro-scale Robots

In formulating a high-level design for the millimeter scale robot, it was helpful to review designs for several macro-scale, walking robots so as to determine desirable attributes for any walking robot. Several robot designs were studied in detail, primarily Thing, a four-legged robot from the University of Massachusetts Laboratory for Perceptual Robotics [18,19]. From this review, it was possible to specify the parameters for several key attributes of the robot's mobility system especially:

- Number of legs
- Degrees of freedom per leg
- Mechanical redundancy or differentiation in legs

a. Number of Legs

From both a hardware standpoint and a software standpoint, the number of legs on a walking robot is one of the most critical parameters. It affects all other aspects of the design. For accurate motion control over uneven terrain and to preserve the integrity of a small and sensitive mechanism, it is desirable for the millirobot to walk in a statically stable gait. A statically stable gait allows a subset of the legs to move while the robot is supported by the remaining legs. In order for the robot to move in statically stable gaits, three legs must remain on the ground, and the center of mass must remain within the triangle defined by those three supporting legs. With four legs, this is quite a complex control problem because each new step defines a triangle that is adjacent to the last, not overlapping. This means that the center of mass must be shifted over this new triangle before another step may be taken, requiring a moving counterweight with at least one degree-of-freedom. In contrast, a six-legged design can move three legs at one time and remain statically stable, because the three remaining legs always form a stable triangle containing the center of mass. This contrast between a four and six-legged robot is highlighted in Figure 2.

b. Degrees of Freedom Per Leg

It would seem that the number of degrees of freedom (D.O.F.) provided for each leg would represent a trade off between increased range of motion of the leg and control simplicity. However, that turns out not to be the case. Only leg designs having two D.O.F. or three D.O.F. were considered, since more than three D.O.F. provides no additional benefits to offset the additional complications in control that would arise [18,19].

Legs with two D.O.F. provide a relatively simple control system, because there is one less actuator needed per leg than for legs with three D.O.F. However, with only two D.O.F., it is very difficult to achieve the above-stated fixed goal of arbitrary navigation on a plane surface. A mobility system can be built using legs with only two D.O.F. This

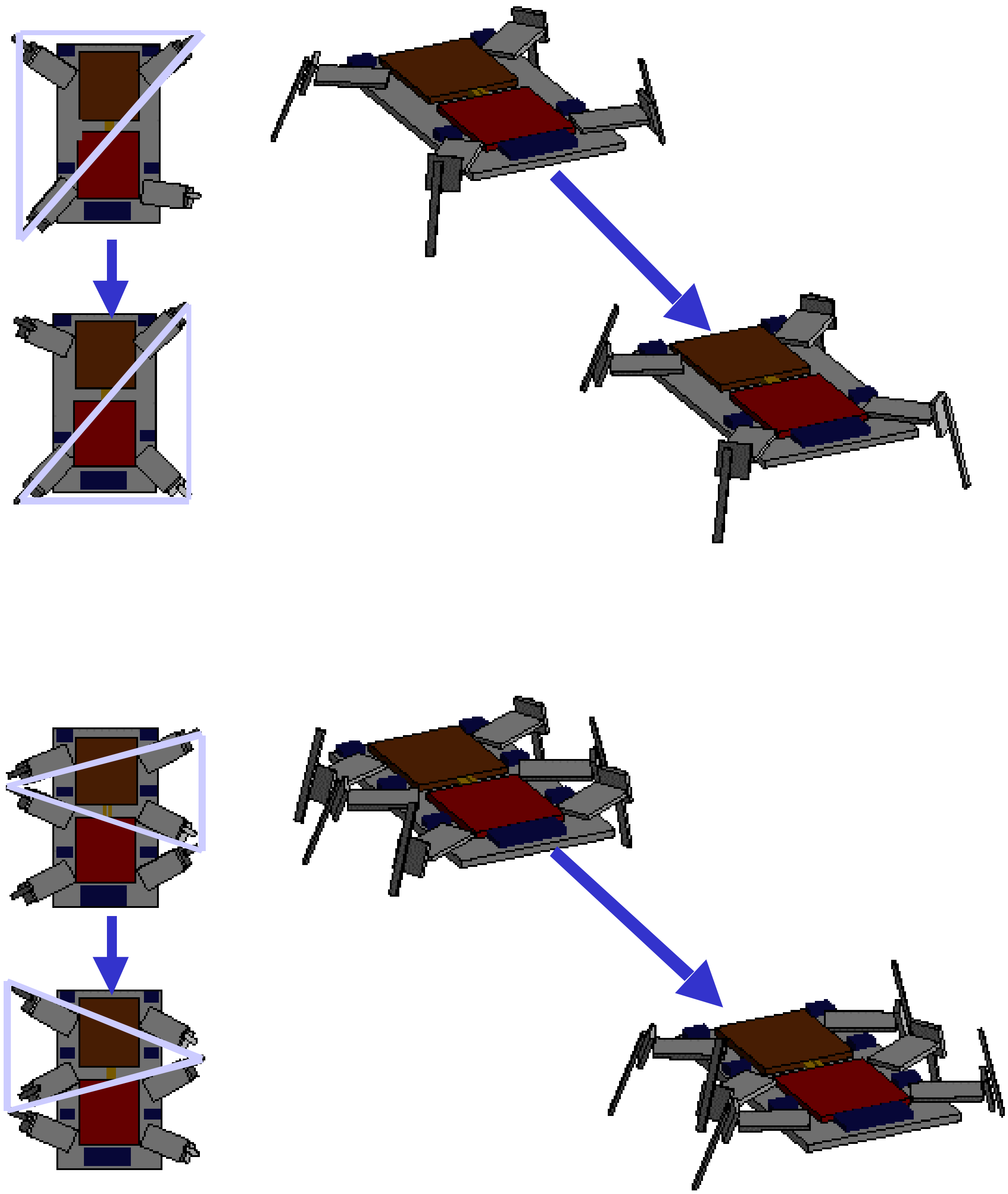


Figure 2

Four-Legged Design vs. Six-Legged Design permits a robot to move forward or backward, but only in a straight line [18,19]. Alternatively, one may build a robot with such two D.O.F. legs that will only move in curved paths, but then it cannot move in a straight line [18,19].

Legs with only two D.O.F. necessarily require a walking gait where the feet slip along the ground, if they are to travel in curved paths as well as travel straight ahead [18,19]. This is undesirable from a control standpoint, though, because systematic slippage of the feet implies that the robot's position no longer can be tracked by feedback from the motor controllers. Additional sensors would be necessary to track the motion of the robot's body over the ground. On the other hand, with three D.O.F per leg, the foot can be positioned anywhere within a three-dimensional workspace [18,19]. This means that using six such legs the robot can navigate in either a straight or curved path over uneven terrain to reach any point on the terrain surface.

c. Mechanical Redundancy vs. Differentiation

In nature, very few animals have more than two mechanically redundant legs. Mammals have very specialized limbs to serve a variety of purposes, from walking, to grasping, to jumping. Insects also have specialized limbs, as do arthropods like crabs and ticks. Each of these animals must perform many different tasks and thus requires differentiated limbs. Initially, the millirobot has only one task, that being to walk under its own power. Therefore, it really only needs one type of limb, a walking leg. Each of the six legs can be an identical copy of the others. This would allow for identical control circuitry, as well, making the task of design much simpler. Further, by using six identical legs, and a bilaterally symmetric body, the robot would be able to travel forward and backward using the same walking gait [18,19]. Thus, the millirobot design specified here has 6 identical legs, arrayed 3 per side on a bilaterally symmetric body.

2. Conceptual Design for Millimeter-scale Walking Robot

Based on the attributes determined from reviewing macro-scale robots, a conceptual design for the millimeter-scale robot is shown in Figure 1. This conceptual design exhibits the desired properties as discussed in detail above. It also conforms to the planar construction required by MEMS fabrication techniques as is discussed below. Further, the design shows the power system and distributed nano-controllers, which together with the MEMS fabricated legs and body would make up the complete robot.

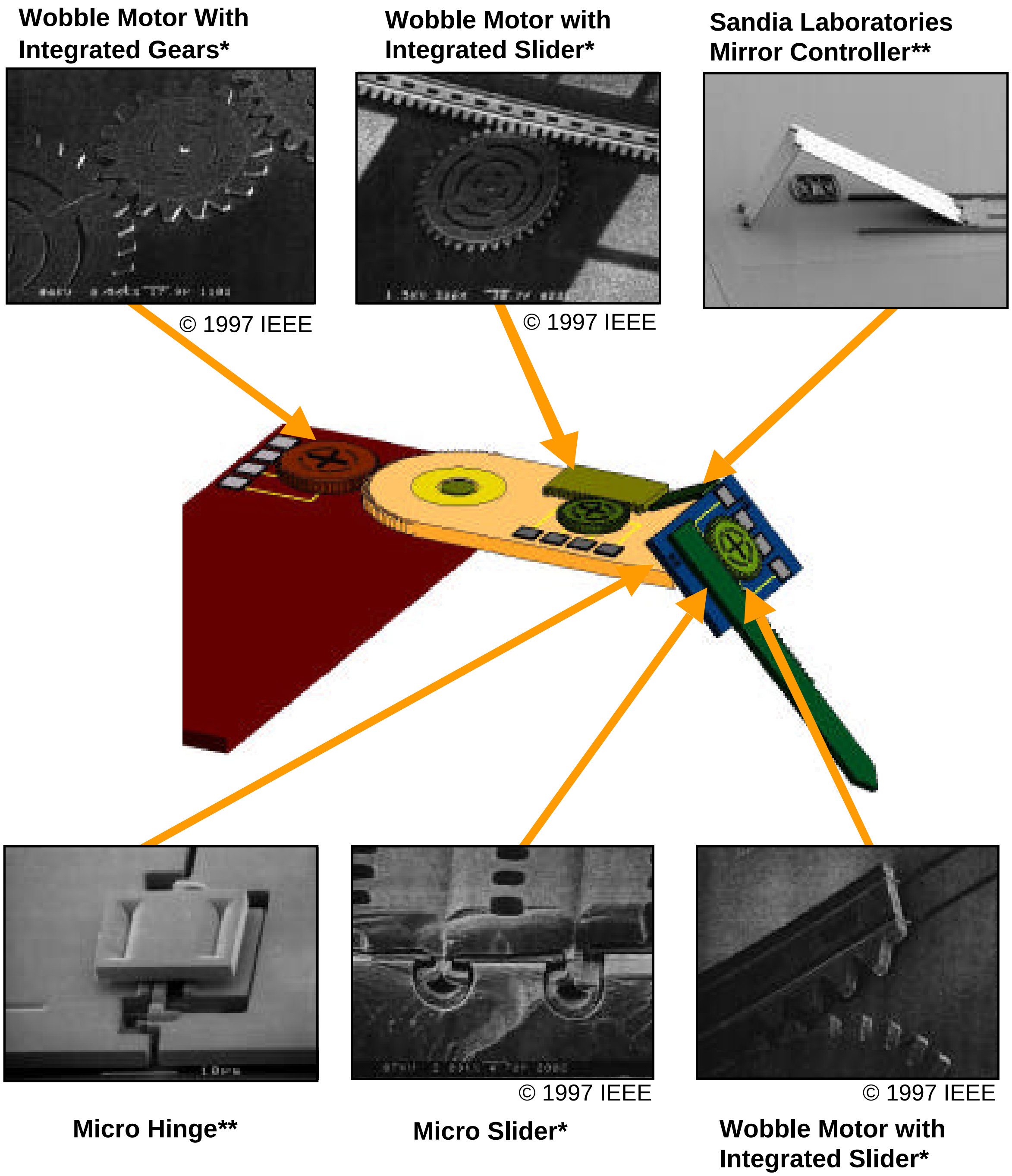
B. Detailed Design of Leg for Millimeter-scale Robot

A detailed design for a single leg was formulated by piecing together existing MEMS components in such a way as to “assemble” the high-level design. Each MEMS component selected has been fabricated, tested, and shown to have promise in engineering experiments conducted previously elsewhere. The specifics of this systems engineering strategy are illustrated in Figure 3. Since the robot design is an integration of many planar MEMS subsystems, it yields a highly planarized leg structure, which conforms to the MEMS fabrication requirements for low aspect ratio structures.

The fabricated leg assembly would closely resemble the design shown in Figure 4a when sent from the foundry, and it would be encased in a sacrificial oxide layer for protection. Upon release from the protective coating, motor 2 would be activated, advancing slider 1 and bringing the whole lower stage out of the plane as is shown in Figure 4b. In addition to bringing the leg into a usable position, the out-of-plane rotation of the lower stage would also serve as one of the working degrees-of-freedom employed by the leg in walking. Once the leg is folded into the working position, the end of slider two, which will act as the foot, can be manipulated in any direction using a combination of motions from the three motors.

Among the actuators considered for the robot were rotary and linear comb drives [1,20], magnetic and electrostatic stepper motors [15,21], and electrostatic wobble motors [22-26], as well as non-motor actuators such as piezoelectric [27] and thermal actuators [10,11]. The non-motor actuators were eliminated quickly because they produced neither strict linear motion nor rotary motion and were thus difficult to control with the precision required for precise navigation. They were also dismissed because they dissipate large amounts of power [1,27]. However, non-motor actuators have however been fabricated and used successfully in certain robot-like applications such as thermally activated micro-conveyors [10,11]. The stepper motors also dissipate large amounts of energy because they draw full current even when they are not moving [15].

Wobble motors are differentiated further into radial gap and axial gap motors. Both operate using electrostatic attraction and both have an inherent gear ratio with only a single moving part. The main difference in the types of wobble motors is the way that power is taken off the rotor. The rotor of a radial gap motor does not rotate around a fixed axis



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Legtenberg et. al** ***Journal of Microelectromechanical Systems, Vol. 6, No. 3, September 1997
****Courtesy Sandia National Laboratories, SUMMiT (tm) Technologies, www.sandia.gov/mems**

Figure 3

Previously Fabricated MEMS Subsystems
to Be Used in Millirobot

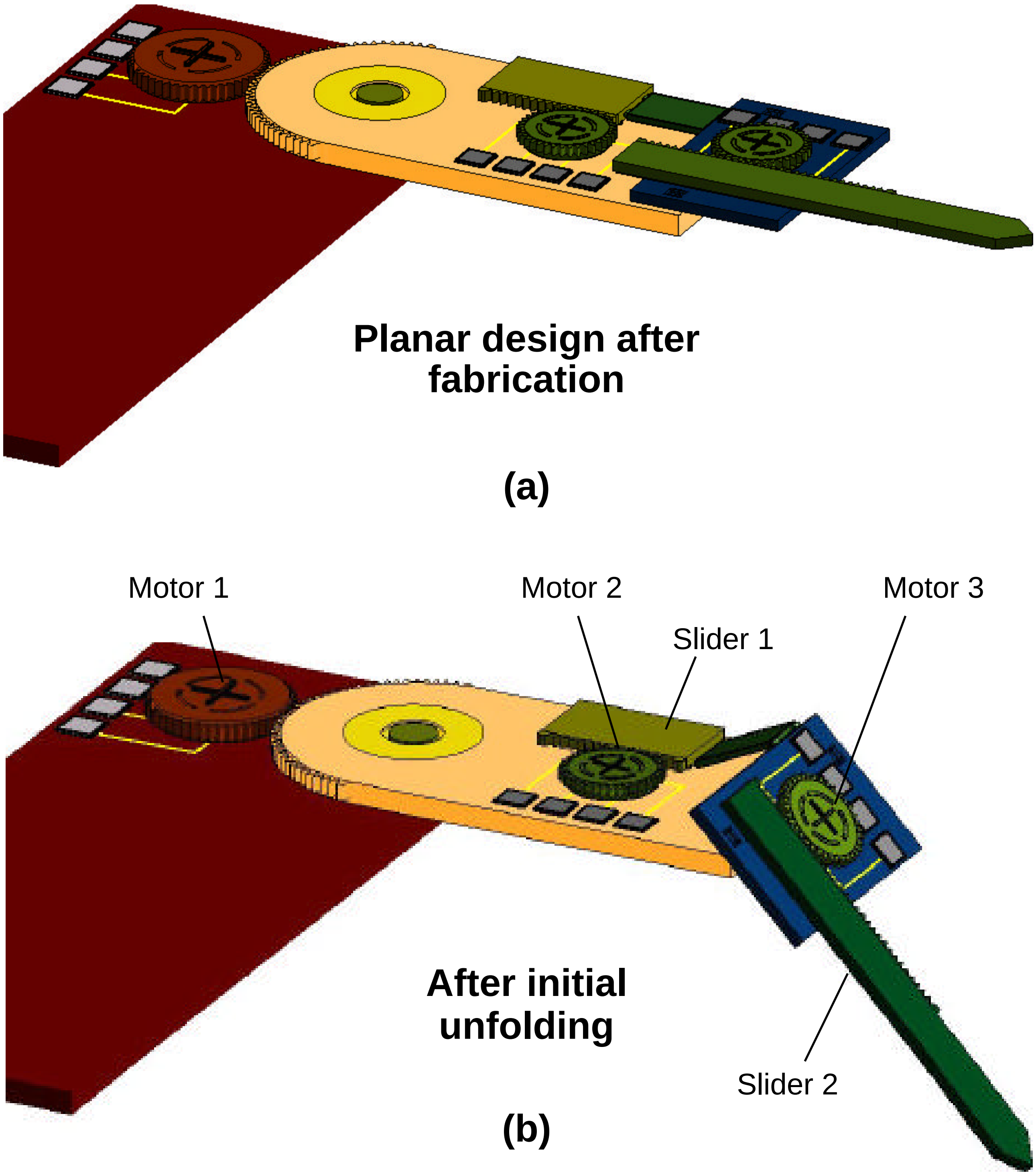

Figure 4

Detail of Design for Millirobot Leg
with 3 Degrees of Freedom

of rotation. Instead, the axis of rotation moves in a circular pattern, concentric to the circle defined by the stator poles. This makes power-take-off extremely difficult, and renders the motor less useful in powering rotating mechanical elements than other rotary motors [23,25].

The axial gap wobble motor is much more useful. In an axial gap motor the rotor is stacked on top of the stators so the edge of the rotor is exposed for power-take-off. The rotor can be fabricated with gear teeth to drive a gear linkage or slider [23]. Axial gap motors also have high gear ratios and high holding torque [24-26] both of which are requirements for the motors that will drive the millirobot. Another benefit of the wobble motor is that it does not draw any electrical current while holding stationary, thus it uses power more sparingly than a magnetic motor.

The motors chosen for the robot were three axial gap wobble motors. By using three identical motors, the same control circuitry is can be used in several places and this makes the design process much quicker. The initial design includes electrical contact pads connected to each stator pole of the motors allowing the robot to be driven by an external power supply and controller for testing purposes.

V. POWER SUPPLY FOR MILLIROBOT

Identifying a satisfactory method for supplying electrical power to the controllers and actuators is a major step in the design process of any robot. This issue becomes much more complicated when the robot is the size of an insect. Like any power supply system, the micro power supply must be composed of three parts [12].
These parts are as follows:

- Energy source
- Energy capture
- Energy storage and delivery

Directly through an engine, or, indirectly, from a steam turbine electrical power plant, the energy source for much machinery today is combustion. Miniature versions of these power plants do exist in the form of micro turbines. These micro turbines burn liquid or gaseous hydrocarbon fuels, but they are still rather large compared to the overall robot, and require a constant supply fuel which would have to be stored on-board in a heavy tank [12].

Another readily available source of energy is light. If it is available, light is a much more desirable energy source than combustible fuel, because there is no need for a heavy storage tank. The energy source is the sun or a light bulb. Either way, it is external to the robot.

Using a photovoltaic cell to capture the energy, light can be harnessed to produce an electrical current. The electrical current produced by the photovoltaic cells can be used to drive the robot in one of two ways. First, the current can be routed directly to the controllers that would, in turn, route current to the motors when so directed. This configuration would be sufficient assuming that lighting conditions were always optimal, but would not allow for any auxiliary power, should light levels drop below the operating threshold.

In order to ensure operation in non-optimal lighting, a method of power storage is necessary. The second and more desirable way to configure the photocells is in conjunction with a battery. The photocell would charge the battery, and the battery would drive the robot. This arrangement would allow the robot to operate on battery power in dim light or darkness. Further, the photocell could temporarily be used along with the battery if higher voltages or currents are required.

A search, conducted by the author for commercial off-the-shelf (COTS) products to be used in a micro-scale power supply led to a micro-battery designed by Bipolar Technologies, Incorporated [28]. The battery, which would be fabricated using the same processes as for MEMS, can be made in any size or shape, as small as 50 microns on a side. These cells are planar and multi-cell systems can be fabricated either co-planar or stacked vertically. This is illustrated in Figure 5.

In principle, these power storage cells could be distributed throughout the robot and could occupy every space not needed for mobility, control or photocells. Bipolar Technologies was contacted with a sample request specifying a battery occupying one mm^2 with an operational voltage of 7 volts. The specifications for that cell are shown in Table 1. Based on the availability of a COTS battery and photo-voltaic cell, the production of a micro-power supply for the millimeter-scale robot seems to be quite feasible.

VI. CONCLUSIONS AND FURTHER DISCUSSION

This paper has proposed a design for a five-millimeter-long, six-legged robot that is to be fabricated using micro-lithographic techniques. Each of the millirobot's legs incorporates only motors and drive mechanisms that previously have been fabricated and demonstrated elsewhere, individually, in other types of MEMS devices.

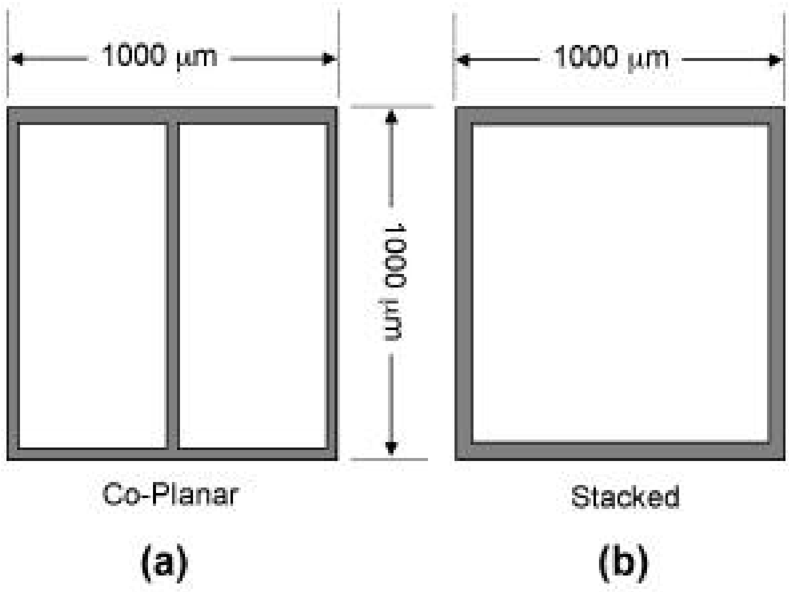

Figure 5

Two Alternate Configurations for a Bipolar Technologies, Inc., 5 - 7 V Lithium-Ion Micro-battery.
The micro-battery would occupy 1 mm^2 area, and could be either (a) co-planar or (b) stacked [27].

Characteristic	Co-Planar	Stacked
Cell Dimensions (µm)	450 X 900	900 X 900
Cell Specific Capacity(mAhr/cm2)	1-2	1-2
Total Capacity (@ 1mAhr/cm2; µAhr)	4	8
Operating Voltage (V)	6.6 - 8	6.6 - 8
Discharge Power (@6.6 V; 10 ms; mW)	1.5	3.0
Discharge Power (@6.6 V; t≥1sec; mW)	0.5	1.0
Height (µm)	40 - 50	80 - 100
Mass (mg; approximate)	0.06	0.12
Energy Storage Capacity (µJ)	28	56

Table 1

Micro-battery Specifications from Bipolar Technologies, Inc. [27]

A. Issues: Tribology on the Micron-Scale

One area of research that is presently receiving a great deal of attention is tribology, or the study of friction and wear. Both wear and static friction are substantial obstacles in the path towards realizing complex MEMS devices, such as the millirobot described here. The lifetime of most MEMS actuators is currently determined by how quickly they grind themselves to pieces. However, before they can begin to function, moving parts must overcome the force of static friction. Static friction can have a substantial effect on MEMS, where the ratio of surface area to volume is much greater than that of conventional mechanical systems [29-33].

At the present time, the most common method for dealing with both issues is to deposit low friction coatings on the surfaces of sliding parts as they are fabricated [31,34]. A small change in frictional coefficient can reduce wear drastically and greatly prolong the life of a device [29,31,33]. However, small changes in frictional coefficient do not solve the problem of overcoming static friction. One possible solution to this problem is to turn back to conventional engineering and develop MEMS-specific lubricants. These lubricants are likely to be polymer chains loosely bound to the sliding surfaces and may reduce friction by as much as a thousand fold [29,32]. Another possible way to deal with friction is to change materials completely, from silicon to diamond. Diamond has a much better ratio of hardness to frictional coefficient than silicon and is a promising new material in the field of MEMS [30].

While successful strategies for lubricating MEMS are very close to realization, there has yet to be a truly satisfactory solution to the problem of friction in micro-scale machinery. Until such a solution is developed, wear and static friction will continue to plague MEMS devices and hinder their operation.

B. Prospects

Our primary objective in proposing a design for a robot of the size and type described here is to explore the feasibility of shrinking complex electromechanical systems down to millimeter and even micron scales. For example, this design will serve as a testbed for small, dense, low power electronic control circuitry.

However, when it is fabricated, the millirobot could have practical applications as a micro-sensor platform in military or industrial uses. It is possible that such complex micromachines could be mass fabricated and deployed in large numbers.

The process of designing, fabricating, controlling, and operating a complex millimeter-scale machine such as the one described above is likely to have beneficial impact upon efforts to design and manufacture other less complex, multi-component microsystems that might be used in industrial applications. The next phase in this process is to begin fabrication of the millirobot. Steps in this direction already are underway.

A longer-term goal of the research and development on this millimeter-scale robotic system is also to determine requirements and techniques for shrinking such a walking robotic system even further, down to sub-millimeter scales. Machines of this sort might have significant *in vivo* medical applications, as well as applications for the military, intelligence, and law enforcement agencies.

VI. ABOUT THE AUTHORS

David A. Routenberg is a Technical Aide in the MITRE Nanosystems Group. Prior to coming to MITRE in 1999, he had gained extensive experience in the practical aspects of designing and building macro-scale mobile robots. In the autumn of 1999, David entered the University of Virginia as a Rodman Scholar, where he is studying electrical engineering.

Dr. James C. Ellenbogen is Senior Principal Scientist in the Nanosystems Group at The MITRE Corporation and Principal Investigator of MITRE's Nanosystems Modeling and Nanoelectronic Computers Research Project. Dr. Ellenbogen received his Ph.D. in chemical physics from the University of Georgia in 1977. He is the author of a number of technical papers on the modeling, simulation, and testing of military systems, on the theory of command and control, and on diverse topics in computer science, physics, and chemistry. He taught at several universities before joining the MITRE Corporation in 1984. Since 1993, he has devoted his energies to furthering the science and technology for designing and developing electronic computers integrated on the nanometer scale. In that effort he has collaborated in the development of unique designs for nanoelectronic devices and co-authored several widely cited technical articles on nanoelectronics.

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