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Twilight Zones and Cornerstones

A GNAT ROBOT DOUBLE FEATURE

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Abstract

We want to build tiny gnat-sized robots, a millimeter or two in diameter. They will be cheap, disposable, totally self-contained autonomous agents able to do useful things in the world. This paper consists of two parts. The first describes why we want to build them. The second is a technical outline of how to go about it. Gnat robots are going to change the world.

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Cornerstones for Creating Gnat Robots

Abstract

There are a few cornerstone technologies that need to be developed in order to build even the simplest gnat robot. We focus here on the most critical issues and outline our ideas for solving these problems. Our solutions involve some major breakthroughs but they aren't impossible. Mostly they're things that haven't been thought of or tried before.

Specifically, we describe some new approaches for micro-actuators using piezoelectrics materials, several novel ideas forfabricating three dimensional gnat robot bodies and some micro-batteries that double as part of the superstructure. We also propose some different types of micro-sensors, such as room-temperature infrared cameras, that would be useful for various gnat robot tasks. Although we envision the end goal being a completely autonomous robot, we foresee that many of the ideas and breakthroughs will lead to spinoffs along the way, creating stand-alone technologies that will be useful in and of their own right.

Introduction

The creation of integrated intelligent electromechanical systems holds the potential for vastly changing the way we think about solving problems. By lowering costs for robotic technology through the use of integrated circuit techniques and silicon micromachining, completely new possibilities arise in a wide variety of applications. Small size draws many advantages as Nature has shown. The common housefly is able to crash into ceilings landing upside down, because its small size gives it a large surface area to volume ratio, making it very strong. In the small domain, designs are possible which would be totally impractical at a larger scale. In addition, by thinking in terms of massive parallelism (utilization of millions of simple, small robots) and cheap, disposable robots (throw them away when they're done), robotics becomes a whole new ballgame.

What are the hardest problems involved in building a gnat robot [Flynn 87] - a completely autonomous micro-robot which can be mass produced? Of a robot's four major subsystems, the intelligence engine, the sensors, the actuators and the power supply, it seems relatively straightforward to be able to target the electronics for the brain down to the gnat scale. Sensor technology too, has seen plenty of advances recently and micro-sensors for an integrated robot seem doable although not quite as far along as digital electronics. The toughest problem in building a gnat robot though will be obtaining enough mechanical power to physically move the robot. That means developing both a strong actuator and an efficient power transmission system. Equal to that is the challenge of fueling the robot. A small gnat robot doesn't have the bulk to carry around large batteries nor the size to support wide solar panels.

In addition to the agenda of developing micro-motors, tiny transmission systems and micro-batteries, another crucial appointment is finding a means to create three dimensional miniature bodies for the robots so that motors and appendages can be oriented perpendicularly to the direction of travel. Normally, micro-actuator and micro-sensor processes stand on the shoulders of integrated circuit technology, using standard photolithography and etching techniques. The problem with counting on these techniques however, is that integrated circuit technology is for the most part two-dimensional, so although it's possible to etch a movable rotor onto a silicon substrate, the rotor will be constrained to rotate parallel to the silicon surface. A gnat robot which needs wheels, legs or propellers may require actuator movement out of the plane. Developing fabrication methods to meet such constraints will call for diverging from standard silicon processing. If all that's left though is discrete assembly, then the advantages of batch production, the cornerstone of integrated circuit fabrication, may be lost.

In this paper, we outline some of the technological issues that need to be addressed and focus on problem solutions that we feel would be the best avenues to pursue. In the first section, we relate some background on recent work in micromotors and propose a new type of actuator, a *piezoelectric micromotor*, which looks promising for effectively coupling mechanical power out to a load. The second section addresses the problem of finding adequate power sources for propelling a small vehicle and points out some recent work in other fields on *micro-batteries* which may be useful for small robots. Section three is a discussion of the limits of two-dimensional integrated circuit fabrication methods and proposes some novel ideas for forming *three dimensional structures* suitable for a micro-robot's chassis. In section four, we look at the issue of sensors and propose a *room-temperature infrared imager* which would be useful for a variety of tasks and yet could be implemented with the same technology which would be needed to fabricate the actuators. In section five, we discuss the organization of the *brain* and how our past research in building autonomous creatures has led to the realization that with the proper organization, the intelligence system can be made to fit into a very small amount of silicon. This fallout from our previous research, along with recent breakthroughs in actually fabricating motors onto chips, has been the inspiration for this gnat robot project. Finally, we point out possible spinoff technologies and products that may become viable along the way to building completely integrated gnat robots.

I. Micromotors

The first problem we need to tackle in making gnat robots realistic is developing an actuator that can deliver some useful power to a load. Several groups are working on various types of micromotors and there have been some early successes, but many hurdles still remain [Bart et al 88], [Tai, Fan & Muller 89], [Trimmer & Jebens 89], [Jacobsen et al 89] and [Fujita & Omodaka 87]. The general approach in building motors in the micro domain has been to focus on building electrostatic motors instead of the magnetostatic motors we are familiar with and which are found in everyday appliances or consumer items.

In general, electromagnetic motors fall into these two categories - magnetostatic motors and electrostatic motors, which are differentiated by the primary mode of energy storage in the rotor to stator gaps. At macroscopic scales, magnetostatic motors are the clear winners because magnetostatic motors can achieve much higher energy densities in the air gap between the stator and rotor than electrostatic motors can. Magnetostatic motors are almost universally used in every commercial application.

In the discussion that follows, energy density will be the common denominator for describing various types of electrostatic micromotors, such as variable-capacitance micromotors, wobble motors and piezoelectric ultrasonic motors. These three electrostatic micromotors differ from each other in the manner in which they convert electrical energy in the gap to mechanical energy.

The energy density in an everyday magnetostatic motor is described by

$$\frac{1}{2}\frac{\mathbf{B}^2}{\mu_0}$$

where μ_0 is the permeability of free space in the gap and $\mathbf{B}$ is the magnetic flux density.

Typically, magnetostatic motors use highly permeable materials such as iron to create large magnetic fields. These magnetic fields are generated by pumping current through windings which are wrapped around the highly permeable material. The saturation limits of these materials limit the magnetic fields and consequently the energy storage in the gap.

In an electrostatic motor on the other hand, the energy density in the gap is

$$\frac{1}{2}\varepsilon_0\mathbf{E}^2$$

where ε_0 is the permittivity of free space in the gap and $\mathbf{E}$ is the electric field.

Typically electrostatic motors create force through the application of electric fields between the two plates of a capacitor which are offset from one another. Figure 1 illustrates the interplay between voltage, electric field and energy storage in a parallel plate capacitor.

Normally, as [Bart et al 88] points out, the energy density for large magnetostatic motors is many orders of magnitude larger than for macroscopic electrostatic motors. However, for electrostatic motors at very small scales, such as in the case of a one micron gap, it is possible (as shown by Paschen) to apply much larger electric fields before breakdown than at larger scales, and so at small scales electrostatic motors have energy densities comparable to the energy densities of small magnetostatic motors.

Energy density calculations bring electrostatic motors up to par with magnetostatic motors, but fabrication arguments tip the scales in favor of electrostatic motors for micro-work. Fabrication techniques make electrostatic motors the preferable form of energy conversion at small scales because silicon processing can be used to build the capacitive structures (using readily available dielectric materials such as silicon dioxide and silicon nitride) necessary for the electrostatic actuators. In addition, if micromotors can be fabricated using integrated circuit technology, then it is feasible to build silicon control circuitry on the same substrate as the motor. Magnetostatic motors accrue none of these advantages at small scales because thin film magnetic materials are not readily available, the current densities required are hard to achieve and true three dimensional windings are not currently possible to fabricate. The remainder of this section then will discuss various types of integrated electrostatic motors, as magnetostatic motors do not scale well to the micro domain.

The basic technology which makes it possible to actually fabricate freely moving compo-

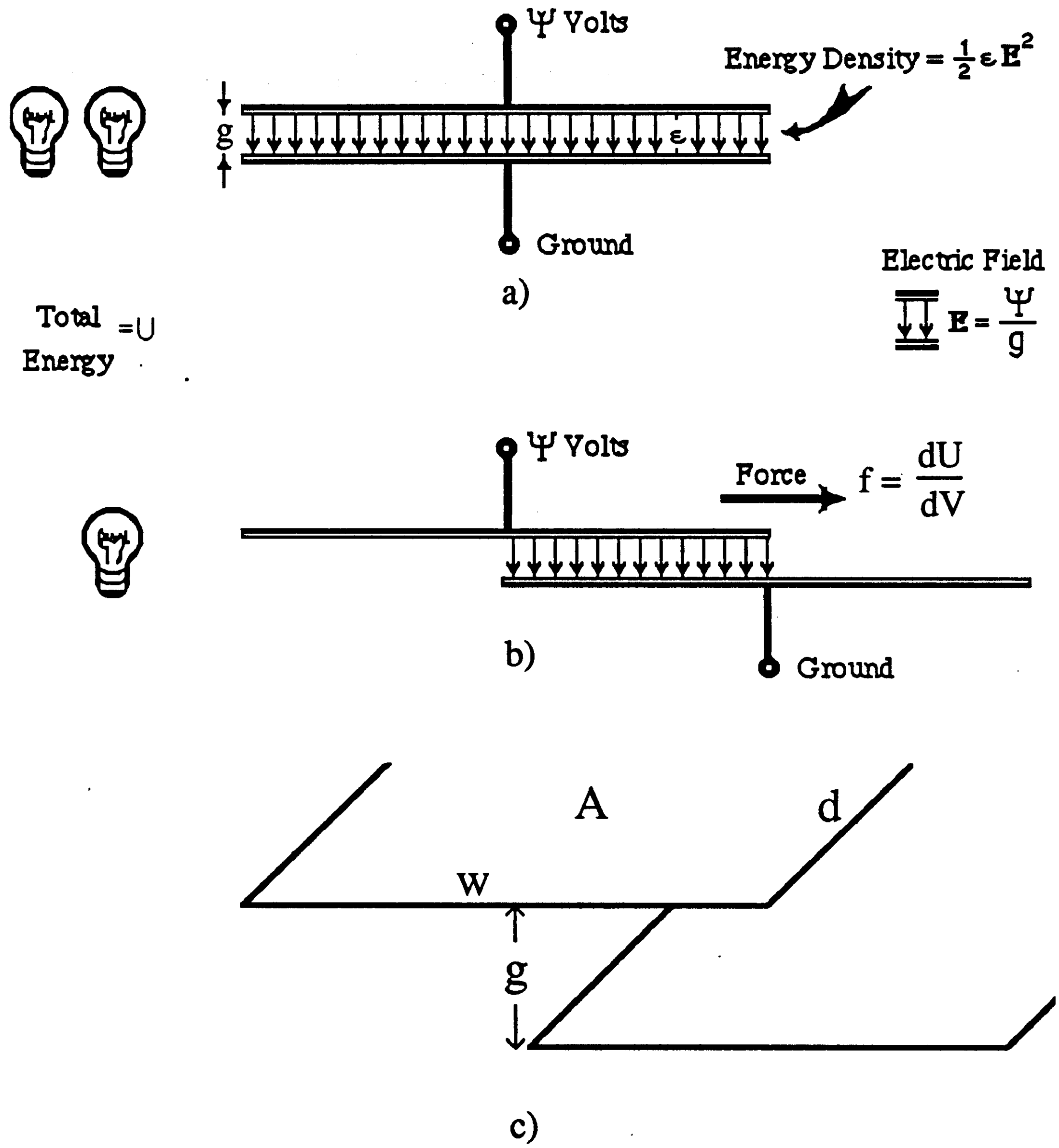

Figure 1. a) A parallel plate capacitor with a voltage applied across the plates stores a certain amount of electrical energy (symbolized by two light bulbs). b) Offset plates of a capacitor will feel a force tending to align them which is equal to the change in energy with respect to the volume of the gap (symbolized by one light bulb). c) For the change in volume that occurs when the plates slide past each other, the gap depth, d, and the gap spacing, g, are constant.

nents on chip is termed *silicon micromachining*. Micromachining is the ability to etch structural shapes in silicon for mechanical purposes [Petersen 82]. Mechanical structures such as cantilever beams and bridges have been etched in silicon in sizes on the order of a few tens of microns. Much of this work was first developed in order to produce micro-sensors [Petersen 85]. Pressure sensors, chemical sensors and accelerometers are just a few of the wide variety of micro-sensors now commercially available which convert mechanical motion to electrical signals in order to transduce some physical phenomenon into information. Due to the fact that these sensors can be both mass produced and fabricated with on-chip signal processing, they are rapidly finding homes in such places as the automobile industry.

One reason for the quick establishment of the micromachining and micro-sensor industry was that they borrowed extensively from techniques and equipment painstakingly developed over the past 20 years for making electronic integrated circuits. Now, by extending micromachining to the etching of completely freely moving parts and then electrifying them, a new field of micro-actuators is opening up. As creating new materials processing techniques takes an enormous investment of time, we want to borrow as much as possible from prior work in micro-sensors and micro-electronics in developing micro-actuators and eventually gnat robots.

With these two main points in mind, namely that energy density arguments and the availability of silicon micromachining techniques point towards focusing on electrostatic motors, we turn now to the advantages and disadvantages of the various implementation possibilities.

We will compare and contrast three classes of micro-scalable motors: variable-capacitance motors, harmonic wobble motors and piezoelectric ultrasonic motors. These motors hardly make up a complete list of all micro-scalable motors but are the most promising designs we are aware of. Extensive work has been done on the variable capacitance and wobble motors by us and by others, but the technology for the possibility of producing piezoelectric micron-scale motors is only now emerging.

In all three electrostatic motors, electrical energy in the form of voltages and currents is used to charge up a capacitor, the simplest type of which is a parallel-plate capacitor, shown in figure 1. The energy in the gap between the plates of a capacitor is the integral of the energy density over the volume of the gap. This energy density, as found by Maxwell's laws, is

$$\frac{1}{2}\varepsilon_0 \mathbf{E}^2$$

as was stated earlier. In the case of a parallel-plate capacitor, the electric field **E** is constant in the gap and is:

$$|E| = \frac{\Psi}{g}$$

where |E| is the magnitude of the electric field,
g is the plate spacing and
Ψ is the voltage

and thus the total gap energy is given by

$$\frac{1}{2}\varepsilon_0 E^2 V$$

where V is the volume of the gap = dwg
d is the depth of the plates
w is the width of the plates

The energy in this gap is then converted to mechanical energy which causes the actuator to move. The specific way in which the electrical energy is converted to mechanical energy differentiates the above three motors. The variable capacitance motor and the wobble motor convert electrical energy directly into mechanical force using coulombic attraction of unlike charges accumulated on the two plates of a capacitor. The variable capacitance motor takes advantage of the component of the induced force which acts to *align* the plates while the wobble motor takes advantage of the component which acts to *collapse* the plates. The piezoelectric motor on the other hand, first converts the electric field into vibratory motion which is then rectified to mechanically propel the rotor. With these mechanisms in mind, it is useful to ask certain questions when evaluating specific actuator designs.

Two critical parameters for motor comparison are power density and efficiency. Power density is the amount of torque generated at a specified velocity for a given size motor. Efficiency is the ratio of mechanical power output to electrical power input.

High power density is necessary for propulsion of vehicles such as those that move by turning a wheel or driving a leg. High efficiency allows for a small power source and more importantly, circumvents the problem of disposing of waste heat. The product of the two, the power density and the efficiency, is the critical parameter for a successful motor design.

Another aspect of interest when evaluating actuators is gearing. The power density-efficiency of a motor is meaningless if the torque is only available at superfast, unusable speeds. Since efficient gearing is currently infeasible in the micro domain, especially for the gear ratios of 10,000:1 which might be needed for some motors, the speed at which the motor delivers its maximum power must be custom tailorable by the designer.

Other criteria are also important for successful actuator design. Stability problems can affect the complexity of the control system. The form of the input power necessary may be difficult to produce, such as high voltage, high frequency waveforms. The type of bearing material is important in terms of friction and wear. Some method for attaching a load and coupling power out is a critical issue, and finally, cost, packaging and manufacturability can make all the difference between a benchtop novelty and a successful consumer item.

Is it possible for one motor to win in every category? We look now at the details of the variable capacitance motor, the harmonic wobble motor and the piezoelectric ultrasonic motor, comparing and contrasting their primary attributes.

Variable Capacitance Micromotors

The variable capacitance electrostatic motor is based on a radial air gap capacitor. Figure 2 shows a scanning electron microscope photograph of one such a motor which we (Tavrow) have fabricated. The rotor is roughly 200 microns in diameter and the entire structure was built without hand assembly using standard integrated circuit microfabrication technology and equipment.

The rotor freely rotates parallel to the substrate around a pin bearing. The rotor is restrained in the vertical dimension by a bearing cap, a lip at the top of the bearing which extends slightly over the rotor. Figure 3 illustrates a bearing structure, which in this case has been placed inside a slider mechanism. The lower portion of the photograph shows a closeup view which clearly illustrates that the bearing has been etched free from the surrounding structure.

If we model rotor to stator side-to-side overlap of this radial air gap actuator as an infinite

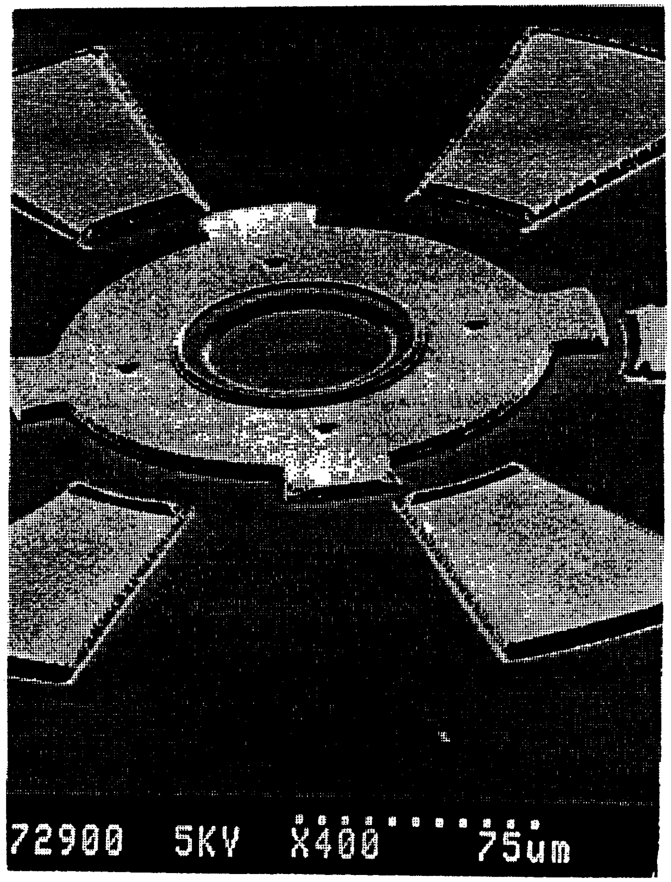

Figure 2. Scanning electron microscope photograph of a silicon variable capacitance micromotor driven from the side. The poles of the rotor align with the electrodes of the stator as voltages are stepped around the stator.

parallel-plate capacitor, the total energy stored in the gap (U) is

$$U = \frac{1}{2}C\psi^2$$

One way to derive the stored energy for this geometry is by noting that the energy is given by

$$\frac{1}{2}\varepsilon_o E^2 V$$

where V is the volume between the plates = Ag
A is the area of a plate
g is the gap between the plates and

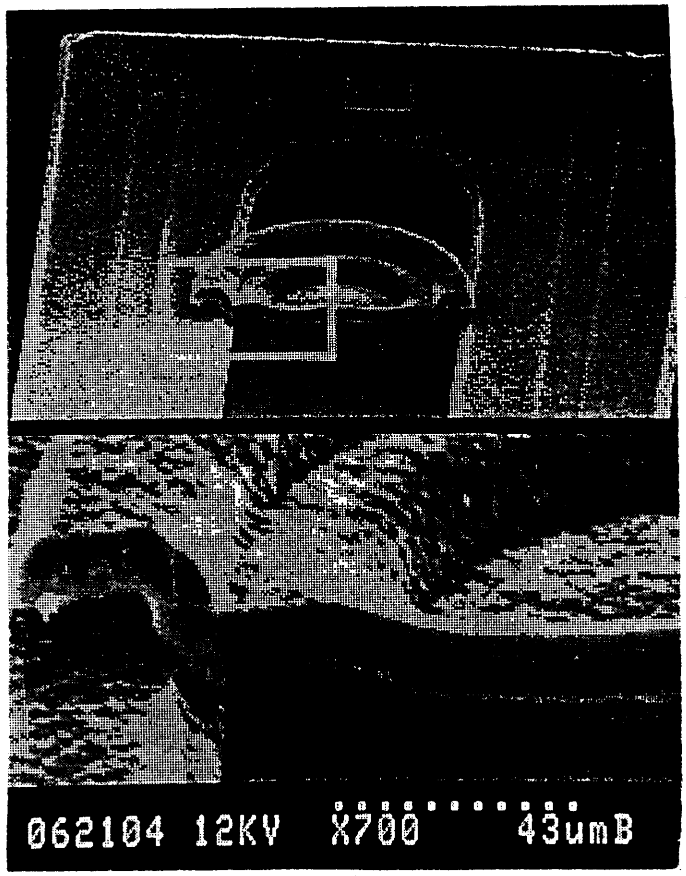

Figure 3. Cross section of a bearing structure. The top photograph shows a bearing resting within a slider mechanism. The bottom view is a closeup showing that the round bearing is actually etched free from the structure below.

$$|E| = \frac{\Psi}{g}$$

Substituting, we find that the energy stored between the plates of a parallel plate capacitor is proportional to the voltage squared

$$U = \frac{1}{2}C\psi^2$$

with the constant of proportionality collecting all the geometric and material property terms

$$C = \varepsilon_o \frac{A}{g}$$

If the two plates don't overlap at all, the total energy in the gap is thus zero (from V=0) and the energy increases linearly as the two plates move across one another (to first order).

Consequently, for a constant voltage Ψ, physically moving the plates over one another increases the energy storage in the gap (a generator), or conversely, application of a voltage across two misaligned plates creates a force which acts to align them (a motor). Mathematically, there is then a force equal to the change in energy with respect to the change in volume

$$|f| = \frac{dU}{dV}$$

and this force is used to propel the rotor. On a variable capacitance motor, once the plates have become aligned, a voltage is then stepped to the next set of plates which are not aligned to give the rotor continuous circular motion. Essentially, fringing fields create the aligning forces. Figure 4 gives a top-view schematic representation depicting this setup.

[Bart et al 88] calculated some theoretical limits for maximum torque and speed for a top-driven, axial-gap variable capacitance micromotor as illustrated in cross-section in figure 5a, in which the stators overhang the rotor. This configuration of driving the rotor is advantageous given the greater rotor-stator overlap as compared to the radial gap motors. Unfortunately, this drive mechanism has been shown by one of the authors (Tavrow) to be impractical due to rotor instabilities and fabrication difficulties. However, the numbers calculated are still valid for giving an order of magnitude feel for the relative speeds and torques available for variable capacitance micromotors. Calculations show a maximum velocity assuming no load and viscous damping due to air being the limiting factor opposing the drive torque, of roughly 600,000rpm. For comparison, the fastest turbos spin at 20,000-100,000rpm. These actuators would contain the fastest spinning rotors ever made. The maximum torque, at zero velocity, would be about 29nNm - not very big to say the least. If these motors were connected in parallel (if that were possible), about 1000 would be needed to spin a paperclip at a velocity of one rotation per second. Since power is the product of torque and angular velocity, and if the motor is driven at the torque and velocity which produces the maximum power available to a load, that mechanical output power available would be 0.4mW, which is a fair amount of power - provided the vehicle is small and designed to not draw much power.

The problem however, is that although there may be significant power inherent to this design, it arrives in the wrong ratio of torque to speed for applications such as propelling a small vehicle. What would be more desirable would be much higher torques with speeds of a few hundred rpm. The high speeds of a variable capacitance micromotor mean that some sort of transmission system is required to gear down the motor to more useful levels.

Coupling such a gear to a variable capacitance motor is difficult because the design depends on the rotor essentially being able to float freely on an air bearing. Friction at small scales introduces unique problems. The issue of friction is addressed in more detail in the discussion on wobble motors. In a top-driven axial-gap variable capacitance motor, floating the rotor is exceedingly difficult given the overwhelming destabilizing forces. These have to then be compensated for with closed loop control. The side-driven radial-gap motor of figure 5b skirts some of these stability issues by transforming the vertical instability into a horizontal instability which can be mechanically controlled through the aid of a center bearing which restrains the lateral motion of the rotor. Nevertheless, coupling a load to this rotor is still difficult as the rotor needs to spin frictionless above the substrate.

First order theoretical considerations might suggest a usable amount of power available from a variable capacitance micromotor, but practical problems limit the mechanical output to power far below calculated values. [Tai, Fan & Muller 89] have produced an electrified actuator which has spun at 400rpm for about one minute.

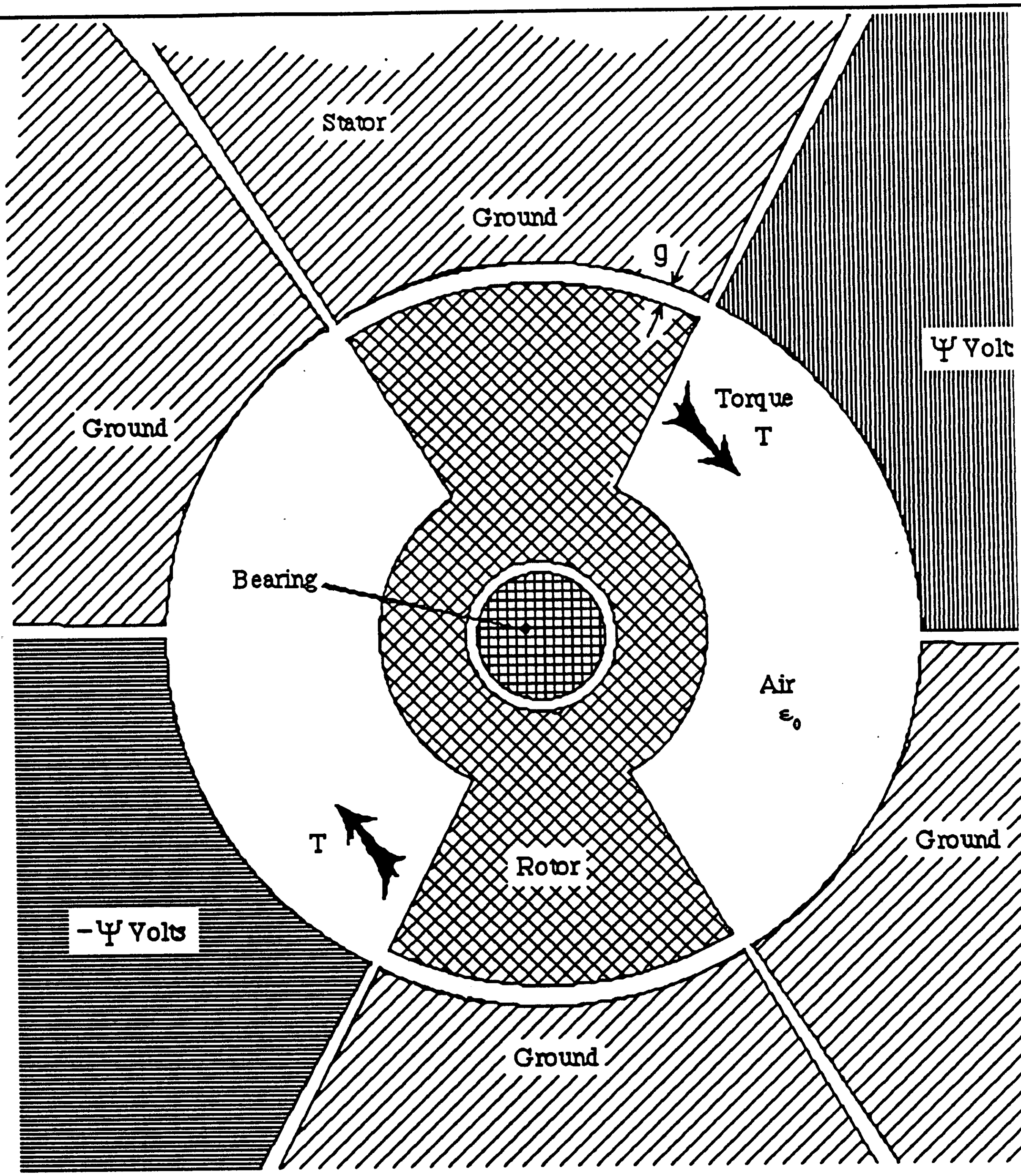

Figure 4. Schematic diagram of a variable capacitance micromotor. The rotor is free to move about the bearing. Applying a potential of 2Ψ volts across the rotor and the 2g gaps of stator electrodes that are offset from the rotor, gives rise to a change in energy in the gap, and hence a force. In this case of a radial air gap, a torque is produced tending to drag the rotor towards the electrified stators. Just as it lines up, the voltage is applied to the next pair of stators and the rotor spins.

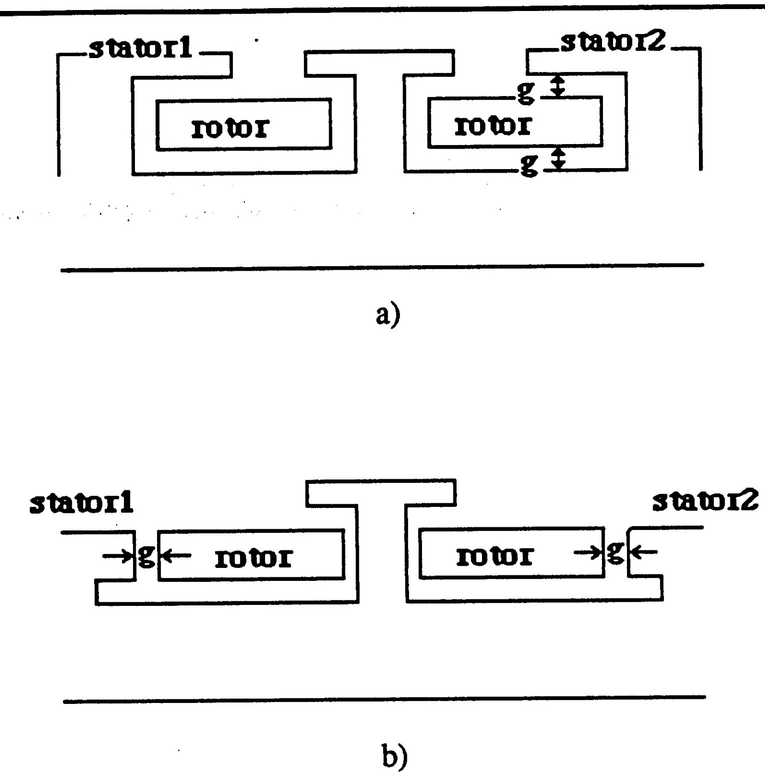

Figure 5. a) An axial-gap variable capacitance motor, where stator electrodes above and below the rotor levitate it halfway between while causing it to spin through voltages stepped around the stators. b) A cross-section of a radial-gap variable capacitance motor, in which a ring-shaped rotor slides around a bearing due to forces induced by voltages applied to opposite stators.

There are several avenues of design that can lead to ways around these problems. To address the gearing problem, completely different mechanical designs could lead to better methods for attaching a load. Wobble motors and piezoelectric motors both have built in gear reduction schemes for converting to more useful forms of mechanical output power. Another way to increase the available output power is to start with more energy storage in the gaps. The piezoelectric motor also implements this approach. Through the use of high dielectric constant materials, piezoelectric motors can potentially store far more energy for a given size and drive voltage.

To increase the total energy storage of a gap

$$U = \frac{1}{2}\varepsilon_o E^2 V$$

of a side driven variable capacitance motor as shown in figure 6 and thus the eventual output force or torque of the motor, we must increase either the permittivity (ε) of the gap, or the

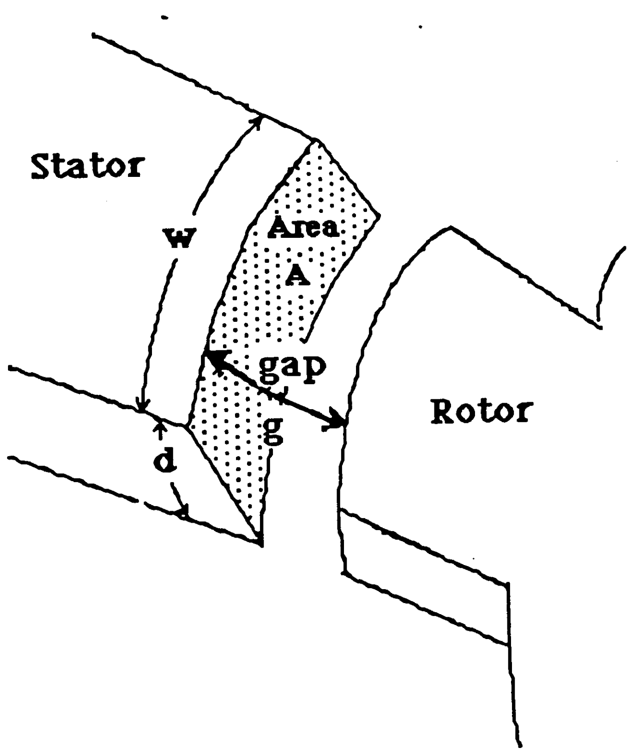

Figure 6. The energy stored in a radial gap variable capacitance micromotor can be increased by three means: 1) using a material with higher permittivity, 2) increasing the electric field, either by increasing the voltage or decreasing g, or 3) increasing the volume of the gap as the rotor slides past the stator, by increasing d.

magnitude of the electric field

$$|E| = \frac{\Psi}{g}$$

or the volume between the plates as they overlap

Since the variable capacitance motor requires the rotor to turn past the stator, a gaseous or possibly liquid gap is required (as opposed to a solid one). It is only practical for this gap material to be gaseous (usually air) which has a relative permittivity of 1:

$$\varepsilon_{air} = 1$$

For a variable capacitance motor, without the option of increasing the permittivity of the material in the gap, the remaining parameters available for adjustment are the electric field and the volume of the gap. Maximizing the electric field requires a large voltage and/or a narrow gap. The ability to make narrow gaps comes naturally with the microfabrication process, yet we have found that we still require high voltages, on the order of 100-300V, to achieve large enough electric fields for motor operation. Fortunately, voltages up to 400V will not induce breakdown in these very small gaps.

The volume can be increased by maximizing the area of the plates, as g should be as small as possible from the previous condition of creating a large electric field. As the force is the change in this energy per unit volume:

$$|f| = \frac{dU}{dV}$$

the only variable in this geometry that can increase the change in volume as the plates slide past each other is d. In this case, the standard fabrication sequence is not very helpful for the side driven variable capacitance motor because it is very difficult to make these high steps, d, using integrated circuit planar technology.

Harmonic Wobble Motors

The wobble motor is built around a harmonic gear to provide automatic reduction. This configuration uses *attractive* electrostatic forces (pulling plates of a parallel plate capacitor towards each other instead of across each other) and rolls the rotor around inside the housing instead of sliding it. Figure 7 shows a wobble motor consisting of a single-electrode cylinder which acts as a rotor rotating inside a ring of stator electrodes [Jacobsen et al 89]. The cylinder is successively stepped to neighboring stator electrodes as voltages are stepped around the stator.

Since the rotor's radius is smaller than the housing's inner radius (otherwise the rotor would simply stick), each time the rotor rolls once around the inside of the housing it only rotates a small amount about its own axis. As labeled in figure 8,

θ is the angle of revolution of the rotor
while ϕ is the angle of rotation of the rotor about its own axis.
R_s is the housing radius
R_r is the rotor radius

From [Bart 89], if it is assumed that the rotor rolls on the stator surface without slipping, the arc length from A to B must equal the arc length from A' to B. Thus,

$$R_s\theta = R_r[\theta + (-\phi)]$$

where ϕ is the rotation of the rotor about its own axis and is chosen with a negative sign to indicate that the direction of rotation of the rotor is opposite the direction of rotation θ, about the stator's center. Note that $\frac{d\theta}{dt}$ corresponds to the electrical excitation frequency. The gear down ratio can then be discerned by noting,

$$\text{geardown} = \frac{\text{rotor rotation about stator center}}{\text{rotor rotation about rotor center}} = \frac{\theta}{\phi}$$

$$= -\frac{R_r}{R_s - R_r}$$

Note that for fixed R_s,

$$R_r \rightarrow 0;\ \text{GDR} \rightarrow 0$$

$$R_r \rightarrow R_s;\ \text{GDR} \rightarrow \infty$$

$$R_r \rightarrow \frac{R_s}{2};\ \text{GDR} \rightarrow -1$$

This geardown can be made arbitrarily large by specifying a rotor radius which is

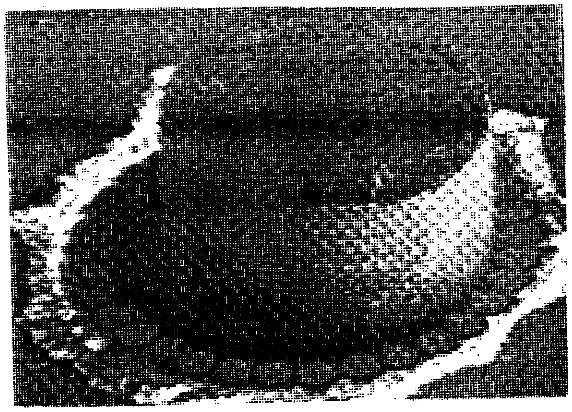

Figure 7. A wobble motor, extruded as opposed to silicon micromachined, uses electrostatic forces applied by the surrounding stator electrodes to force the rotor to "wobble" much like a harmonic gear [Jacobsen et al 89]. Reprinted by permission.

infinitesimally smaller than the housing radius. In practice, a geardown ratio of 50-100 is probably the maximum available.

Wobble motors make use of the force associated with collapsing two capacitor plates as opposed to aligning plates as with the variable capacitance motor. One can think of the wobble motor operation as similar to the variable capacitance motor operation described in figure 6, except that the wobble rotor moves in the direction g instead of w. As a first approximation, we can compare the forces produced by the variable capacitance and wobble motors if we model the wobble motor at the point furthest from contact as a parallel plate capacitor of gap g.

$$f = \frac{dU}{dV} = \frac{1}{2}\Psi^2\frac{dC}{dV}$$

$$|f|_{\text{wobble}} = \frac{1}{2}\Psi^2\frac{dC}{dg} = \frac{1}{2}\varepsilon_o\frac{wd}{g^2}$$

$$|f|_{VC} = \frac{1}{2}\Psi^2\frac{dC}{dw} = \frac{1}{2}\varepsilon_o\frac{d}{g}$$

where d,w and g are as shown in figure 6.

Therefore,

$$\frac{|f_{\text{wobble}}|}{|f_{VC}|} = \frac{w}{g}$$

and for typical dimensions attainable with a silicon fabrication process,

$$\frac{w}{g} = \frac{20\mu m}{2\mu m} = 10$$

which estimates that a wobble motor produces about 10 times as much force as a variable capacitance motor. However, a wobble motor is actually better than that because as the plates collapse, the fields get stronger (as opposed to staying constant as in the aligning case with the variable capacitance motor).

The amount of energy imparted to the rotor for each stator phase is given by an expression identical to the case of the variable-capacitance motor:

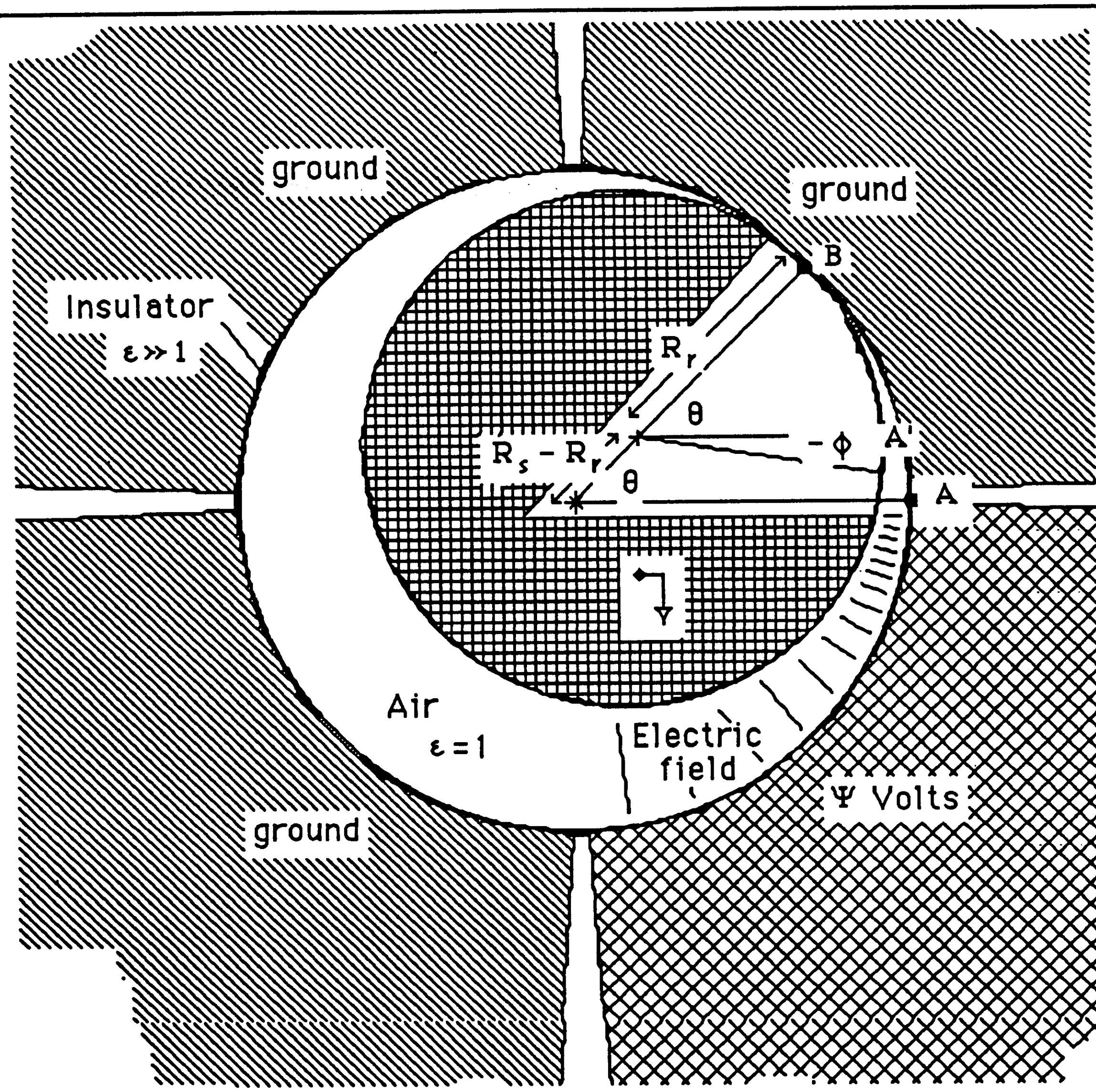

Figure 8. In a wobble motor, stators are pulsed in turn, attracting the rotor with the collapsing force of a capacitor as shown by the electric field lines in the diagram. This causes the rotor to roll inside the housing. The wobble motor provides inherent gear reduction as it takes many electrical cycles around the stator to achieve one rotation of the rotor.

$$|f| = \frac{dU}{dV} = \frac{1}{2}\Psi^2\frac{dC}{dV}$$

which when integrated gives the amount of mechanical energy imparted to the rotor per phase:

$$\Delta U = \frac{1}{2}\Psi^2(C_{max} - C_{min})$$

where C_{max} and C_{min} can be thought of as the capacitances of the gap when the wobble rotor is as close as possible to and as far away from, the stator electrodes respectively. For the case of a variable capacitance motor, C_{min} occurs when the plates do not overlap at all ($C_{min} = 0$) and C_{max} is the case when completely aligned. For the wobble motor, its C_{min} is the same configuration as C_{max} for the variable capacitance motor.

The ratios of changes in energy per phase of the wobble motor and variable capacitance motor gives a measure of relative strengths of the two motors when we take into account the collapsing field in the wobble motor

$$\frac{\Delta U_{wobble}}{\Delta U_{VC}} = \frac{(C_{max} - C_{min})_{wobble}}{(C_{max}-C_{min})_{VC}}$$

As C_{min} for the variable capacitance motor is zero and C_{max} for the wobble motor is much greater than C_{min}, and recalling that the maximum C for a variable capacitance motor is the same as the minimum for a wobble motor, the ratio reduces to:

$$\frac{\Delta U_{wobble}}{\Delta U_{VC}} = \frac{(C_{max})_{wobble}}{(C_{max})_{VC}} = \frac{(C_{max})_{wobble}}{(C_{min})_{wobble}}$$

Since the rotor rolls against the insulation on the inside of the housing, the air gap is completely collapsed leaving only the insulator gap at the contact point. This thin insulator gap can create a very large capacitance and so this is the dominant term in the production of torque for the wobble motor. Normal integrated circuit compatible thin-film insulators often have permittivities of around 4 or 8, with thicknesses as small as 1000 angstroms. For a 1000 angstrom nitride film for example, which has a permittivity of 7.9 given a standard 2μm air gap,

$$\frac{(C_{max})_{wobble}}{(C_{min})_{wobble}} \cong 160$$

This means that when we consider the wobble motor as producing torque due to the collapsing, increasing force between the stator and rotor as they come into contact, we see that the wobble motor produces even more change in energy than our earlier constant-force calculations.

The wobble motor yields improved performance over the variable capacitance motor, but it is possible to increase it even further. It is conceivable to place a high-permittivity insulator in the gap with $\varepsilon > 1000$ to achieve even that much more energy density improvement over a variable-capacitance motor of equivalent dimensions, although this does require precise mating of the surfaces.

The wobble motor has some interesting advantages for other reasons also - essentially in the way it interacts with frictional forces. Friction and wear phenomena are very different at small scales than in the macroscopic domain we're accustomed to.

The wobble rotor rolls around within the stator as opposed to sliding against a bearing, as in the variable capacitance motor. Many researchers hope to solve the friction problem in a variable capacitance motor by "floating" the rotor on an air bearing, which would reduce friction (but not completely eliminate it, since air is viscous in the micron-scale domain) and thus try to eliminate wear. However, an air bearing will not withstand the coupling of a mechanical load and thus is not useful for robotics.

The standard frictional approximations are no longer valid at small scales. Generally, a frictional retarding force is proportional to the normal force between two contacting objects, with the constant of proportionality referred to as the coefficient of friction. There are two coefficients of friction, one for dynamic friction, for the case when two surfaces are sliding against one another and one for the case of static friction, in which there is no sliding. For large, non-smooth contacting surfaces (most cases), the frictional retarding force is independent of the area of contact because in actuality, the surfaces only physically touch in a very few spots due to surface roughness, irregularities, and overall non-flatness. This phenomena is often understood intuitively by imagining contacting two mountain ranges top to top.

However, in the micron-scale domain, surfaces are very smooth and standard notions of friction no longer hold. Atomically flat surfaces often "fuse" together and cannot be separated without fracturing the materials. Even in less extreme cases, friction is more of a problem in the micron-scale domain. For example, ball bearings and lubricants do not produce the same magnitude of friction reduction as they do for larger systems and often increase the friction instead of reducing it.

Wear is another important issue in the micron-scale domain. A contacting surface such as a piston in a cylinder may be expected to wear a few mils in its lifetime ($25\mu m = 1mil$). However, wear of more than $1\mu m$ would destroy the variable capacitance motor. Wear is even worse in the micron-scale domain since no lubricants are present to remove the residual wear particles.

With sufficient friction, the contact point between the rotor and the housing in a wobble motor will not slide. In a wobble motor, the stators are pulsed in turn, to electrostatically attract the rotor to the housing as shown in figure 8. This causes the rotor to roll inside the housing. The rolling motion of the rotor is the same as the rolling of the tires of a car on a road or the meshing of gear teeth. In all three cases, the contacting surfaces do not slide but statically come into contact and push away from each other. A large coefficient of friction is thus desired to make the system work without loss. For example, the friction of rubber tires with asphalt is large unless there is water on the road which lowers the friction and allows the wheels to slip. Similarly, the large friction in mircon-scale structures is ideal for wobble motors as it prevents the rotor from sliding. Furthermore, without sliding, the wear of the two contacting surfaces is virtually nonexistent and is only due to the deformation of the surfaces.

Using a metal machining technique called electric-discharge machining (EDM) which is completely three-dimensional and not integrated circuit based, researchers at the University of Utah have produced wobble motors with rotor radii as small as 150 µm [Jacobsen et al 89] and have successfully operated these motors for weeks without any signs of wear or performance degradation.

In terms of monolithic silicon fabrication however, even though these wobble motors can have energy densities orders of magnitude higher than variable capacitance motors, they are still reliant on radial gaps which are limited by integrated circuit planar technology. If it's desired to make the wobble motor compatible with a silicon process for integrating electronics, then silicon micromachining techniques will have problems fabricating large d dimensions.

A Piezoelectric Micromotor

The variable capacitance micromotor was an important idea because it completely changed our way of thinking about building actuators. By taking advantage of thin film technology with its capabilities for making very small gaps (~ 1 micron) and compatible electronics, mass produced motors smaller than we ever dreamed of have been prototyped. Some of the problems with silicon variable capacitance motors have been overcome with the introduction of the wobble motor. The wobble motor did two things: 1) it incorporated gear reduction right into the motor and 2) it exposed technologies other than silicon micromachining as viable for micromotors.

There are still many improvements that can be made however. The actuator we propose here, a piezoelectric thin film ultrasonic motor, stands on the shoulders of the ideas introduced by the variable capacitance and wobble motors, yet pushes forward in a few directions. On the one hand, as with the variable capacitance motor, it aims to stay as close to silicon fabrication methods as possible in order to gain the advantages of integrated on-chip control circuitry. On the other hand, it follows the lead of the wobble motor in seeking out new strategies for coupling mechanical power out to a load.

In addition, the piezoelectric motor idea incorporates the notion that if we step slightly outside the bounds of traditional integrated circuit materials and use new materials with high dielectric constants, then we gain an advantage in the ability to obtain higher gap energy densities. Furthermore, if we choose our materials carefully, we find that the same material that grants us higher permittivities can also perform the transduction of electrical energy to mechanical energy as a property inherent to the material itself. This class of materials, which has a long history in bulk ceramic form, but which has only recently appeared in thin films, is known as *ferroelectric thin films*.

Before we delve into the details of how to fabricate an actuator out of such a material, let's first relate a little background. Ferroelectric materials typically come in bulk ceramic form and as such are not compatible with silicon fabrication techniques. However, putting that issue aside for the moment, ferroelectrics are a subset of a wide range of electro-ceramic materials that have some very interesting properties.

As [Jaffe, Cooke & Jaffe 71] points out, of the 32 different crystal classes, 21 have lattice formations with an inherent asymmetry. Twenty of those 21 crystals exhibit piezoelectric properties, which means that application of a voltage across the material causes a mechanical deformation and conversely, bending the material produces an electrical signal. Of these 20 substances which have piezoelectric attributes, 10 contain an electric dipole moment in the unstrained condition, which leads to pyroelectric characteristics. The pyroelectric phenomenon appears as creation of an electrical signal when the crystal is exposed to a change in temperature. Some of these latter 10 materials also display ferroelectric traits. A ferroelectric material can have its polarization dipole reversed in direction through the application of a strong electric field. After the electric field is removed, the crystal retains the polarization direction, effectively acting as a solid-state switch.

A ferroelectric then, being a subset of pyroelectrics and piezoelectrics, contains all three attributes: it can transduce mechanical bending, sense changes in temperature and remember

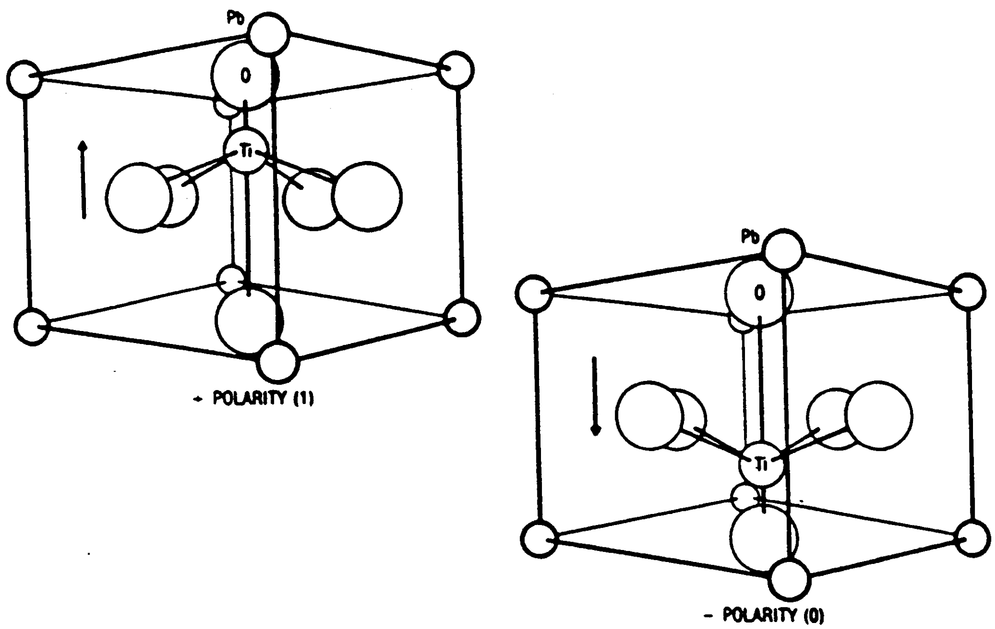

Figure 9. The crystal structure of the ferroelectric lead zirconium titanate, PZT, has an inherent bistable assymetry. The center titanium atom can be switched to one of two states creating a reversible polarization vector depending on the polarity of an applied electric field. The polarization dipole is also the cause of the piezoelectric and pyroelectric effects in which bending or heating creates a change in the magnitude of the dipole [Ramtron 88].

the sign of an applied electric field. In addition, ferroelectric materials are characterized by having very high dielectric constants, which makes them a good capacitor material.

Piezoelectric, pyroelectric and ferroelectric phenomena have been used in a wide variety of applications. Materials that are predominantly piezoelectric are often used in items such as speakers, touch sensors or microphones and can be found in bulk ceramic or thin film form [Kynar]. Ceramics with large pyroelectric coefficients are used in applications which sense changes in infrared energy such as burglar alarms or night-vision scopes [Eltec]. Recently, some materials which exhibit ferroelectric properties have been produced in thin film form and incorporated into memory chips to create non-volatile random access memories [Ramtron 88].

One ferroelectric material with a very high piezoelectric coefficient is lead zirconium titanate, otherwise known as PZT. Figure 9 depicts the crystal structure of PZT illustrating the inherent assymetry in the lattice and the bistable states of the central titanium atom which leads to the polarization dipole creating the ferroelectric effect.

Recently, macroscopic motors made out of bulk ceramic PZT have been designed with very high efficiency [Kumada 85], [Inaba et al 87] and some even appear commercially [Panasonic]. What we propose is an actuator very similar in basic mechanical design to the latter, but scaled down to the micro domain and fabricated using thin films of PZT such as

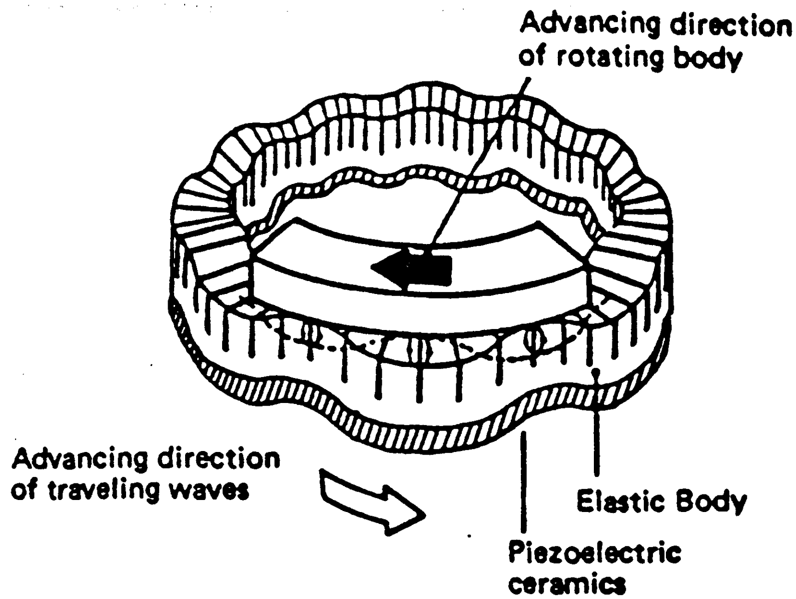

Figure 10. A piezoelectric ultrasonic motor induces a traveling wave of deformation in the stator. The bending motion creates a tangential force at every point in contact with the rotor, causing it to turn [Panasonic].

those developed lately by [Ramtron 88] and [Cross 89]. We'll discuss why we think this undertaking is appropriate, but first let's see how the Panasonic piezoelectric motor works.

Figure 10 shows the mechanism employed in the Panasonic motor. A traveling wave of mechanical deformation is induced in two piezoelectric ceramics and then mechanically amplified through the use of an attached elastic body. This structure effectively acts as a stator. An inert rotor rests on top of the stator and is caused to rotate by a tangential frictional force at every point which is in contact with the stator. The traveling wave mechanism then, essentially rectifies small vibratory motions of the piezoelectric ceramics into macroscopic rotory motion of the rotor. Note that a load can easily be attached to this rotor as there is no need to levitate the rotor (as in the case of a variable capacitance motor). Indeed, friction is actually necessary here to cause actuation.

In order to transduce electrical energy to mechanical energy, a ferroelectric material, such as PZT, must be "poled" (the process of permanently aligning the random polarized crystal orientations in the ceramic) through the application of a strong electric field. Once poled, a ferroelectric material will expand piezoelectrically when a voltage of one polarity is applied across it and contract when a voltage of the opposite polarity is applied. Figure 11 shows the bending moments due to this piezoelectric effect and illustrates how an alternating voltage applied to a ceramic such as PZT with alternately poled segments can produce a standing wave of elastic deformation.

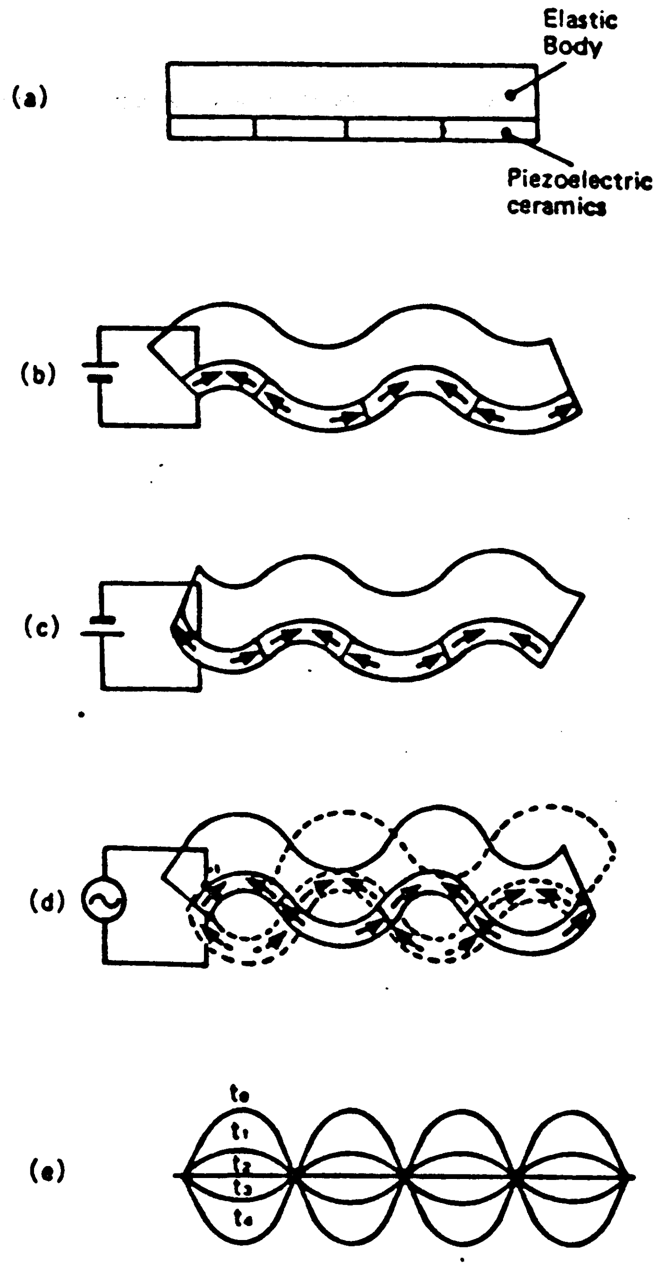

Figure 11. a) Alternately poled ceramic PZT segments with an attached elastic body (steel in this case). b) Application of a positive voltage causes expansion and contraction of the PZT segments. The elastic body grants mechanical amplification. c) Applied voltage of the opposite polarity induces contrary bending moments. d) Alternating voltages produce standing waves of elastic deformation. e) The amplitude of deformation increases and decreases over time [Panasonic].

This bending effect can be extended into a traveling wave phenomenon by using two sets of segmented and alternately poled PZT ceramics which are offset by half of their segment

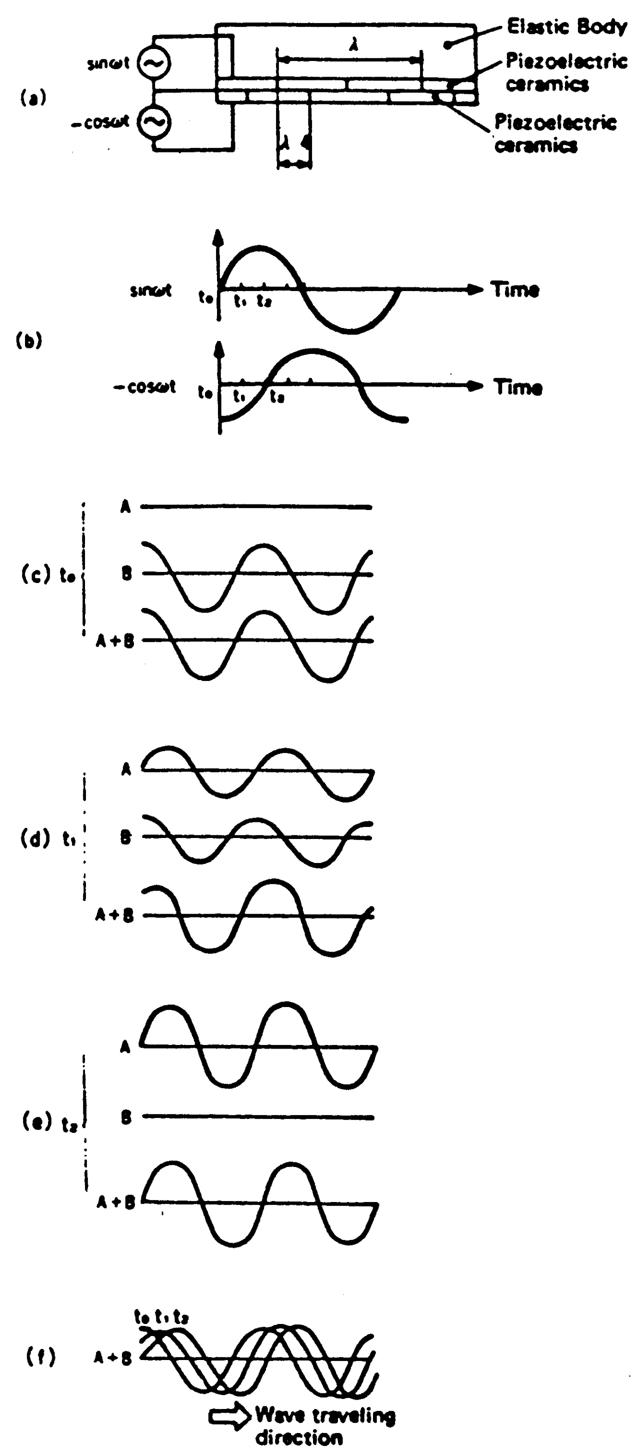

Figure 12. a) Two plates of alternately poled segmented piezoelectric materials are offset and attached to an elastic body. b) Each plate is excited with sinusoidal driving signals 90 degrees out of phase. c) d) and e) Deformation along the body at various time steps. f) A wave of deformation moves along the body over time. [Panasonic].

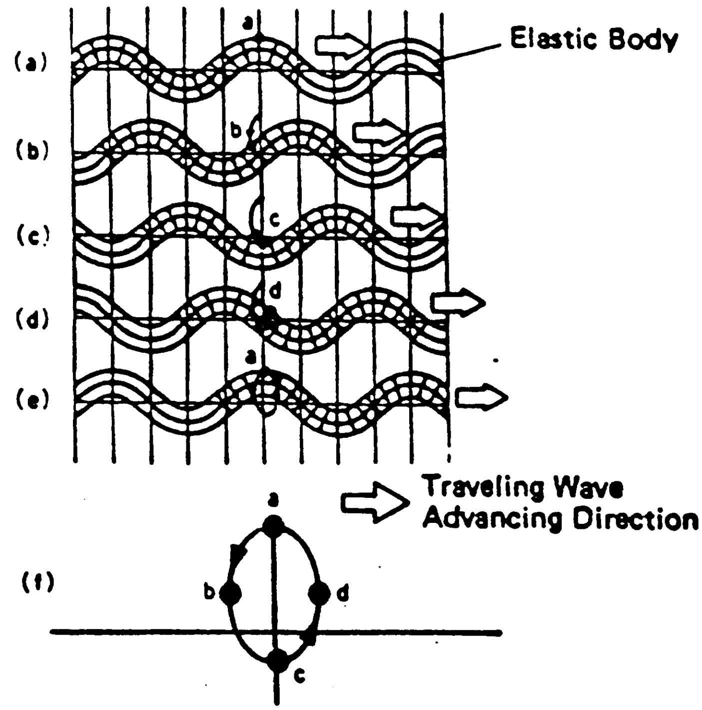

Figure 13. As a traveling wave of bending moves to the right through the stator, any point on the surface of the stator traces out an ellipse moving in the counterclockwise direction from A to B to C to D and back to A. Note that at position A, the stator point is moving to the left. If a freely moving structure (a rotor) is laid on top of the stator, it will be in contact with the stator during bending, at points A, hence the rotor rotates to the left. [Panasonic].

length, as shown in figure 12. By applying alternating voltages 90 degrees out of phase to each of the ceramic pieces, a traveling wave of deformation is induced in the elastic body which is attached to the ceramic driving plates. The deformation wavelength is twice the segment length.

As this traveling wave moves through the body (to the right in the example shown in figure 12), it can be shown that any point on the elastic body moves such that it traces out a counter-clockwise elliptical trajectory over time. This motion is graphically illustrated in figure 13. Intuitively, this motion can be seen as a coupling between the motion that would come about from expanding and contracting, together with the energy of the traveling wave moving to the right. Note that when the traveling wave is moving to the right, point A is moving to the left. If a rotor is placed on top of the stator then, it will contact the stator when it is in position A and so will rotate to the left.

Note that friction is used as a feature here. Gravity, or some normal force holding the rotor and stator in contact is necessary for this tangential force from the stator at each point A, to be rectified into continuous motion of the rotor. In some sense this is similar to the mechanism the wobble motor employs by rolling one cylinder in contact inside another cylinder. Both use friction as a method of coupling power out, as opposed to the variable capacitance drive which relies on a rotor sliding around a bearing, where friction creates losses.

The ferroelectric materials used in these piezoelectric motors have extremely high dielectric constants. PZT has a dielectric constant of 1700. Compared to the energy stored in the gap of a variable capacitance or wobble motor (if we take the gap here to be the thickness of the PZT material)

$$\frac{1}{2}\varepsilon_{air} E^2 V$$

then for the same drive voltages and similar geometries, if we replace ε_{air} by ε_{PZT} then we effectively increase the energy stored in the gap by a factor of 1700 for a piezoelectric motor. Even better, there are some new ferroelectric materials, germanium silicates, which have dielectric constants of over 100,000!

Traveling wave motors such as the Panasonic ultrasonic motor have inherent gear reduction due to the rectification of high frequency vibratory motion into continuous rotary motion. These high torque, low mass, low speed motors are ideal for robotic applications as complex gearing can be omitted.

Let's not forget of course, that one of the main reasons we're interested in piezoelectric micromotors, is that they are not magnetostatic in character. As we've already seen, magnetic motors do not scale well to the micro domain due to current density problems and fabrication incompatibilities. Piezoelectric motors don't require magnetic materials, large currents nor three dimensional windings or coils. They do however, need a material not normally found in integrated circuit processes, a ferroelectric.

For the three reasons just stated, namely that piezoelectric motors are electrostatic, they can store high energies in their gaps and they can easily couple mechanical power to a load, piezoelectric motors look very promising for gnat robot micromotors. However, the final question remaining is whether or not it is possible to fabricate such motors in an integrated sequence, as the driving force behind a gnat robot is mass producibility and eventually lowered costs.

Fortunately, recent breakthroughs in materials processing have produced a thin film PZT material which is compatible with integrated circuit processing as a post-processing sequence [Ramtron 88]. By sputtering PZT onto digital memory chips, Ramtron Corp. has taken advantage of the ferroelectric properties of PZT to create a non-volatile memory. They use the fact that a ferroelectric material can have its polarization vector changed by application of an electric field (with that polarization "remembered" after removal of the field). Essentially they can set or clear a bit by application of the appropriate polarity electric field and then "read" the bit by sensing the polarization charge. Although this ferroelectric RAM makes no use of the piezoelectric properties of the thin film PZT they have developed, nevertheless the piezoelectric properties are still retained and could be put to fine use in a micromotor. Figure 14 shows a schematic of the ferroelectric RAM using PZT film. One reason for significant interest in these types of memories is that they are radiation hard. Memory storage is implemented essentially at the molecular level.

Other groups have been studying thin film ferroelectric materials and have recently developed a sol-gel process for creating crack-free films of PZT from 6000 angstroms to 1.2 microns thick [Cross 89]. Figure 15 illustrates this process in which a slurry of PZT is spun onto a wafer to a desired thickness and is then annealed at high temperature to form the crystalline lattice. After the anneal, the material is poled to induce the desired piezoelectric properties.

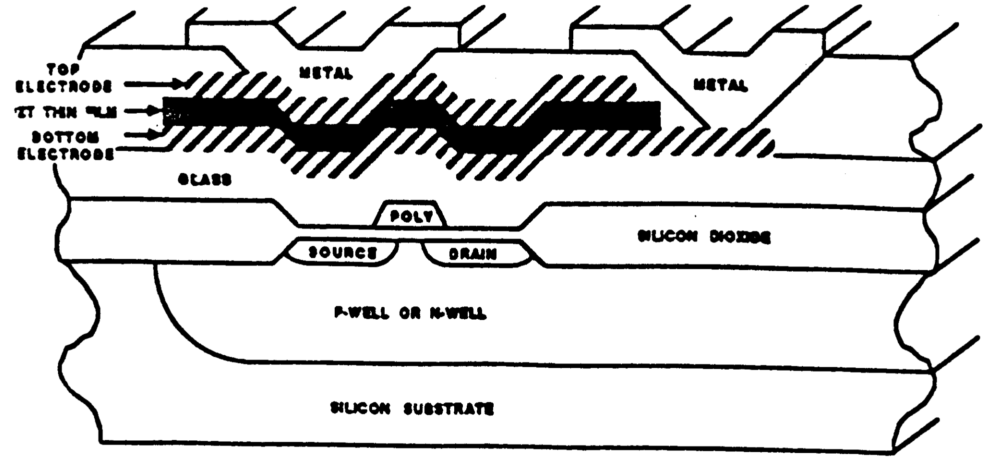

Figure 14. A ferroelectric non-volatile random access memory can retain its state after the loss of power due to the fact that a ferroelectric material can have its permanent polarization charge reversed with the application of an electric field [Ramtron 88].

With the availability of thin film fabrication processes for these ferroelectric films and even the demonstration of a form of compatibility with traditional CMOS processes, along with the added benefits mentioned earlier, piezoelectric micromotors appear extremely promising.

Eleven Advantages of a Piezoelectric Micromotor:

In summary, piezoelectric motors possess a number of attributes that make them attractive for scaling to the micro domain:

1) they are electrostatic and don't require any magnetic material
2) the rotor does not have to be levitated
3) friction is a feature rather than a bug
4) it inherently operates at high torques and low speeds
5) due to high dielectric constants, the gaps can store large amounts of energy
6) drive voltages can be correspondingly lower
7) any material can be used as a rotor, not just a conducting material, as the motion is coupled through friction and bending as opposed to charge attraction
8) it can be compatible with silicon fabrication processes allowing for integrated electronics
9) it's a top-drive mechanism, which means there is more surface area over which to create force
10) linear actuators can be designed, an advantage over wobble motors, and
11) it provides holding torque even in the absence of applied power.

What needs to be carried out now is an investigation into the materials' properties of PZT thin film to determine the mechanical coupling coefficients and piezoelectric properties, as PZT in thin film form is likely to be different than PZT in bulk ceramic form. The efficiency of the piezoelectric form of energy conversion is given by the coupling coefficient,

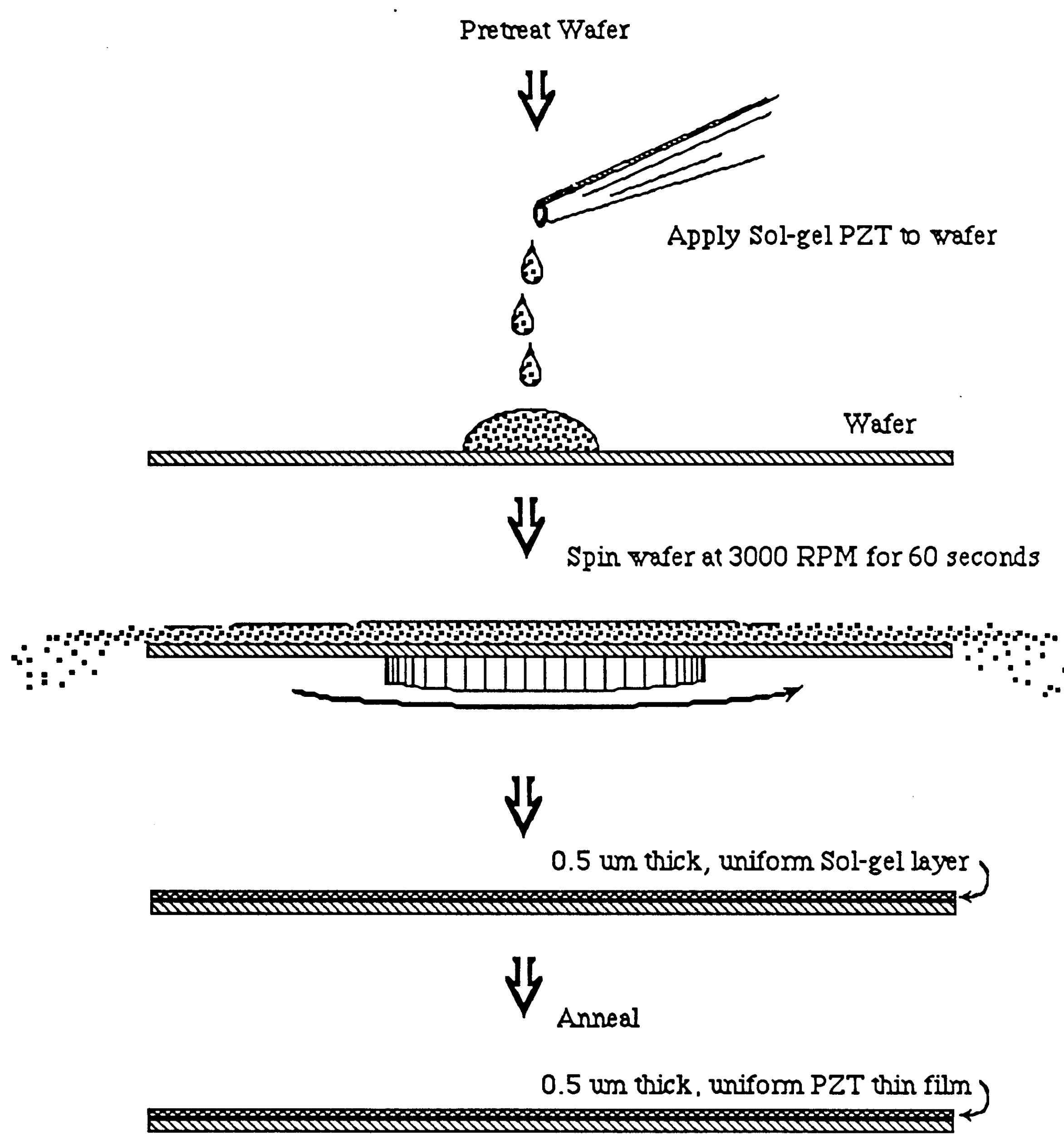

Figure 15. A sol-gel process can be used to make thin films of PZT. A slurry is formed and then spun onto the wafer in a thin coat. After a high temperature anneal, the film can be poled by the application of large electric fields to create a piezoelectric effect.

$$k^2 = \frac{\text{mechanical energy out}}{\text{electrical energy in}}$$

This can be as high as 0.7 in ceramic ferroelectrics, but hasn't been measured in thin film. Techniques also need to be developed for combining ferroelectric processing with silicon micromachining in order to produce freely moving members that are actuated by these films. Tools need to be developed for designing optimal actuators. These tools will probably take the form of finite element simulations as it's necessary to understand where the greatest mechanical bending or output power occurs for a given geometry. Finally, more thought needs to be given to packaging and to coupling motion of the actuator out of the plane.

At present, we are attempting to build membrane structures using silicon micromachining techniques. We are working with others [Cross 89] who possess sol-gel technology to lay down thin films of PZT on silicon micromachined membranes. These will be plated with electrodes and electrified in order to study the bending moments of the PZT films.

II. Power Supplies

Once motors are designed and fabricated, the next major hurdle is finding a source of power so that an autonomous gnat robot can carry out its business unencumbered by tethers to external power supplies. The majority of the bulk of large macroscopic robots is taken up by motors and batteries, and much of this bulk can be non-essential to the mission at hand (especially if the task is to collect information). The major theme in the design of small actuators is that if the total mass of the vehicle that needs to be driven can be made small, then we can get by with very tiny actuators. Similarly, in this power supply arena, if we can design our total system to draw only very small amounts of power, then we can get by with very tiny power supplies. Fortunately, the shrinking of motors and the shrinking of batteries go hand in hand, as smaller motors draw less power.

What are the potential sources of power for a small gnat robot? Solar cells are a possibility as they're made of silicon and can be manufactured very thinly (under a hundred microns) with low mass. Unfortunately, they aren't very efficient and indoors give only about a tenth the current provided by normal sunlight. In addition, there are fabrication problems with connecting solar cells in series on the same substrate due to junction leakage.

Batteries are another possibility, but even the smallest commercially available batteries would be far too large for a gnat robot. Unfortunately, the packaging of a typical battery takes up a large amount of room. If we could integrate batteries onto a chip, it would be possible to eliminate the package and tailor the energy source to the requirements of the robot.

This idea has actually been pursued recently with some interesting results. [Wrighton 89] has produced micro-batteries integrated onto a silicon substrate with an active area of only a few square microns - essentially the world's smallest battery. Using gold electrodes overlaid with a polymer, a chemical reaction is initiated which produces electrical energy. Although this work is only in the very early stages of testing, we support and encourage further research in this area as it promises to be a cornerstone technology for the development of gnat robots.

It's possible to extend this micro-battery idea to other materials as [Wrighton 89] has pointed out. Lithium-air or zinc-air batteries produce much higher energy densities. Furthermore, one could imagine actually using the lithium or zinc metals as the superstructure for the robot. Then as the robot goes about its work, using up its power source, the superstructure shrinks. Eventually the robot shrivels up and becomes non-functional and must be carried away from the worksite by its brethren - just like ants.

While we're speculating, we may as well consider the latest arrival on the high-tech front page - cold fusion. If cold fusion pans out, then all the old rules are off as the availability of such a cheap, dense source of power abruptly changes the practicality of old designs. Imagine now an actuator made out of palladium. Soak it in deuterium for a while, let it get hot, and then couple out power through a stirling engine...

III. Useful Gnat Robots and the Recursive Assembly Line

Two dimensional motors and structures are all very fine, but can they be used to build gnat robots that can do useful work? One idea called for a flying gnat robot. In that case the turbines would be integrated with the motors themselves, and the air would flow through the silicon chip perpendicular to the plane, so 2-D fabrication techniques would work fine. But for gnats that are to operate on surfaces with legs or wheels, the picture is not so clear. It is further complicated if one wants gnats with onboard manipulators. How can one build anything but a planar manipulator?

[Smits 89] has described a partial design for a complete antlike gnat robot. It uses torsion elements fashioned from cantilever beams as actuators. By using pairs of such elements reasonable excursions perpendicular to the silicon wafer can be attained. However simple calculations reveal that this design will need to make hundreds of thousands of steps to move a centimeter. The total robot is a couple of millimeters long, so this does not seem a promising way to locomote.

It seems necessary to move to a three dimensional structure. But ideally, we would like to integrate an entire gnat robot on a single chip which could be mass-produced cheaply and efficiently. We need to develop new low cost manufacturing techniques for three dimensional structures. Furthermore, the complete integration of electronics, sensors, actuators and batteries is frought with processing difficulties, mostly due to cross-contamination and process incompatibilities.

Fortunately there is an ideal solution for both these problems. Use three dimensional gnat robots themselves to do the three dimensional manufacturing steps on identical copies of themselves. At first this may sound outlandish; self-reproducing machines! But we will still use lithography as the primary detailed manufacturing step, working at a much finer scale than the three dimensional manipulations necessary for the robots. Thus they are only building copies of themselves at a very coarse scale, much as a human can sculpt a coarse full scale likeness of a human from clay.

The gnat robot we are proposing will be approximately spherical in shape, and about two or three millimeters in diameter. It will have a number of identical appendages distributed over its surface. The idea is shown in figure 16. Sometimes these appendages will be used as legs. At other times, pairs of them will operate in tandem as a manipulator/gripper combination, as figure 17 illustrates.

We propose a hybrid assembly of individual silicon dies onto a laser sculpted plastic body. The dies would be separately fabricated for electronics, sensing, etc. and mounted on the plastic body using special fixtures as will be described. Laser selectively-deposited tungsten (a process called laser pantography) will then be used to wire up the complete robot. Issues of silicon passivation will also be discussed for protecting the robot from the environment.

3-D Laser Molding

Three-dimensional free-form laser molding appears extremely promising for producing the inner shell of a gnat robot. Since the structures are made out of one material, they are useful

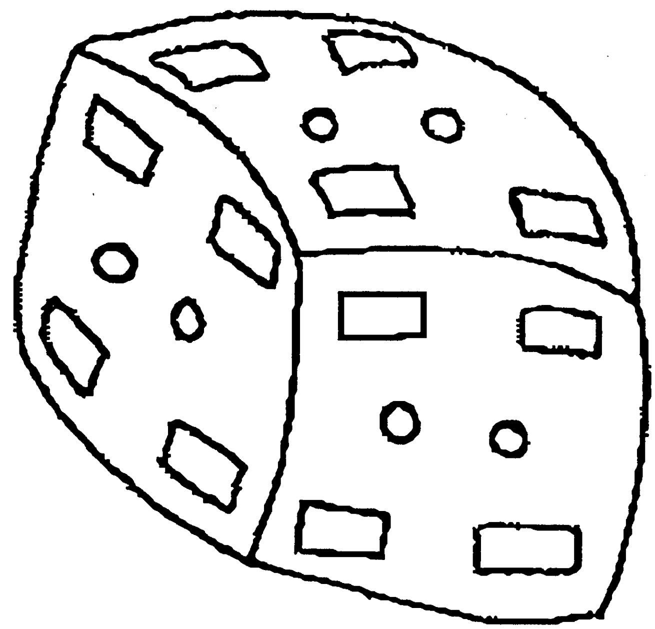

Figure 16. A dismembered gnat robot. An appendage will eventually be mounted through each rectangular hole.

for structural support but not necessarily electrical function (however, it may be possible to use the structure as the electrolyte of an air battery such as a lithium-air battery).

It works as follows. A platform sits just beneath the surface of a liquid bath of polymer. A steerable ultraviolet laser is used to draw a pattern on top of the support. The polymer solidifies at every place hit by the laser. There is now a very thin solid structure sitting on top of the support. The support is slowly lowered and new layers of solid polymer are drawn on top of the existing layers. Eventually a complete three dimensional structure is built.

3-D systems Inc. [3-D Systems] currently markets a free-form molding system for producing plastic three-dimensional objects up to 9 inches on a side and with tolerances of around 0.5 millimeters. Market pressures have steered 3-D Systems into making systems which can create larger and larger models with the eventual goal of, for example, creating the entire prototype body of an automobile. We have investigated this system and see no reason why we cannot build a similar system with a maximum modeling size of 1 cm and a resolution approaching 1 micron.

Currently, the material of choice for free-form laser modeling is methyl-acrylate which is also used by 3-D Systems. The produced structures are plastic and electrically insulating.

Methyl-acrylate is part of a broad range of organic photosensitive resists which are the cornerstone of the integrated circuit industry. The photoresist, polymethylmethacrylate (PMMA) is often used for defining features down into the submicron and deep-submicron range (1μm - .01μm) in state-of-the-art silicon processes. Thus, the granularity of the related methyl-acrylate will not limit the size or resolution of the proposed robots. These photo polymers are also cheap and non-toxic when polymerized.

Using these techniques, a body will be fabricated. It will essentially be a hollow three dimensional sphere with many holes in it at carefully designed places. Inside will be various flat surfaces usually opposite a hole on the other side of the sphere. Laser sculpting will also be used to independently build a set of appendages. Silicon building blocks will now be placed inside the robot body.

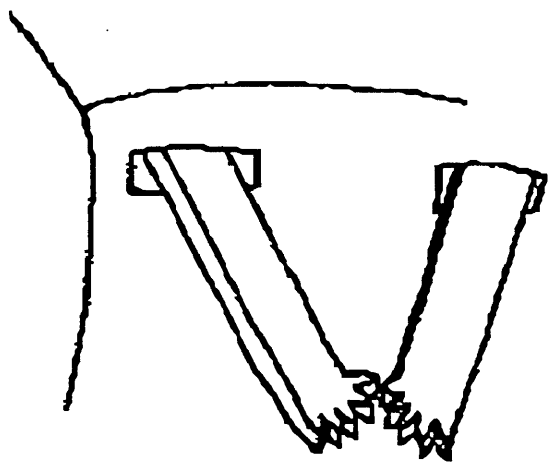

Figure 17. Two rigid appendages work in tandem as a manipulator. Working separately they can operate as legs.

Silicon Building Blocks

Most of the key ingredients of a gnat robot can now be made directly in silicon: electronics and sensors, and more recently, motors and batteries. However, this does not necessarily imply that these parts can be made on the same piece of silicon at the same time. Fabricating the metal oxide semiconductor (MOS) transistors for the robot's brain, control, and drive circuitry requires very special process considerations as combining such diverse requirements can lead to contamination problems.

There are three major effects of impurities which can ruin MOS transistors: high electron-hole recombination rates due to deep-level donor impurities, voltage thresholds shifts due to mobile ion impurities in gate oxides, and large interface charges due to surface contamination. Some materials that cannot be present during MOS transistor fabrication are for example, gold, copper, iron, and zinc which are deep level donors and sodium, potassium, and lithium which are mobile ions in oxides. These materials and others will also cause excessive interface charges and in extreme cases, fermi-level pinning (which will destroy MOS transistor action), if present during deposition or thermal growth of thin films.

In addition to contamination problems with combining processes for various different types of devices and structures, thermal problems also create headaches. Many processing steps can be ruined by later steps that use high temperatures. For instance, it's desirable to dope the source and drain regions of small MOSFETs to only very shallow levels, but subsequent processing steps may require high temperatures which will inadvertently cause the doped junctions to diffuse to deeper levels. To prevent these junctions from diffusing inappropriately, the wafer cannot be exposed to temperatures above 800 C for any length of time. In addition, high temperature cycling of wafers tends to both reduce mobilities and overstress wafers, affecting transistor yield and performance.

Furthermore, while the integrated circuit industry has proceeded towards finer features, thinner layers, and lower temperature processing for higher performance transistors with greater packing density, mechanical microstructure rigidity requires much thicker films, and often correspondingly higher temperatures. Some of the processing techniques which have been lovingly tweaked by the semiconductor industry for years have produced the opposite characteristics for what we need for gnat robot structures and actuators. So, while we'll want to borrow as much technology as possible, we'll have to invent new processing methods for integrating entire robots.

There are ways around some of these problems. Unlike cross-contamination issues, thermal management problems do not prevent mechanical and device wafers from being processed in the same lab using the same equipment. This allows for sharing of resources which is important during research and development considering the large expenses associated with a fabrication laboratory. Wafers containing films that could possibly contaminate the normal fabrication procedures can often be protected or passivated with special layers. Finally, special layers are often applied on top of, and thus after, fabricated transistors and consequently can be removed to a separate fabrication laboratory with a much reduced subset of equipment for final processing [Ramtron 88]. Passivation layers, while important for protecting circuitry from contamination due to further processing, are also crucial for protecting the circuitry from the environment during use. This problem is particularly important for most sensors and actuators which cannot be hermetically sealed in packages. Water absorption and metal interconnect rusting may shorten a part's lifetime to only weeks or months before failure.

Passivations layers range from phosphosilicate glasses to silicon nitride (or often a non-stoichiometric form of silicon nitride called silicon-rich nitride which has a lower stress). Nitride layers are particularly good passivation layers because they effectively block the diffusion of most elements. They also do not absorb water unlike the phosphosilicate glasses.

Although it's possible to integrate different processes and avoid contamination by adding protective layers, these steps lead to an overall increase in process complexity. It is much simpler to separate functions onto different wafers and later recombine them during packaging. Without transistors on chip to provide buffering, preprocessing, and signal conversion, noise limits greatly reduce sensitivities of solid-state sensors. To reduce this noise, hybrid packaging and multi-chip carriers are often used to move the electronics and sensors into closer proximity. The added cost and complexity of such a system usually is justified in greater performance. Packaging issues remain the single most difficult problem in solid-state sensors (and now actuators) and are often the stumbling block to commercial realization of excellent laboratory devices.

We understand the difficulties relating to packaging and will pursue packaging issues, in some cases, even before devices are designed.

Assembling The Robot

We propose to assemble functionally separate dies onto the faces of the plastic free-form molded bodies and wire them up with laser selectively deposited tungsten. The dies will be constructed to either snap into exactly prescribed places (like Legos) or possibly to simply adhere to the plastic body with wide placement tolerances (like Velcro). We term these assembly types, exact placement and proximity placement, respectively.

Using exact placement, the difficultly of assembly will be offset by simpler interconnect and reduced size from tighter tolerances. Tungsten lines will be deposited from die to die using the same scanning laser system as with the free-form modeling. Snap connections can be made either by bulk micromachining the silicon die edges into long appendages which will fit into predefined holes in the plastic bodies or conversely, by spikes on the surface of the plastic bodies which snap into bulk micromachined holes in the dies. The first approach mounts dies perpendicular to the bodies while the second approach mounts them parallel (i.e. flush). While the flush mounting may seem to be easier to "wire up" components, the micromachined appendages in silicon can transfer interconnect directly to the plastic bodies, which may be desirable.

With proximity placement, pieces need not be applied as accurately. Instead, they will stick down wherever they are placed. This system should allow greater flexibility by allowing the user to configure the robot to his specifications without changing the robot body. Computer vision systems will be necessary to detect exact die placement in order to wire the dies correctly. Active vision based on laser scanning can reduce the offboard computational load of this process.

Lastly, the pre-built appendages will be attached to the new motors.

So now the robot is built, but it has included a number of steps which require manipulation of very tiny parts. In general, these steps will be expensive and so the cost of the total robot will not be comparable to the cost of 2-D robots built on a fab line. But there is a solution to this problem. The robots themselves are built to do micro-manipulation tasks! So with a little care in design, the robots will be able to do all of the manipulation steps on later versions of identical twins of themselves. The reason that this can possibly work is that the scale and accuracy of the required jobs is much more coarsely grained than the finest grain structure of the robots. All fine grain work is still done with lithography by a large fabrication line.

IV. Micro Sensors - A Room Temperature Infrared Camera

A gnat robot will need sensors in order to interact with its environment. A wide variety of silicon micromachined sensors are commercially available now and being based in silicon, would seem to be the proper components for integration into a micro-robot. Unfortunately, many of these micro-sensors don't provide the information a robot needs. Pressure sensors, accelerometers and chemical sensors can be made extremely small and integrated with smart signal processing, but what a robot needs most often is proximity sensors and recognition sensors. Often we put sonar rangefinders, active near-infrared proximity sensors or laser light-striper imaging systems on our robots to endow them the capability of roaming through their environments avoiding obstacles and searching for specified landmarks or goals.

The problem with these types of systems however, is that they are active - they emit energy to the environment. A gnat robot needs to use its power source conservatively and can't afford to send energy out in order to interrogate its surroundings. Ideally, we would like to use passive sensors which gather information from ambient conditions [Viggh & Flynn 88]. Imaging sensors such as cameras fall into this category and draw less power than many of the traditional systems used in robotics. There is a drawback however. Passive systems typically deliver less signal to noise ratio than active systems and so it takes more computation to extract useful information from the signal, but since software doesn't take up much space and computation can be done with low power CMOS electronics, the tradeoff is worthwhile.

Cameras made from solid-state charge coupled devices which are sensitive to visible light are commonly used by vision researchers to develop algorithms for image understanding. In robotics, visible light vision systems have had only limited success despite numerous advances in picture quality, algorithms, and computer power. The problems with visible-light image recognition stem from the incredible complexity of everyday scenes where objects have shadows, obscure other objects or blend into the background. Our eyesight is clearly our most complex sense, requiring close to a half of our actual brain volume to function. Furthermore, our eyes require high bandwidth to the brain even after greatly preprocessing the visual information in the retina. Instilling human level perception into a robot is a very difficult task, as we take so much human competence for granted.

There's a big difference between *sensing* and *perceiving*. It's one thing for a transducer to convert optical energy into an electrical signal. It's even fine to print out the pattern and show it to a human who will have no trouble understanding the image, but it's a different story to convince a robot that useful information lies hidden somewhere in a large array of bits. Optical image processing often starts with detecting intensity changes or edges in an image. The hard part however, is assigning meaning to all the edges produced by a typical scene.

Infrared imaging, on the other hand, promises much better image recognition for certain objects while requiring only a fraction of the computing power of visible light vision. Edges in an infrared image will be primarily outlines of a single body, free from any extraneous edges due to texture or optical patterns. Most objects, and especially animate objects, tend to have a characteristic temperature which is invariant and distinct from the background temperature in nearly all conditions. Imaging systems that are sensitive to temperature can thus easily spot these objects and recognize them from their temperature.

The problem with most silicon infrared imagers is that they need to be cooled to the temperature of liquid nitrogen. These are charge coupled device sensors designed for long wavelength electromagnetic energy. As these photons have less energy than visible light, the detected signal moves down into the noise floor unless the sensor is cooled. Carrying around a bottle of liquid nitrogen though, is not practical for a gnat robot.

What is practical, is using pyroelectric sensors to build a room temperature infrared camera. Since pyroelectric elements are based on a polarized crystal which changes magnitude (inducing charge) when exposed to infrared radiation, as opposed to silicon sensors which create charge carriers when hit by long wavelength photons, a pyroelectric sensor does not need to be cooled. Unfortunately, although pyroelectric imaging array cameras are commercially available, they are prohibitively expensive, running in the tens of thousands of dollars. The reason is that the ceramic crystals which pyroelectric arrays are made out of are assembled by hand, ground down manually to 20μm, diced into small cells and bump-mounted onto a hybrid substrate. Then, often a mechanical chopper is placed in front of the sensor to produce a static image of what normally would be a motion image. Typical readout circuitry often senses the current (the *change* in charge) produced by a *change* in temperature, hence a pyroelectric camera normally needs relative motion to produce any signal.

What we desire is a static imaging camera that works at room temperature, can be very small and can be mass produced cheaply. Since it just so happens that the ferroelectric material we will be making our piezoelectric actuator out of is also pyroelectric, we can build our sensor with the same technology! Not only does the resulting sensor fit our bill entirely, but it doesn't even add any new steps to the fabrication sequence we'll need to build the motor.

By combining high-peformance analog VLSI with a high-quality pyroelectric material, we propose to create a static, solid-state, room-temperature infrared camera. Recently developed switched analog circuit techniques have made possible the measurement of very small absolute capacitances using automatic calibration and noise cancellation. By measuring the actual capacitance of a pyroelectric film, as opposed the common method of measuring the charge produced from a change in temperature, a static infrared picture results.

Furthermore, we can get even better "fill factor" than a charge coupled device (CCD) sensor. Fill factor is a measure of how much of the chip area can be devoted strictly to sensing sites (as opposed to support circuitry). In a silicon CCD sensor, part of the chip surface area is devoted to silicon areas that collect photons and part is devoted to transistors and shift registers, etc. This means its fill factor is much less than one, leading to less than optimal resolution.

With a thin film pyroelectric sensor, support circuitry such as transistors or operational amplifiers can be built onto the silicon substrate and then the pyroelectric film, which acts as the sensor, could be laid down on top. Since no silicon areas are necessary for sensing, the fill factor for a thin film pyroelectric sensor can approach one.

Will an infrared sensor be sufficient for all the perception needs of a gnat robot? Possibly, if all it needs to do is detect or follow people or warm moving objects, but in general, it will probably need some mechanisms for recognition and/or obstacle avoidance. An infrared sensor may not fill these requirements. For these cases, optical imaging may be worthwhile, using simple algorithms, for instance such as optical flow, to avoid obstacles.

One problem with having both an optical and an infrared imager onboard the robot, is that it may be desirable to register the two images, carrying out some sort of sensor fusion. Sensor fusion is the notion that if you can combine information from multiple sensors into one model, you can achieve better perceptual acuity. The problem with sensor fusion though, is that it is computationally expensive and it's not clear that it helps in carrying out tasks. What we've found from our previous research in mobile robots is that the best way to deal with sensor fusion is to ignore it. Instead, our control systems use a form of sensor fission where different sensors trigger different behaviors and arbitration is done at the actuator level rather than the sensor level.

One way to get out of the sensor fusion bottleneck here is to invent our way out. As long as we're inventing the room temperature infrared sensor of our dreams, let's just invent a dual optical-infrared imaging system that doesn't produce any sensor fusion bottlenecks.

Ideally, an infrared system would be coupled to a visible-light system, the strengths of one system used to complement the other. As our thin film pyroelectric material is compatible with traditional silicon processes, what we do is build a visible light CCD sensor in the traditional way. If silicon photosensor sites take up 50% of the chip area and transistors take up the other 50%, then we lay down thin film PZT over the transistors which provide the support electronics for both transducers and use this 50% of the chip area to become another sensing area - only this time for infrared energy. Now the fill factor approaches one; 50% for visible light and 50% for infrared. For the same fill factor we would have had anyway for a typical CCD camera, we now have a multispectral imaging system in which the images are perfectly registered.

It's interesting to note the versatility of these ferroelectric films. We've already seen how it's possible to build actuators out of the material. Pyroelectric sensors are another application as discussed here. The switching properties can also be tapped to make non-volatile memories. In addition, the material is both radiation hard and compatible with traditional CMOS processes as Ramtron has shown. By taking advantage of the piezoelectric, pyroelectric and ferroelectric properties of these materials, we can essentially build most of the components of a gnat robot in a single process. That's luck.

V. Intelligence for Gnat Robots

Now we have robots with sensors, power supplies, actuators and silicon area available for micro-circuits. The micro-circuits must endow the gnat robots with enough intelligence to do useful work. How can this be done with current technology? One of the primary areas of research in the mobile robot group at MIT over the last fours years has been to develop an architecture which allows us to control robots with very small amounts of computation,

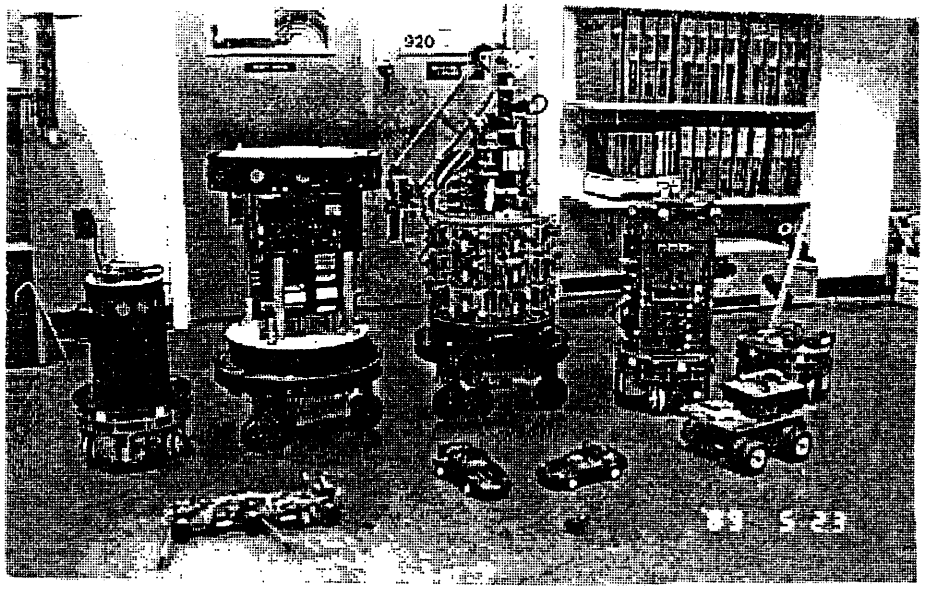

Figure 18. The MIT mobile robots (from left to right, back perimeter): Toto, Allen, Herbert, Seymour and Tito; (middle) Genghis, Tom and Jerry and Labnav; (down in front) Squirt.

which is also potentially compilable to small areas of silicon.

The subsumption architecture [Brooks 86] is a parallel and distributed computational formalism for connecting sensors to actuators in robots. The subsumption architecture provides a way of writing intelligent control programs for mobile robots. One writes a subsumption program by specifying layers of networks of augmented finite state machines. These are finite state machines augmented with timers which can be set to initiate a state change after some fixed time period has passed.

The three key aspects of the subsumption architecture are that (1) it imposes a layering methodology in building intelligent control programs, (2) within each network the finite state machines give the layer some structure and also provide a repository for state, and (3) it turns out with this organization that only very small amounts of computation are needed to generate complex intelligent behaviors.

We have built and controlled a large number of robots with the subsumption architecture. The family portrait is shown in figure 18 and includes a robot which successfully navigates in an office environment and collects empty soda cans from cluttered desks, and a six legged walking robot [Brooks 89] which scrambles over rough terrain, chasing infrared-emitting prey. The control system for the six legged-robot is organized into eight incremental layers: Standup, Simple Walk, Force Balancing, Leg Lifting, Whiskers, Pitch Stabilization, Prowling, and Steered Prowling. It is implemented as 57 finite state machines. It could be implemented directly in silicon on less than 5,000 transistors, none of which would need to switch at rates faster than 100Hz.

We have built a prototype silicon compiler for this architecture. More work needs to be done to enable it to compile complete subsumption programs and to process from its current gate

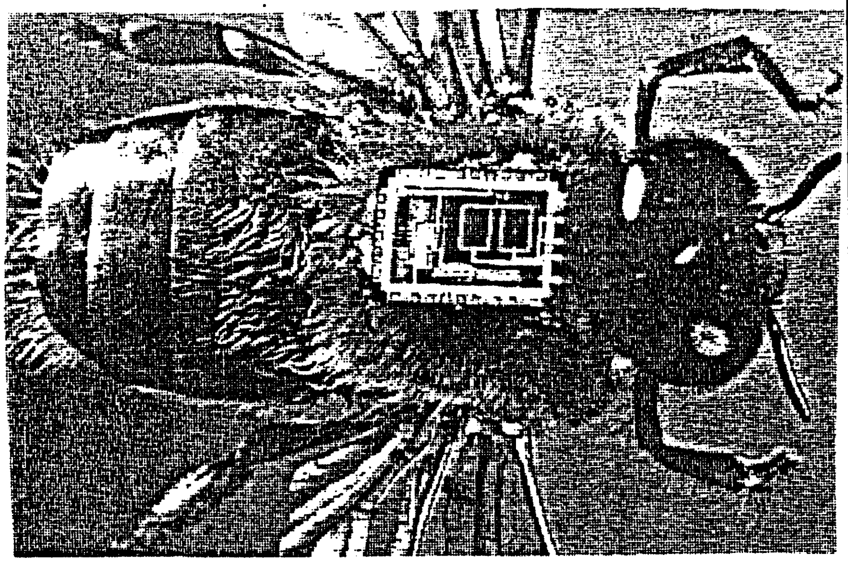

Figure 19. An integrated circuit incorporating signal processing, solar cells and a laser diode is attached to a killer bee to track their progress. [Science News 88].

level output to a silicon design. However, our investigations so far, and our simulations with Xilinx reconfigurable gate arrays, have convinced us that there are no technological hurdles standing in the way of achieving this goal.

VI. Spinoffs Along the Way

Although our end goal is a completely integrated, mass produced gnat robot, we can see even at this stage, that there will be many spinoff technologies and potential products produced along the way. Applications undoubtedly will also appear that we could never foresee from our present vantage point. Nevertheless, a few spinoffs are already visible.

First, a low cost room-temperature camera would spark a huge industry. The military spends $4 billion per year on infrared sensor research for missile seekers and night vision scopes. Most of the technology being pursued now is for high resolution cooled imagers and consequently these expensive components will probably never trickle down to robotics or consumer electronics. Ferroelectric thin films on the other hand, hold huge potential for bringing useful sensors to the marketplace.

The small piezoelectric actuators that we have described could find their way into a host of new products. In fact, a Japanese camera company has already incorporated a piezoelectric (ceramic) motor right into the lens of an auto-focus system.

One interesting property of piezoelectric motors as opposed to variable capacitance motors or wobble motors is that the rotor does not have to be an electrode. That is, the rotor doesn't need to be electrified, as motion in a piezoelectric motor has nothing to do with coulombic attraction between separately charged plates. As the motion of the rotor is induced strictly through frictional coupling from a mechanically bending stator, a rotor of any material can be used. What this means is that the rotor could also propel aqueous solutions. As the solutions would not need to have any conductive characteristics, arbitrary fluids could be pumped with an actuator that has no moving parts. This feature may find itself extremely useful in small blood pumps or medical applications. It also may make hydraulic gnat robots possible.

Many of the subsystems needed for an autonomous gnat robot could be used for teleoperated tasks, remote control situations or remote sensing applications. Figure 19 shows a novel solution to a difficult problem. Researchers at Oak Ridge National Laboratory are investigating ways to track the killer bees headed towards North America [Alley 88], [Science News 88]. They've combined a small power source and a laser diode beacon into a small package and attached it onto the back of a bee for purposes of keeping tabs on the swarms. Not exactly a gnat robot, but not too far off either.

Besides the components such as sensors, actuators or batteries developed for gnat robots, some of the most useful spinoffs might be the tools we invent along the way. For instance, a free form solid modeling system with very high laser scanning resolution may find its way into completely different fields. Medical doctors doing research on treatments for burn patients have expressed a keen interest in this as precise laser surgery poses a potential breakthrough in burn therapy.

VII. Conclusion

We have shown that all the component technologies necessary to build a gnat robot are plausibly within reach of their required maturity. All of them require further work. The most critical however, is a demonstration of the feasibility of a piezoelectric thin film motor. Besides the component technologies, systems integration will also be a major issue. We believe it's possible for a dedicated team to build a prototype gnat robot in the next three years.

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