MASSACHUSETTS INSTITUTE OF TECHNOLOGY
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Fine Grained Robotics

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Abstract

Fine grained robotics is the idea of solving problems by utilizing multitudes of very simple machines in place of one large complex entity. Organized in the proper way, simple machines and simple behaviors can lead to emergent solutions. Just as ants and termites perform useful work and build communal structures, gnat robots can solve problems in new ways. This notion of collective intelligence, married with technologies for mass-producing small robots very cheaply will blaze new avenues in all aspects of everyday life. Building gnat robots involves not only inventing the components from which to put together systems but also developing the technologies to produce the components.

This paper analyzes prototype microrobotic systems, specifically calculating torque and power requirements for three locomotion alternatives (flying, walking and swimming) for small robots. With target specifications for motors for these systems, we then review technology options and bottlenecks and sort through the tree of possibilities to pick an appropriate path along which we plan to proceed.

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1 Once Upon a Solar System

Long, long, long ago there was a big bang.

In the confusion that followed, things got scattered.

Then a few eons later here on Earth, intelligent life appeared and developed complex societies.

Our mission is to figure it out.

(And then change it.)

2 A Robot Invasion

Changing the world involves changing the way people think. There are so many ways to make life better!

From space exploration to animated soap bubbles, we can change the world in all sorts of ways.

2.1 Space Exploration

The year is 2010 A.D. Mobot Lab Spinoffs, Inc. has delivered thousands of shoe-box-sized six-legged walkers to the Moon, Mars, Venus and Jupiter. These autonomous artificial creatures have changed the way we approach space exploration. No longer do missions rely on a single teleoperated robot to be the extensions of man's eyes and hands. Instead, hordes of small, cheap, self-controlled, redundant robots spread out to explore and send back their findings.

At even smaller scales, gnat robot micro-airplanes serve as forward scouts for the walkers. Dispersed from orbiters launched from backyard rail guns, millions of these sensor-laden airplane/gliders soar through the atmosphere attracted to feature points of interest. Micro-rovers notice the flocking behavior and scramble off in the direction of their winged friends for a closer look (figures 1 and 2).

As the legged micro-rovers traverse new terrain, they periodically drop gnat-sized sensor-signal mines. These tiny robots never move or locomote themselves but instead sit, sense and signal. Using passive sensors which only draw on otherwise dormant power packs when important events occur,

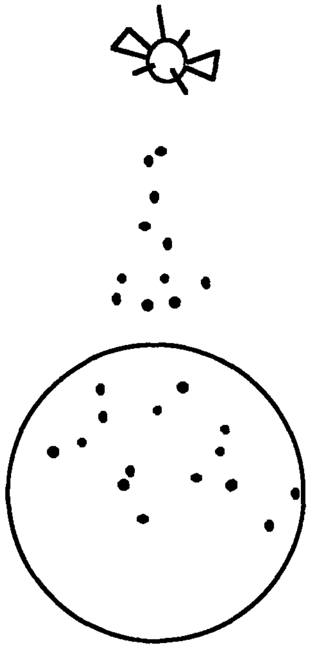


Figure 1: A rocket booster can carry hundreds of small robots in place of one behometh. Six-legged micro-rovers deploy with micro-airplanes for air support and sensor-signal mines for long-term surveillence.

these gnat robots can wait for years (for extra-terrestrial life perhaps, to wander by) before snapping a picture or setting a signal mirror (figures 3 and 4).

Terraforming robot ants in mass numbers dilegently scramble day and night to move grains of sand into piles, forming home bases for humans years before manned missions land. Other cosmic-bots perform mapping and mining missions. Just as prospectors pan for gold to find a surface hint of deeper treasure, prospector ants swarm the surfaces of other planets looking for crumbs of basalt and copper. Chemical factories in their mouths perform the taste test and when a strike is uncovered, these modern 49ers set their signal mirrors to beckon for beefier help.

Our robot invaders of the solar system are everywhere, listening, watching, being, acting and extending man's presence far beyond what manned

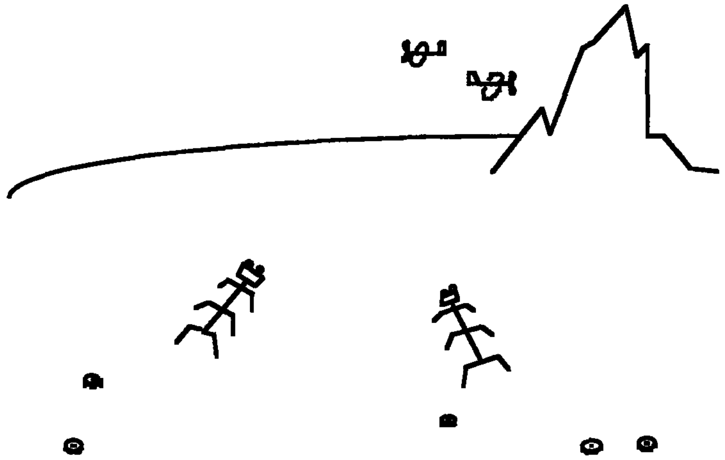


Figure 2: Forward scouts look for interesting phenomena. Communication is accomplished by side effecting the world. Flocking behavior of the winged craft draws the attention of the rovers, and they change course, dropping small sensor-mines.

space flight alone could ever achieve.

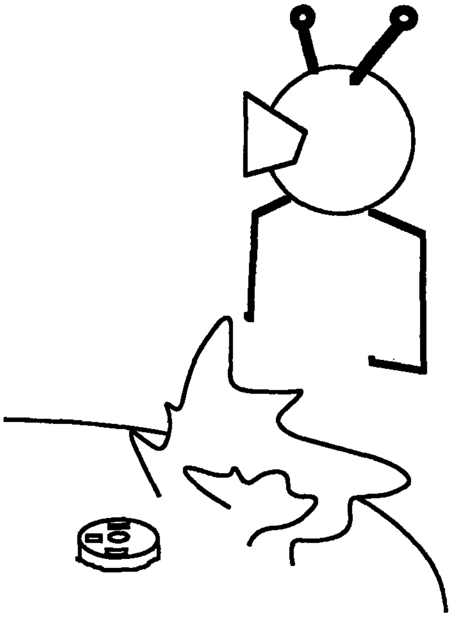


Figure 3: The sensor-mines willingly wait for eternity or something interesting (whichever happens first). Passive infrared sensors fire when extraterrestrial life forms amble by. The image is stored in non-volatile memory for later retrieval. Small actuators uncover a signal mirror for alerting the orbiting laboratory.

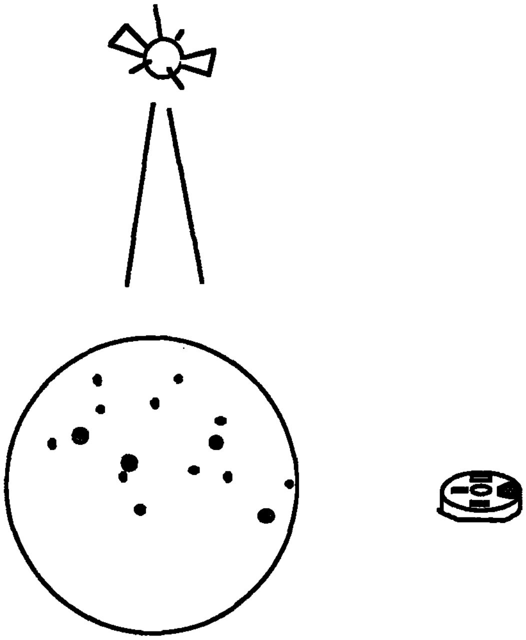


Figure 4: Successful target detection is marked by actuating a mirror/reflector. An orbiter can then scan the planet for marked sensor-bots, calculating a statistical distribution of life forms. Landing craft later retrieve the robots and the stored images.

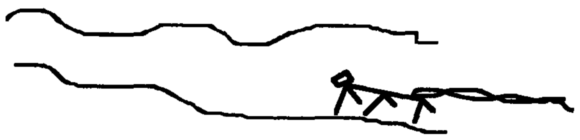


Figure 5: Small legged robots walk through internal organs transmitting images through a fiber optic tether.

2.2 Medicine

Back on Earth, medicine has reached new frontiers. Surgeons routinely perform exploratory endoscopic surgery with legged fiber-optic-trailing gnat robots, alleviating the need for cumbersome tools and discomfort to the patient (figure 5).

Micro plaque cleaners scrape cholosterol deposits from arteries. Autonomous surgical vehicles carrying acoustic links to the outside make their way to hard to reach spots. Doctors no longer make large incisions merely to make room for their hands. Other robots act as autonomous test and X-ray devices, carrying tracer pellets to targeted organs.

2.3 Electronics

While small size and low mass have created perfect niches for gnat robots in space and medical applications, low costs due to mass-producibility of these integrated machines produce even more markets. Factories now employ disposable robots, machines that require no maintenance and no spare parts. Circuit board factories use autonomous daddy-long-legs robots "that know where to go" (that is, they know their own pin-outs). They place one foot at one node, then stretch to place another foot at the point that needs to be connected. If the second node is too far away, the robot-connector enlists the help of a connector friend and they form a train. Batteries and motors only have to work for a short while. Once the robots have scattered to make all their connections, they just remain in place forever, serving their purpose

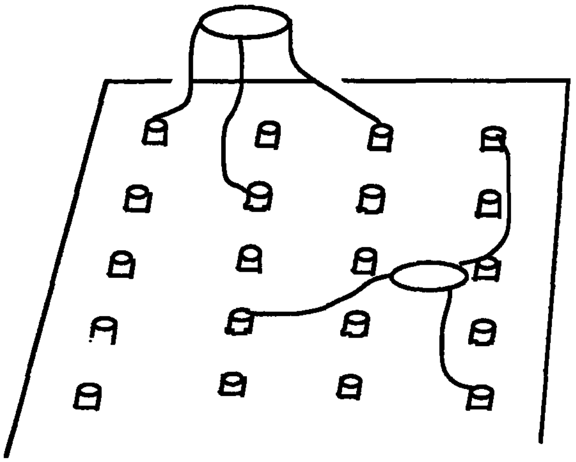


Figure 6: These legged robots use their legs to solve the task of wiring up a board. Once connections are made, toe to toe, the robot has served its useful purpose and remains fixtured in place forever.

as petrified autonomous pieces of wire (figure 6).

2.4 Under the Sea

Collective intelligence and multitude robotics emerge as yet another consequence of gnat robots. For oceanographic research, instead of one or two large scale teleoperated submarines working from an attendant ship, planes drop artificial minnows by the millions as autonomous sensors. They detect noises or sense chemical gradients and swim towards the source. Once they reach an area of equilibrium, the minnows eject a small amount of signal dye. Surveillance planes patrol for any signs on the surface, and the color concentration of the dye provides a hint as to what lies below (figure 7).

Bottom cleaning robots move along the floor of Bedford harbor searching for PCB nodules and toxic waste dumped there for years. The bottom cleaner munches bits of nuggets and stores them in its stomach compartment. When it is full, a nitrogen cartridge fills a balloon and the cleaner-bots float to the surface where a surface vehicle scoops them up. Mining of the sea bottom for manganese modules and precious metals, in an analogous way, is also a very profitable business these days.

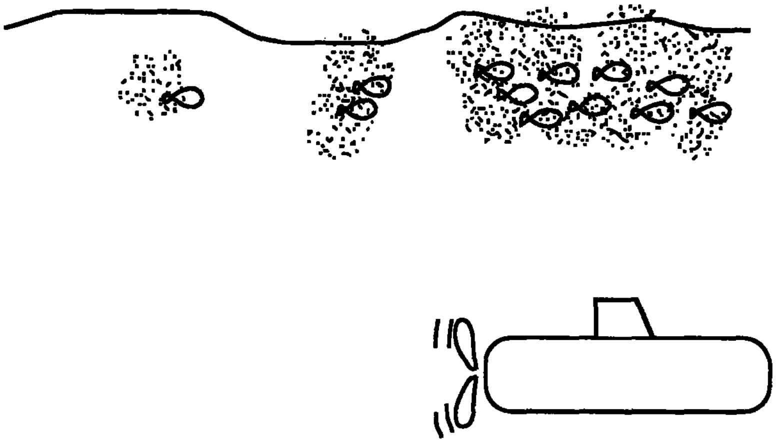


Figure 7: Swarming behavior of artificial minnows assists in oceanographic research. Each submersible robot independently and autonomously moves towards gradients of sensor-fare, which might be chemical pollutants, oil slicks or submarine noises (such as in the submarine detecting scenario pictured here). Global information is observed by noting location and density of the steady state minnow population near the surface.

Crab robots gnaw and brush away at barnacles which have fouled underwater oil rigs. In the olden days, when enough parasites attached themselves to the structures to render them unsafe, divers (at several hundred dollars per hour) would habitually swab the scaffolds. Now, the task is performed autonomously and unsupervised. Scrubber robots now perform hull maintenance on large ships. Toxic paint is from eras gone bye.

Surface scimming microrobots act as Boston Harbor pollution cops. If visiting ships inhospitably bilge their tanks, cop-bots signal the violation by emitting brightly colored tracer dye, alerting the harbor patrol.

Massive net fishing is a thing of the past. This form of hunting, by dragging huge nets between parallel ships would catch every living creature, profitable or not, destroying the ecostructure in the process. Now, fish-herd robots swim alongside sought after schools of fish and coax them into nets. The catch is fine-tuned and efficient.

Sport fishermen employ active smart fishing lures, which look and act like the sport fish's favorite meal.

Kelp harvester robots are the farmers of the underwater world. Entire new industries have sprung from this abundance of nutrition and cheap labor.

Weather forecasters now predict weeks and months ahead. Large array weather station robots floating by the millions in the gulf stream transmit fine grained reports of temperature, salinity and pH to orbiting satellites. Improved weather prediction impacts modern life in inumerable ways, from early storm warnings to farmers' almanacs.

2.5 Terrestrial Geo-Sensors

Micro robots which act as sensor mines not only affect space exploration, but change our image of our own planet. We sprinkle them on volcanoes and plant them along fault lines. Tremors and environmental changes are no longer spatially sparse data points. Large scale coverage and data transmission to satellite receivers make early warnings much more reliable.

Demilitarized zones are peppered with peacekeeping micro-mines. They sit and sense unwarranted action and signal appropriate authorities.

2.6 Environmental Task Masters

Insect robots control agricultural pests without recourse to chemicals. Fertilizers and pesticides of the past often reached levels of marginal value added, but at tremendous cost. Farmers now return to nature via robots. Migrant harvesters collect food and spread seeds.

Contaminated areas which no longer support earthworms and natural insects are coaxed back to life by robot bugs which aerate the soil.

2.7 Harzardous Job Replacers

Microrobot painters relieve humans of the job of scaling tremendous heights to paint corrosion-resistant coatings on bridges and other large structures, a job which usually began again as soon as one coat was applied.

Nuclear facilities with mishaps send in micro-explorers for damage control and status reports.

2.8 Manufacturing – Robot Compilers

Manufacturing has taken a quantum leap too. In fact, the gnat robots themselves which have changed the world in so many ways are the product of new ways of thinking. Complete machines are now totally designed in software using robot compilers. Sensors, electronics, motors and batteries are specified at the system level and then the details of geometry layout and process planning are automatically generated and handed off to backend programs which interface with numerically controlled machine tools and optical lithography equipment.

Robot compilers now allow designers to express functional descriptions for components. Sensors, batteries and intelligence networks are compiled with standard silicon compilation techniques. Mechanical devices are similarly incorporated. The inventor can request items such as a rotary arm or leg motor with such and such torque and speed. Then a finite element simulator runs several passes optimizing geometry to achieve that specification. With the geometry picked, the robot compiler then generates CAD files for mask layout for a given process sequence.

Similarly, linkages and transmission systems are chosen from a library and integrated with this all-purpose design tool. They are then handed off to a backend program which numerically controls a laser deposition 3-D printer.

Since gnat robot parts are too small to see and handle (no recourse to blue prints or eyeballing cuts on a lathe here), software for machine control was involved anyway. Now robot compilers just take the software engineering one step further to create a tool where designers can specify an entire robot or machine on a computer and send the file off to a micromechanical foundry for production.

3 From Inspiration to Implementation

Our glimpse of the future tells us that gnat robot technology has the potential to change the world in three distinct ways.

Integrated and cheap – Low cost creates new applications.

The idea of making robots without connectors, by manufacturing entire robots in one integrated process, that is, without hand assembly, would vastly reduce costs. The ramification is that economies of scale lead to bizarre possibilities, like the daddy-long-legs connector-bot.

Small and low mass – Small size creates new applications.

> The mere idea of integrating entire robots makes one think small. Even if complete automation of the manufacturing process is never achieved, thinking small begets micro-airplanes, outer-space mines and medical probes.

Collective intelligence – Multitudes create new applications.

> Finally, mass-production and small size taken together lead to fine-grained robotics. Some problems may be solved better through many simple machines as in for instance, the artificial minnow application.

The best, most time-efficient path for implementing gnat robots is not obvious though, as at this stage, building systems involves wishing for components that do not exist. We must invent these micro subsystems – motors, sensors and power sources. Unfortunately, the appropriate tools and materials for inventing components often also do not exist and so we must develop them too.

Picking our way through the tree of possibilities (figure 8) is going to require a few good guesses. The first heuristic for pruning the space of technology options would be to focus on micromotors. We can imagine (and indeed they exist) microsensors and microelectronics which would integrate easily, but high torque, low speed motors for the microrobotics applications envisioned here do not exist. Our first best shot in this direction has been to investigate piezoelectric traveling wave motors and to develop thin film ferroelectric materials for the highest energy density actuators possible. The intuition is that this class of motors has the characteristics that a microrobot is most likely to need and is also compatible with microfabrication processes.

To this point we have demonstrated active films on an initial intuition run of stator designs and we have seen rather large rotors spin at low speeds under only a few volts excitation, which is exactly what we want [**Flynn et al. 90**] and [**Udayakumar et al. 91**]. In addition to developing this new material, we have also seen the emergence of a new tool, a 3-D laser printer, which we foresee as helpful in fabricating rotors, bearings and transmission systems for coupling power out of the motor [**Bloomstein and Ehrlich 91**].

Our next step is to optimize the motor design, but before we go any further down this path, let us retreat up one level and re-examine the systems we would like to build. To be concrete, we will focus on four of the systems outlined in *The Robot Invasion*: the micro-airplane, the sensor-signal mines, the legged connector- and medical-bots, and the micro-submersibles.

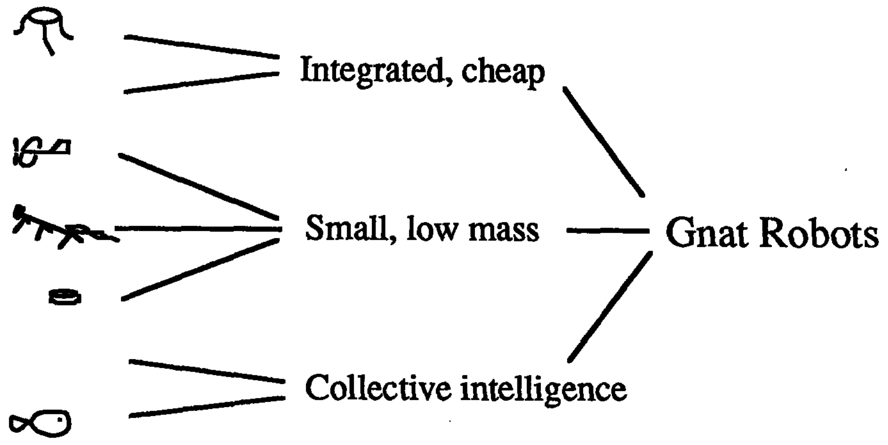


Figure 8: There are a lot of technology routes to choose from in attempting to develop gnat robots. Depending on the systems perspective, some technology choices are more relevant than others. That is, in some applications, batch processing for low cost may be important. For others, compact packaging (whether or not microfabricated) may be the essential ingredient. It is important to keep in mind the task to be performed.

These four specific robots represent generic classes of microrobot locomotion options. A more detailed outline of the force and energy requirements for their propulsion systems will illuminate the paths of the tree we need to explore. That is, by sketching out complete systems, designing transmissions, calculating torques and specifying power needs, we will be in a much better position to pinpoint where to concentrate our research efforts. This should help not only in providing specifications towards which to engineer useful motors, but also in enlisting electrochemists to think about thin film batteries and small power sources.

3.1 Micro Airplanes

First, a very simple one-actuator vehicle would be a small airplane. [Flynn 87] describes a $50mg$ airframe built by Mark Drela of the MIT Aeronautics and Astronautics Department (figure 9). A $30mg$ rubberband powers the airplane which flies in circles due to fixed curvature of the wings. What would it take to replace that rubberband by a micromotor? The propulsion system characteristics of the rubber powered airplane are listed in Table I. We could replace the rubber band by a direct-drive piezoelectric micromotor, as the torque to speed ratio of our motor matches well to the propeller requirements, eliminating the need for any gears. Figure 10 illustrates. The stator of the piezo motor would be fabricated with a thin film ferroelectric material and lithographically patterned wires. The rotor and bearing however would be assembled and manufactured using watchmakers' craft. The target specification to shoot for then is a torque of $1.9 \times 10^{-4} kgf\text{–}cm$ ($2.7 \times 10^{-3} oz\text{–}in$) and a total weight (including batteries) of under $30mg$.

Table I. Flight parameters for the rubber powered airplane – Mark Drela.

Weight of the airframe	$50mg$
Weight of the rubber band	$30mg$
Velocity	$1\frac{ft}{s} = .3\frac{m}{s} = .7mph$
Drag	$0.4G$ force $= .00039N$
Power delivered by prop = drag × velocity	$.12mW$
Overall efficiency	$\eta = .3$
Power delivered by rubber band	$.4mW$
Angular velocity of the prop	$200rpm = 21\frac{rads}{s}$
Torque applied to the prop	$19\mu Nm = 1.9 \times 10^{-4} kgf\text{–}cm$
Reynold's number	800 - 1000
Lift:drag	2.5
Energy density of the rubber band	$15\frac{W}{kg}$

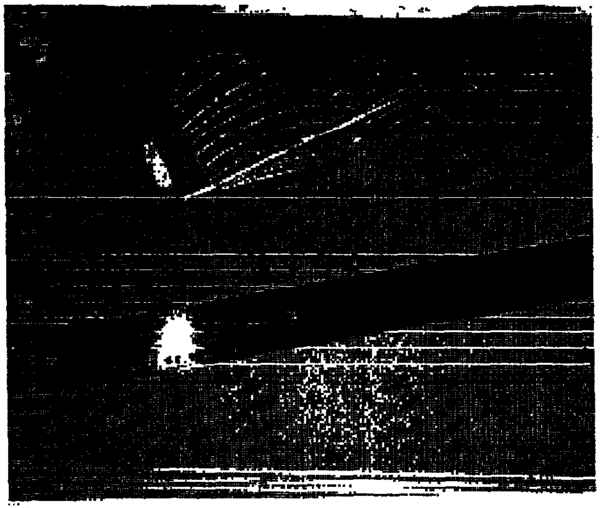


Figure 9: This five inch airframe weighs only $50mg$ [**Drela 87**]. The rubberband which powers it weighs $30mg$ and delivers $0.4mW$ to the propeller. A piezoelectric micromotor could replace the rubberband leading to autonomous flight.

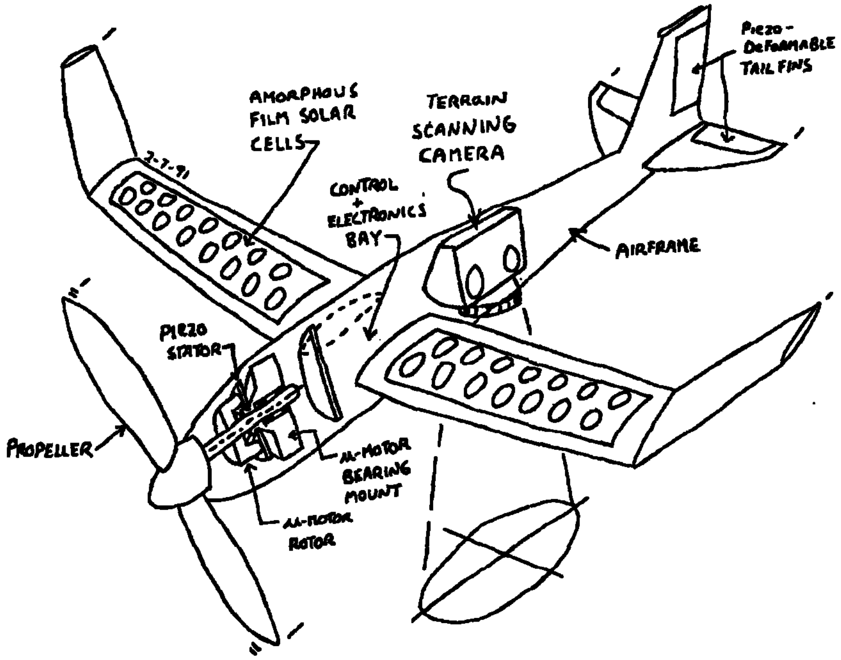


Figure 10: A piezoelectric motor direct-drives a small propeller on a lightweight airframe. The stator is microfabricated from thin film PZT on silicon and the rotor and bearing are handmade and hand assembled.

3.2 Micro Mines

Imagine instead of the thousands of "toe poppers" draped along the Iraqi-Kuwait border, robot mines that sensed hot bodies and then shot them – only with a camera instead of TNT. Saddam's bargain basement price for his little gems was $4.98 each, a tribute to the thought that a tiny robot package consisting of a little bit of sensing, a little tiny microchip, a little bit of battery and a little bit of explosive can be cheap when mass-produced.

If we replace the gunpowder with a slightly more benevolent actuator such as a sliding mirror and take advantage of some recent advances in thin film ferroelectrics, we can batch fabricate millions of these sensor-signal mines and sprinkle them throughout the solar system for remote sensing or even a "Mission to Earth".

First, we solve the power problem by clever packaging of distributed batteries (see figure 11). The idea is to build lightweight batteries by choosing a chemistry where one of the components is air, such as a lithium-air or zinc-air combination **[Wrighton 89]**. Make the bulk of the robot be encapsulated lithium or zinc, forming discrete power packs. From each battery compartment, run a tube to the surface which incorporates a valve for controlling air entry. The valve is controlled by passive sensors which generate a voltage when triggered. Ferroelectric films are excellent materials from which to fabricate these sensors as they are pyroelectric, piezoelectric and ferroelectric. A ferroelectric such as lead zirconium titanate (PZT) could, in a single process step, be put to use as an infrared camera, a non-volatile memory and an actuator.

The key system integration concept is to put the network of sensors, batteries and actuators together in such a way that energy is conserved unless something interesting happens. In this way, the sensor-signal mines can be active for thousands of years. So if a human or hot-blooded alien walks by, the pyroelectric elements in the infrared array generate a signal voltage, triggering the valve in the air tube to the batteries. Air rushes into the lithium cell causing an available energy surge which allows the non-volatile memory to capture the image from the infrared frame buffer. Even once this particular power packet is used up, the image stays resident in the ferroelectric memory. Other behavior networks of lithium cells, PZT sensors and actuators can also exist on-board, activating only when exposed to the proper sensory input. A force sensor for instance, detecting a ground tremor or a misplaced foot, might activate a battery pack which in turn might initiate some data collection and even possibly movement to safer

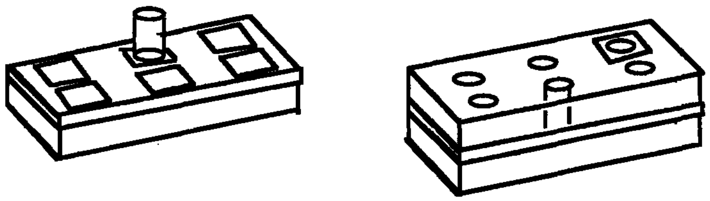


Figure 11: Micro robot power sources might be packaged as shown in the lithium-air battery on the right (cutaway on the left), where an encapsulated battery pack such as lithium has access to its second component, air, through a valved passageway. Sensors and circuitry on the surface are networked with the energy source and either memory modules or effectors for creating the desired output behavior.

terrain.

Another possible behavior network consists of a pyroelectric array attached to a battery pack which in turn activates a small piezoelectric motor that uncovers a mirror. An orbiting craft might look for such flagged sensors by scanning with a laser (figure 12).

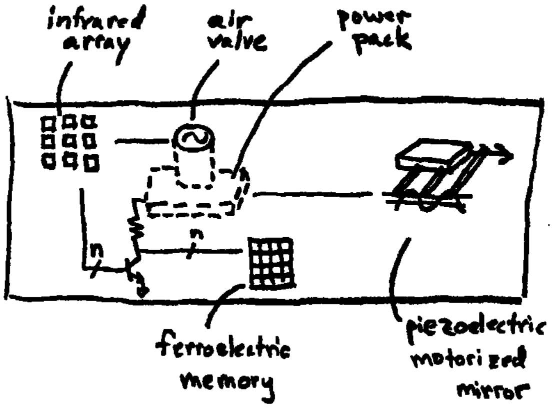


Figure 12: Here is a network of sensors, control, power supplies and effectors that implement a complete robot system. The pyroelectric properties of PZT are used to fabricate an infrared camera. A small amount of control electronics suffices to create the glue logic. PZT's ferroelectric traits are taken advantage of to implement a non-volatile frame buffer. Finally, we make a piezoelectric actuator, also from PZT film, to instantiate a motorized cover for a signal mirror. The power source, a lithium-air battery, is tapped only on demand when a control valve is triggered by an infrared detection.

3.3 Micro Crawlers

Legged locomotion would be a good propulsion system for a micro-robot, as we saw in the examples of the connector-bots and intestine-crawling medical probes. Here is a preliminary design and some torque requirements for a six legged walker incorporating twelve piezoelectric micromotors (figure 13).

Each hip (figure 14) contains two motors marked α and β, (for advance and balance respectively). The robot walks in a tripod gate with power coming from offboard via a tether. The β motors must be able to support $\frac{1}{3}$ the total bug weight and lift the leg clear of the ground. The α motors carry a much lighter load, and so the same β motor design will suffice. What sorts of torques and power supplies are required here? Table II lists dimensions and materials for one specific bug design.

Table II. Bug parameters and torque requirements.

Body	$1'' \times 0.25'' \times 0.125''$	$2.5cm \times 6.4mm \times 3.2mm$
(Aluminum)	$\rho = \text{density} = 0.098\frac{lb}{in^3}$	
Motors	$0.125''$ dia.$\times 0.125''$ long	$3.2mm$ dia.$\times 3.2mm$ long
(Silicon)	$\rho = \text{density} = 0.094\frac{lb}{in^3}$	
Legs	$0.050''$ dia.$\times 0.375''$ long	$1.3mm$ dia.$\times 9.5mm$ long
(Steel)	$\rho = \text{density} = 0.280\frac{lb}{in^3}$	
Leg weight	$2.06 \times 10^{-4} lbs.$	$0.9g$
Total weight	$4.54 \times 10^{-3} lbs.$	$2.07g$
Torque – support	$4.01 \times 10^{-4} in\text{–}lbs.$	$4.6 \times 10^{-4} kgf\text{–}cm$
Torque – lifting	$3.9 \times 10^{-5} in\text{–}lbs.$	$4.5 \times 10^{-5} kgf\text{–}cm$
Power – lifting $\frac{1rad}{s}$	$4.5 \times 10^{-5} W/motor$	
Power – total	$1.35 \times 10^{-4} W$	
Current at $5V$	$2.7 \times 10^{-5} A$	

In a tripod gate, three legs are in the air at any one time. Total weight includes the body, six motors and three legs. The maximum torque required for each of the three motors to support one third of the total body weight is calculated as the legs touch the ground at a 45 degree angle from the body. Power requirements per motor are calculated as though providing this torque at the rate of one radian per second. Table II then gives us some feeling for the ballpark torques and power supplies a small robot might require. In

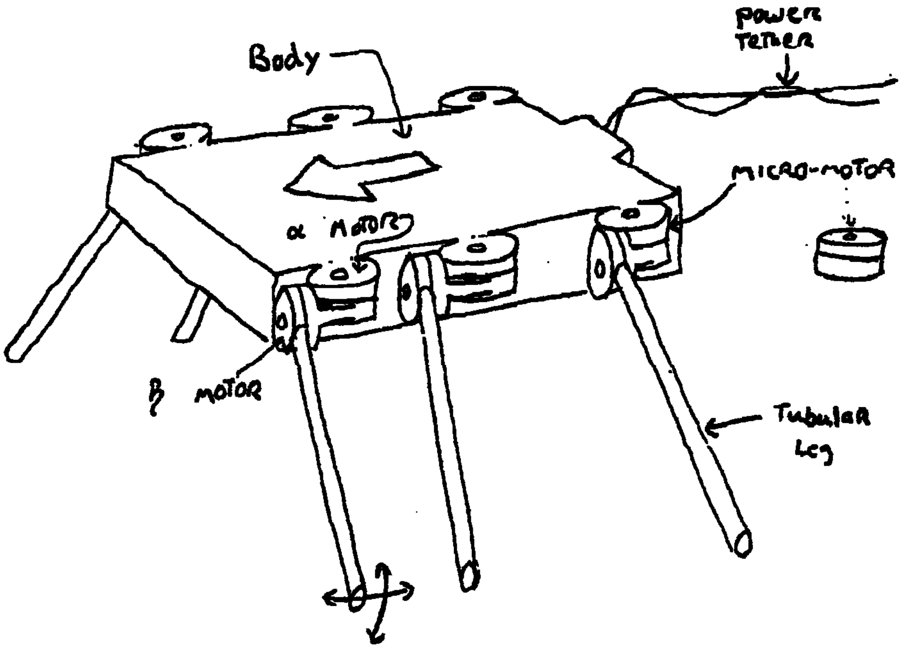


Figure 13: The high torque, low speed characteristic of a piezomotor means that it can be used in a direct drive fashion, which is perfect for robots, especially those with many degrees of freedom such as this one inch long six-legged walker.

this case, required torque is $4.6 \times 10^{-4} kgf\text{–}cm$, roughly equal to that of the airplane.

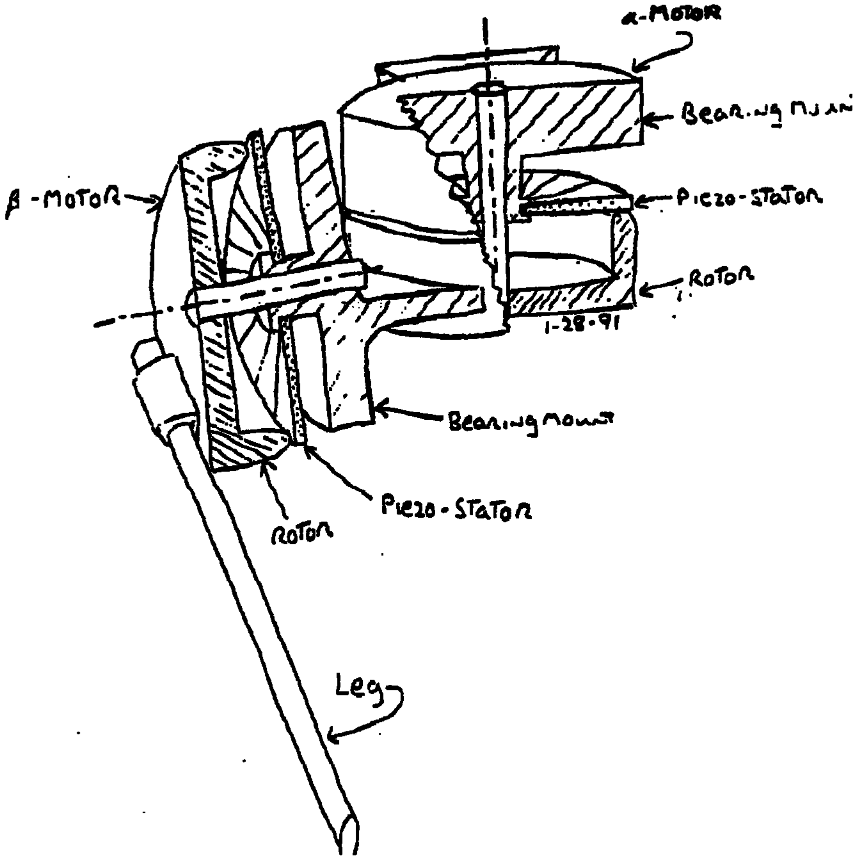


Figure 14: When we have an image in our mind of the final system we want to build, such as the microcrawler, we can fine-tune the design of our actuators. Here we can foresee exactly the linkages we desire and build them straight into the rotors.

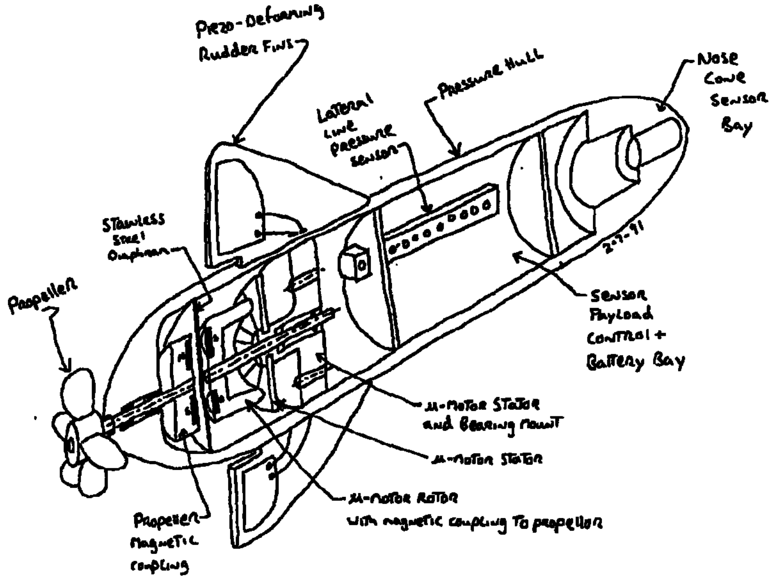


Figure 15: A one inch long submarine robot incorporating a piezoelectric micromotor for propulsion might also put to use a piezoelectric bimorph-bender for rudder control and piezoelectric pressure sensors for obstacle avoidance.

3.4 Micro Submersibles

An underwater robot's propulsion system might be very similar to the microairplane's, as illustrated in figure 15. A floating or submersible robot would be even easier to build than an airplane however, because a neutrally buoyant swimmer can carry weight equivalent to the weight of the water it displaces.

In order to calculate the types of torques a small submarine would need let us assume the submarine is cylindrically shaped with a diameter of $5mm$ and a length from nose to end of $25mm$. We will also assume that the motor is also cylindrically shaped $4mm$ in diameter and $3mm$ long.

$$D_s = 5mm$$
$$L_s = 25mm$$

$\rho_w =$ density of water $= 998\frac{kg}{m^3}$
$\nu_{w=}$ kinematic viscosity of water $= 1.0 \times 10^{-6}\frac{m^2}{\mathrm{sec}}$
$D_m = 4mm$
$L_m = 3mm$
$\rho_{si} =$ density of silicon $= 2.34\frac{kg}{m^3}$

Weight of water displaced $= \frac{\pi D_s^2}{4} L_s \rho_w = 0.49g$
Weight of the motor $= \frac{\pi D_m^2}{4} L_m \rho_{si} = 0.088g$
Weight of payload allowed $= 0.402g$

The drag force in the water is a function of the coefficient of drag, the density of the water, the velocity of the submarine and its cross-sectional area.

$D_F = C_d\left(\frac{\rho_w V^2 A}{2}\right)$
$C_d =$ coefficient of drag $= 0.44\frac{D_s}{L_s} + 0.16\frac{L_s}{D_s} + 0.016\sqrt{\frac{D_s}{L_s}}$

where $1 \le \frac{L_s}{D_s} \le 10 \quad \mathrm{Re} \le 2 \times 10^5 \quad \mathrm{Re} = \frac{VD_s}{\nu_w}$

Let us assume a velocity of the submarine of $V = 10\frac{mm}{\mathrm{sec}}$.

$D_F = 1.72 \times 10^{-7} N$
Re = 10 (regime is correct for our coefficient of drag)

Now we calculate the thrust produced by the propeller. For steady state translation, the thrust must just offset the drag. Assume a propeller diameter of $5mm$.

$d =$ diameter of propeller $= 5mm$
$Q =$ shaft torque
$T =$ axial thrust
$N =$ angular velocity of propeller
$V =$ free stream velocity
$P =$ propeller pitch
$J =$ advance ratio $\frac{V}{Nd}$
$\eta_{p=}$ propeller efficiency $= \frac{VT}{2\pi NQ}$
$\frac{P}{d} =$ propeller pitch to diameter ratio

For steady state translation, $T = D_F$.

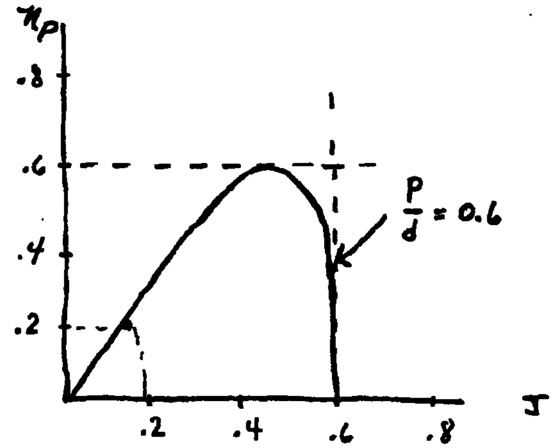


Figure 16: Propeller characteristics are displayed in terms of propeller efficiency vs. advance ratio for a given propeller pitch to diameter ratio. This graph is specified for a $\frac{P}{d}$ of 0.6

$$\eta_p = \frac{VD_F}{2\pi NQ}$$

$$Q = \frac{VD_F}{2\pi N\eta_p}$$

Assuming that the propeller turns at $N = 100rpm$, the advance ratio J is approximately 0.2. From the graph, we can read off that η_p is then also 0.2. Now we can calculate the shaft torque and motor power.

$$Q = 1.3 \times 10^{-10} Nm = 1.3 \times 10^{-9} kgf\text{-}cm$$
$$P_m = Q \times N = \text{motor power} = 1.4 \times 10^{-9} W$$

This tells us that the torques and power requirements are the smallest of all the propulsion systems we have investigated.

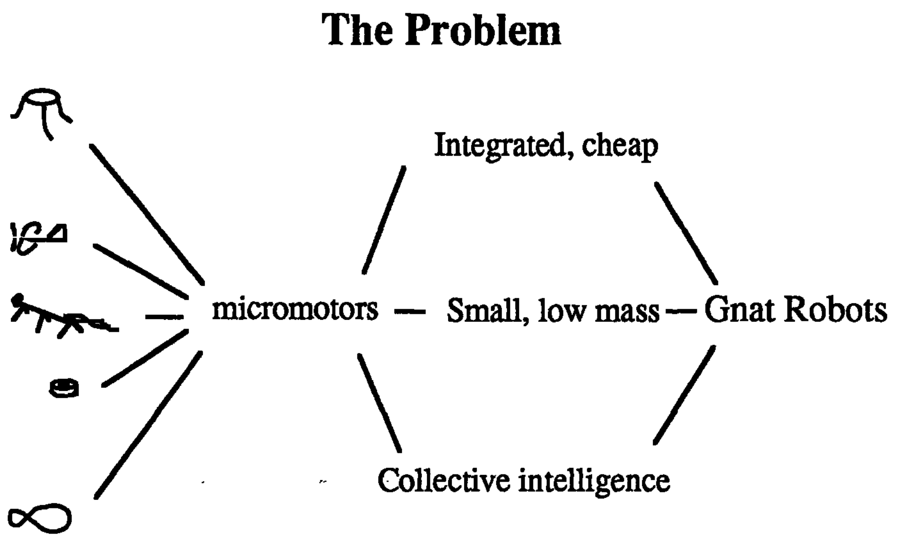


Figure 17: The common denominator preventing the birth of gnat robots is a high torque micromotor. There are a number of options for technologies to pursue to create them, but the important image to focus on is the system we want to build. Is it important there be no hand assembly? Alternatively, is small size the critical ingredient, in which case customization might be perfectly acceptible? Or, is production by the millions the key issue?

4 Picking the Right Problem

A wise carpenter once said, "Measure twice, cut once".

The critical component awaiting all these robots of the future is a useful motor.

Last year's effort saw encouraging results in terms of new technology – that is, new materials (sol-gel PZT films) and new tools (a 3-D printer) for micromotors. Now that we have seen some visions for what artificial microcreatures might be like, what is the best path for bridging the gap between new processing technologies and complete systems?

If we look again at our tree of options (figure 17), we see that high torque, small motors are the common denominator and also the common bottleneck. Earlier in this paper, we talked about this tree of all possible routes to pursue in building gnat systems, where the problem is that in building these systems we are usually in the position of wishing for components that do not exist, with the further complication that the appropriate technology is probably also missing. Figure 17 is key to sorting out our goals so that we can pick the best choice for the first next step in producing useful motors, because proper motor design should be specified by the target systems. That is, if small size (as opposed to cost) is the premier characteristic of our target system, then it may be immaterial whether a motor is manufactured with a rotor in place or discretely assembled. On the other hand, if our projected application involves robots by the millions, then it might be vitally important that the motors be batch processed. The key issue to keep track of however, is the final system.

By pursuing the route of piezoelectric micromotors we know we can achieve high energy density motors operable at low voltages. And by combining these advantages with metal lithography, we can pattern small motors while still being able to get all the wires and connectors in.

Our work and experiences so far have reinforced our initial feeling that piezoelectric motors were the right direction to proceed. What we have yet to do though, is to characterize the motors and optimize the motor design.

Last year we developed the technology. This year we need to develop the device.

4.1 Long Term vs. Short Term

Every research agenda contains a certain tension between long term goals and short term milestones. Concrete short term successes have the advantages of immediate gratification and of maintaining the research team's attention span and morale. The danger of a near term prize however, is that it may sidetrack the research and cloud the original goal. But if chosen correctly, the near term goal can serve to enlighten the project and keep it on track, refining and refocusing the driving vision.

It is for precisely this reason that we have gone to the effort here to step back and reexamine the big picture, for now we are in the position of being able to plan the best of both worlds. That is, we can formulate the long range plan with its required breakthroughs while interspersing short term systems just before each new technology is scheduled to arrive. The idea of building complete systems along the way (this has been very successful for

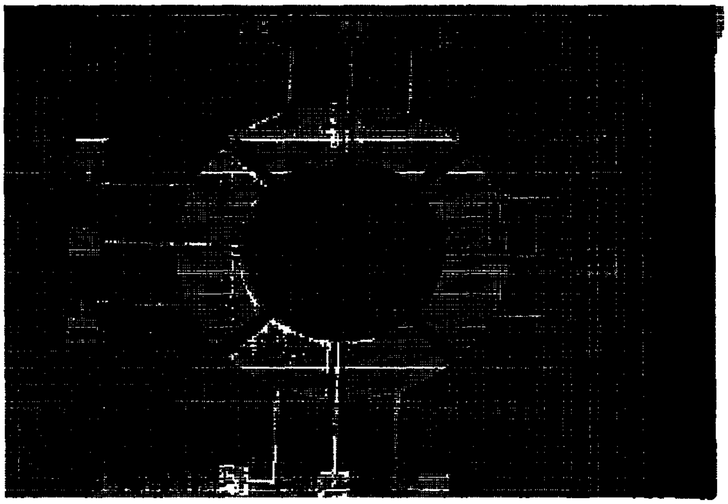


Figure 18: This eight-pole stator of a piezoelectric ultrasonic micromotor is $2mm$ in diameter and approximately $1\mu m$ thick. There is no rotor microfabricated in place. At the present time, we simply place a small object on the stator such as a microlens, and the lens spins around due to frictional coupling with the flexing film.

the Mobot Lab in the past) instead of at the end has the distinct advantage of focusing attention on how all the interfaces will fit together, an area which otherwise has a tendency to fall through the cracks.

4.2 State of Our Art

Last year we microfabricated some stators of piezoelectric ultrasonic motors as shown in figure 18. At the beginning of the year we made a good initial guess at a motor design and directly began fabrication in order to validate our films and our processing ideas.

And then we got lucky. By July, something spun. In fact, something big spun, a $1.5mm$ convex glass lens sitting atop the stator, spun at low speeds under low drive voltages $(3V - 5V)$. It was exactly the outcome we wanted. The experiment was a tribute to the high energy densities achievable with these very active films and to their large piezoelectric effects.

But it worked too well. In fact, the motor worked even when we did not drive it properly, that is, even when we drove it one phase instead of four. Of course, it was never possible to reverse direction, and so our motor was not behaving in the manner we had envisioned.

Microfabrication placed certain constraints on our initial motor pass, specifically in terms of the boundary conditions at the edges of the motor, and therefore our micromotors were not really the same geometry as earlier desktop working models that we had built. The basic problem is that microfabrication is not the proper medium for prototyping motors, experimenting with geometries, developing packages and building rotors and bearings. Microfabrication not only involves long turn around times, but we still face issues of yield and shorting phenomena in our films (the larger the motor area of PZT that we try to metallize with a top electrode, the higher the probability of pin holes and short circuits). What we need to do is decouple the research issues that have to do with motor design from the research issues which pertain to the new piezoelectric films.

4.3 A Proposal

What we propose then is a three-part frontal assault on figuring out how to get these motors to work (figure 19). The first part is to analyze and understand the physics of the motor's energy conversion process better through modeling and simulation. The second flank is to prototype a spectrum of macro-motors to validate simulations. These macro-motors we will make with bulk ceramics and discrete connectors. The third piece is a parallel effort to fix the shorting problem in the films. Only when all three thrusts are ready to converge will we return to the microfabrication phase. Although last year we immediately headed for the lab, the temptation to do that right away this year would be not bring the new knowledge that similar effort brought last year. We now know that we have a viable process for fabricating stators and we know that when the films are good, they are very, very good.

Our goal now is to measure twice and cut once; to understand thoroughly and optimize the design so that we can reach the torque-speed characterization point as quickly as possible.

4.3.1 Need to Know

What we need to know is how design parameters affect performance. Some of the parameters are questions of geometry while others have to do with control and driving points. Some pieces of information we can derive from

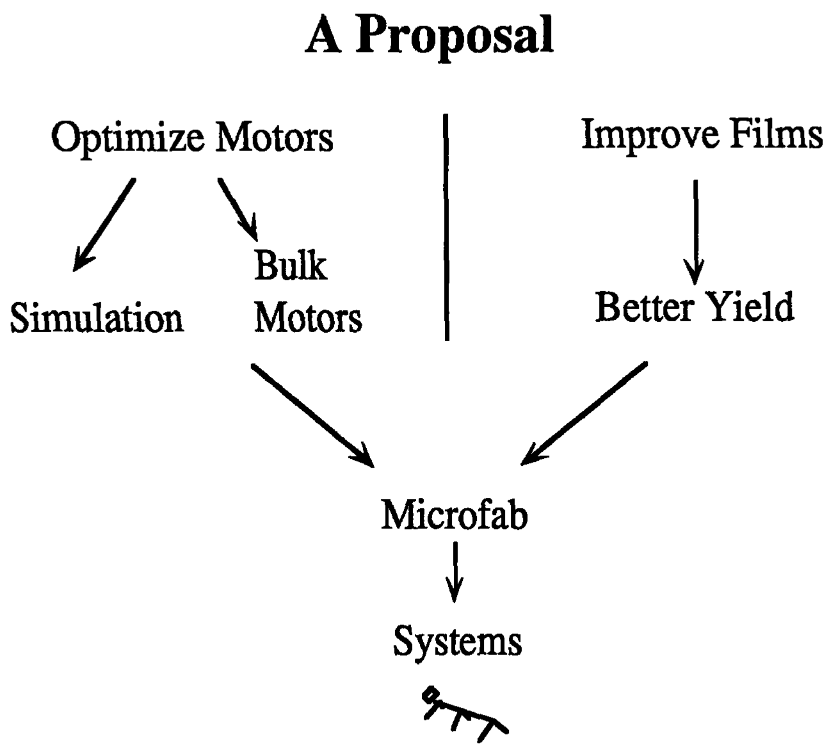


Figure 19: The next stage of piezomotor development requires decoupling device design from film studies. We need to solve a few problems in each department – optimizing the motor design and improving film yield – and then bring the two back together for a new microfabrication run.

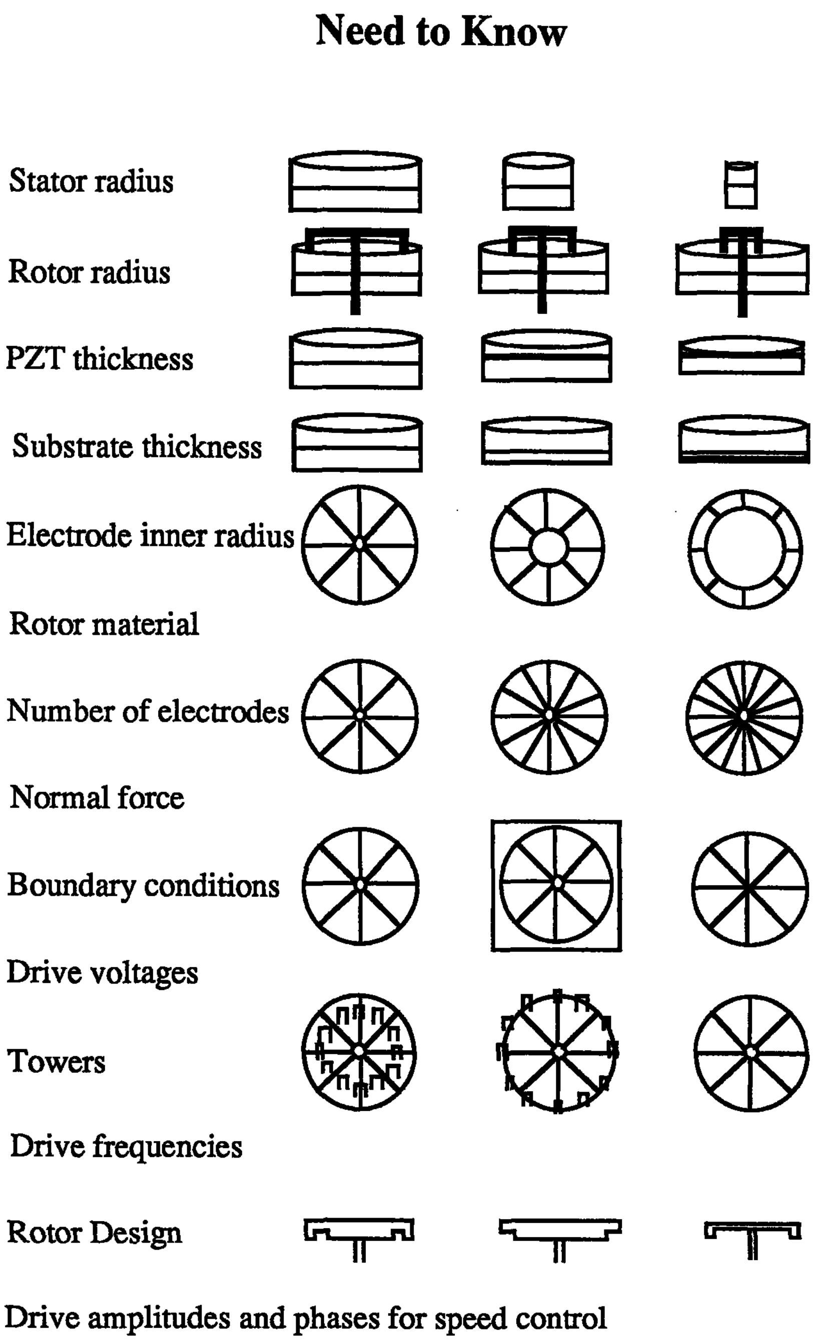


Figure 20: A variety of parameters affect motor performance.

simulations (such as amplitudes of deflection and resonant modes). Others we will only learn by building models (such as output torque and coupling efficiencies). Figure 20 lists parameters which we should investigate.

The first few parameters have to do with scaling the dimensions of the stator. Our intuition is that as we scale the stator radius in, the amplitude of deflection should decrease linearly. However, as we scale the thickness of the PZT thinner and thinner, the amplitude of deflection should *increase* linearly. One of our strongest motivations for pursuing these piezoelectric micromotors is that while scaling the radius from one-inch diameter bulk ceramic desktop motors to tiny motors a few millimeters in diameter should create a loss of about a factor of ten, moving from bulk PZT to our new thin-film PZT should produce a gain of about a factor of 500. We need to determine if our intution is correct and then to go one step further and observe how changes in deflection amplitude affect overall torque.

Another parameter which affects performance is rotor radius because the deflection magnitude will vary along the radius. The rotor should be designed to touch at the maximum spot. The rotor material, surface finish and the normal downward force also influence the frictional coupling.

Substrate materials also matter. Our motors are essentially unimorph structures. That is, there is only one layer of PZT which deforms under applied voltage. That PZT material is bonded onto a non-piezoelectric substrate which it bends against. The choice and the thickness of this substrate material affect how stiff the unimorph structure is and how well it can support a traveling wave.

Other parameters involve excitation patterns. Bending moments created by the applied voltages are constrained by the geometry of the electrode. Simulations will help us evaluate the relative merits of various configurations in terms of numbers of electrodes, angular spreads, radial dimensions, etc.

A critical parameter is the boundary condition imposed on our traveling waveguides. We need to determine the effects of pinning the motor at the center versus at an outer edge, for instance. We could also investigate the effect of a square edge condition (due to dicing a wafer, say) on a circular stator. Waveguide design can also be influenced by the presence of towers or masses which act as mechanical amplifiers. Their shape and location can significantly affect final torque.

Finally, control points need to be determined, such as driving voltages and frequencies, and phase shifting for speed control. Simulations can readily tell us resonant modes and relative amplitudes of deflection.

4.3.2 Simulating and Optimizing Piezomotors

While building bulk ceramic motors will save time over prototyping in silicon, simulations will save time in doing those bulk ceramic experiments. At least for certain questions, finite element analyses should prove useful and guide us towards the most interesting models to then go ahead and build. For instance, finding resonant modes and spatial displacements of a disk of various sizes, shapes and materials is a perfect match for this tool. We can experiment with different boundary conditions, both in terms of clamping constraints and voltage excitations.

One intriguing question is whether or not we can design-in fault tolerance into our electrode pads. Since our PZT films still have some problems of yield, maybe we can take a lesson from DRAM designers who must think of ways to build large memories when it is not possible to assume every transisitor will always work. Maybe we can design our pads "with holes" or in a grid pattern, to create an overall bending moment without having to cover that total area of PZT.

We plan to use a commercial finite element package called ANSYS because it supports coupled field problems in addition to the standard linear structural fare. Coupled field problems include thermo-mechanical scenarios, electro-magnetics and piezo-electrics, to name a few and our models can incorporate the layers of silicon, silicon dioxide, platinum, PZT and gold of our microfabricated stator including all the materials constants and piezoelectric coefficients.

4.3.3 Macro Motor Experiments

Simulators can be a useful tool, but they never quite deliver all we need to know. Specifically in our case, modeling sliding surfaces, which is the inherent coupling mechanism, would be hard. On the other hand, the real world can be hard to deal with also, especially when the final system involves microfabrication.

Fortunately, the really lucky thing about our microfabricated motors is that they do not have to be micro-sized. That is, we are not relying on tiny etched features to make these motors work, such as air gaps between rotors and stators (our thin bending films supply that ingredient and in addition, contribute a much stronger dielectric). We also do not have an upper bound on motor diameter because we are not forced to try to levitate a flat rotor a few microns above the surface. Consequently, instead of trying to think of systems that could use a $100\mu m$ diameter motor, we can start from system

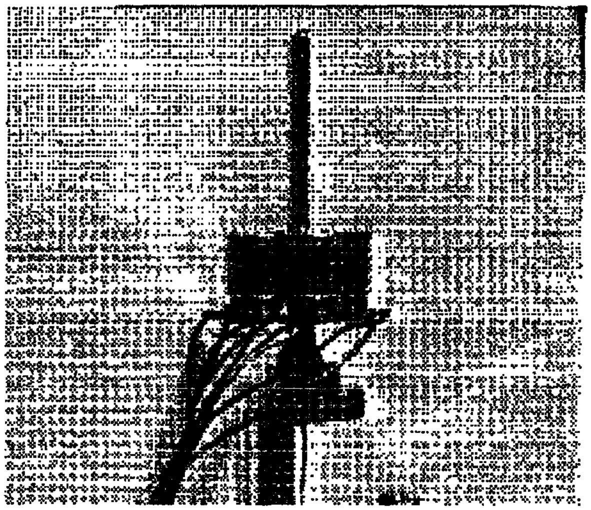


Figure 21: This is a one inch diameter bulk ceramic piezoelectric macro-motor. Off-the-shelf bulk ceramic PZT, 7 mils thick, with nickel plating on both sides is formed into a stator by milling out sectors in the bottom electrode to pattern eight stator poles. Wires are soldered to each pole, with the topside to ground and the stator is driven four-phase to induce traveling waves of bending.

wishes and engineer a small motor that matches our needs, say $5mm$ in diameter.

One big paradox or incongruity in this whole progression of manufacturing technologies leading to micromechanics is a quirk of jump in scale. Small motors we typically buy today might be the size of a fingernail, and now suddenly micromotors appear! What happened to the scales in between?

One place this scale of technology once existed was the Swiss watchmaking industry. The rise of the quartz crystal did it in, but the technology developed was remarkable. And the bearings and couplings developed there would be a perfect match for our small motors. In fact, since our microfabricated motors (and all their accompanying advantages) can be made rather large, fine watchmakers' craft could be used to assemble small rotors and bearings onto a thin-film PZT-on-silicon motor.

What we propose then is a hybrid motor, *half microfabricated, half assembled.* We can batch fabricate the stators by the hundreds and thousands and hand craft and hand assemble the rotor and transmission systems.

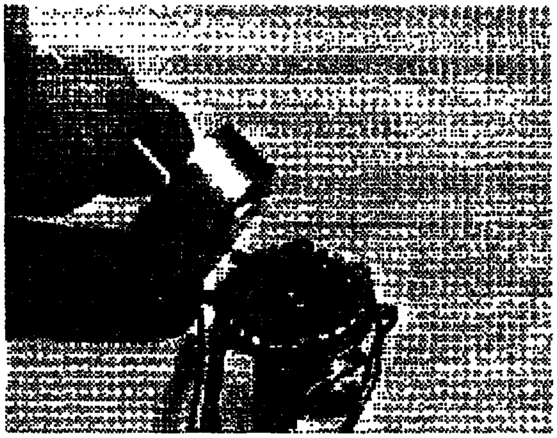


Figure 22: An aluminum ring of fingers is epoxied onto the grounded top electrode to act as a mechanical amplifier of surface deflection.

Later, when 3-D printer tools are ready, we can try to design the entire motor in place in an automated manner. For now, a half-batch-fabricated motor is a step forward in the right direction and is doable.

But wait! Why not take watchmaking craft to the final step and make our prototype motors entirely that way? This way, we can use bulk ceramic PZT, but make motors of the same diameter as our thin-film motors ($5mm$ is a good target size for many of the systems we envision). Now we can decouple the research on improving films from the problem of making small motors work. Then later, when the films are ready, we incorporate them and get even more improvement in performance due to the higher energy storage capabilities.

Building bulk ceramic motors both saves time over silicon and validates and defines the limits of our simulations. Here we can experiment with different rotor materials and measure frictional coupling and output torque. We can evaluate the influence of *craft* (such as fine surface finishes and jeweled bearings) on performance. We can also develop and tweak our infrastructure for testing and measurement of small torques, wave shapes, etc. We need to build a dynamometer to characterize output torques across the spectrum of rotational velocities and we need to invent equipment to visualize the stator traveling waves. Bulk motors also put us in the position to start thinking about packaging and connectors instead of putting that off to some distant

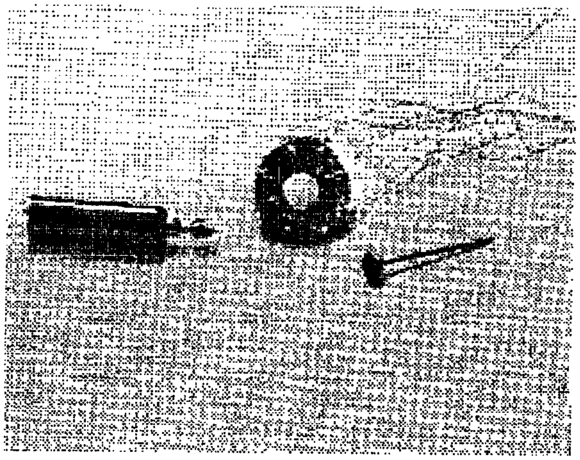


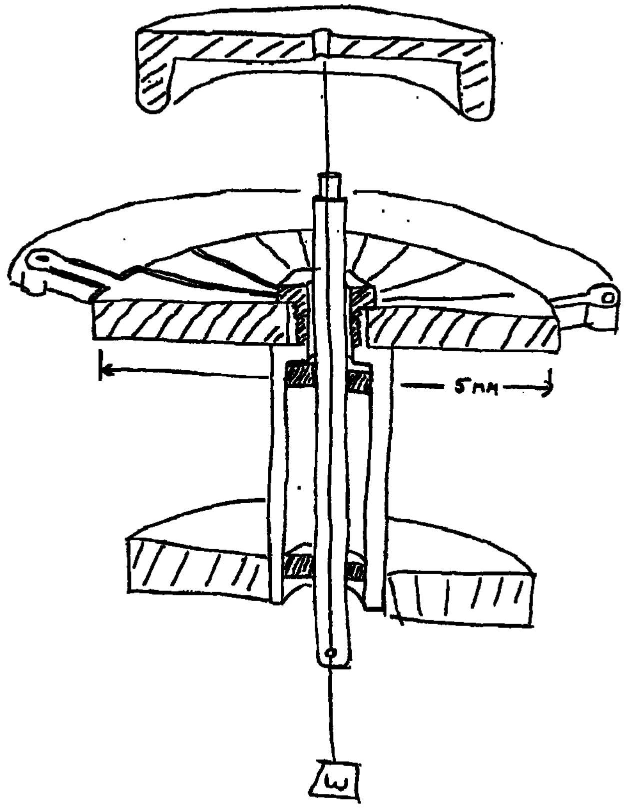
Figure 23: With careful machining and the skill of a watchmaker, we can make very tiny rotors and couplings using jeweled bearings and watch balance staffs for fitting onto small macro-motors made from bulk ceramic.

point beyond microfabrication.

Figures 21 and 22 show a large (one inch diameter) macromotor which we have built from off-the-shelf bulk PZT. An aluminum ring of towers provides mechanical amplification while a brass rotor compliments the aluminum ring for good coupling. Building smaller versions of this macromotor requires finer craftsmanship and delicate wiring as figure 23 illustrates.

For a bulk motor of the same size as our micromotors, roughly $5mm$, we propose something like figure 24, which involves etching grooves in the top of the nickel-plated PZT to pattern electrodes. This can be a very simple process of creating a pattern on a Macintosh, photoreducing to a negative and using a photoresist and ferric-chloride etch step (which we can do up in the machine shop, without recourse to a silicon foundry). Connecting wires for four-phase hookup would be tedious and unreliable by hand soldering, so instead we will lay out a flexible thin printed circuit board connector and vapor-phase surface mount it to the stator to bring all the wires out.

To couple power out, we drill a hole in the center of the stator and press fit a jeweled bearing. The rotor shaft assembly is handcrafted on a small jeweler's lathe and fastened to the mounting via a threaded neck. Next, we affix our motor to a micro-dynamometer and measure the torque-speed



Macro Motor

Figure 24: This $5mm$ bulk ceramic motor would be created from commercially available nickel-plated PZT bonded onto a substrate such as steel to create a unimorph. Photochemical etching, surface mounted connectors and watchmakers' craftmanship make it realizable.

characteristics. Hopefully, these torques will be in the range of the small systems we back-of-the-envelope designed earlier in this paper.

The end effect is that we can create a motor as small as our microfabricated motors using tried and true bulk piezoelectric ceramics, where we work out the kinks and then later marry this device with new and improved materials.

4.3.4 Improving Films

Once we have a small half-centimeter working motor, we can then move to the newer technology of thin-film PZT, which in parallel, will have been the subject of intense research. Replacing bulk PZT which is typically seven mils thick ($175\mu m$), with our $0.3\mu m$ films will result in a factor of 580 reduction. If the deflection amplitude scales appropriately, and even some fraction of that is made available for increased torque, that will be an amazing contribution.

The Penn State portion of this project has been responsible for these beautiful materials. Their proposal for this year (enclosed with this note) targets the shorting problem in the films. Although thin-film PZT is now commercially used in ferroelectric memories, memory applications involve only a small area. As we move to larger structures such as motors, yield falls.

Shorts might be caused by a number of problems, from pin holes to microcracks to contamination. Consequently, they need to characterize the microsturcture of these materials through SEM and TEM microscopy studies, while varying both the chemistry of the composition and the processing conditions. One important set of experiments will involve adding drying control chemical additives which will induce a glassy phase and make the films less porous.

In addition, other dopants such as tin, lead to larger piezoelectric properties and accompanying strains. Experiments with these dopants can be performed in conjunction with the shorting investigations.

Up to the present moment we have always microfabricated our thin-film motors on silicon substrates. However in our design here, we never use any electrical properties of the silicon. It merely acts as a holder for our PZT capacitor structures. Wafers, masks and lithography apparatuses all fit together conveniently and so silicon has been our substrate of choice.

But it may be a bad choice. On the one hand, far down the road, we can envision the possibility of integrating control electronics directly with the motor, but on the other hand, it can constrain our packaging options. For instance, if we would like to cut these motors out from the wafer with a circular boundary, that could be difficult.

Other substrates might be better in terms of machinability, cost or even thermal expansion compatibility. Certain ceramics, for instance, are photoetchable to very fine resolution, and that may lead to an important packaging breakthrough.

4.3.5 Fabrication

At the point where we reach a good motor design and a method for making high quality films, we will be ready to design a microfabrication process for a thin-film motor. Here we will be switching to new technologies as compared to machining bulk motors. Last year we tackled many of the issues of PZT–on–silicon, but getting to the point of holding working micromotors in the palms of our hands is going to involve more legwork.

For instance, the motors we tested last year were not cut out from the wafer and required electrical probes to make connections. The ground electrode was entirely below the PZT film and could not be reached from the surface. We also did not have an adequate waveguide structure. Rotors and bearings were never considered. This was all well and fine for initial experiments in testing the flexing and viability of the films, and for overcoming the hurdles to reach that point (recall peeling films, broken membranes causing contamination, etchant leaving pits in the PZT, and poor gold lift-off), but creating a working prototype micromotor brings up new issues.

One example is the issue of separating motors from the wafer. Should we dice into squares, try to etch through the wafer or excise with a laser? All involve tradeoffs in terms of process complexity, time and money. Another problem is connectors and packaging. Should we wire bond to some sort of surface mount package? Where will the shaft fit? How can we make connection to ground? To this point, we have never attempted to pattern nor etch the PZT to leave an opening for the ground plane underneath, but clearly we will have to some spend time on this task.

Correct mechanical requirements will have to be addressed also. Shaping a true mechanical waveguide might require a ring mass concentric with the outer boundary. Should we try to etch it from the backside with bulk micromachining or deposit it with a 3-D laser printer? Can we form towers and fingers in a similar way?

Finally, provision for rotors and bearings has to be established. In silicon electrostatic micromotors, the rotor can be etched in place since in the final configuration, the rotor levitates. In our motor though, we require a normal force pressing together two sliding plates, so it is not clear how microfabrication can help us. If we go with partial hand assembly, can we cut a hole in the center with a laser and press-fit a jeweled bearing?

In the end, what we are really interested in is making sure this device is viable for a small robot or machine. We will need to build test equipment for characterizing torques and then put the micromotors in a system.

4.4 A Better Proposal

The research outline just proposed has one serious drawback. The system is a long way off. To reiterate, we have proposed first simulation, then bulk models and finally film improvement as a three-pronged parallel effort to find the optimal point at which to put them all together and microfabricate a stator (while assembling the rotor). Then, the idea would be to take these microfabricated devices and build a system.

But let's think.

Our driving goal is to build gnat robots. In the past, our successes have always come from building complete systems that while simple, interact directly with unstructured real environments (as opposed to earlier AI subsystems which lived in simulated worlds and made assumptions about interfaces to other subsystems).

In engineering, the same is true. Building a subsystem in isolation often leads to the wrong interface. Imagine for instance, if we pursued this entire research plan and developed a microfabricated motor that fit in the palm of our hand. Then we paraded it around to potential customers asking if they would find it useful. Imagine our dismay to their reply of, "No! I can't control it. There are no position encoders!"

Back to the drawing board.

Ah ha, let us go back to the idea of building not only the rotor and bearing from watchmaker's craft, but also the idea of crafting the stator itself from bulk PZT. Why not keep going and build an *entire system?*

A better proposal then, is to tightly couple building complete systems along with each step of technology development. That is, design small motors, build a system. Incorporate thin films, build a system. Incorporate integrated electronics, build a ..., etc.

Figure 25 illustrates the plan. First we run simulations to ferret out correct design parameters, while at the same time hammering on the issues of film yield. Then we build bulk macromotors, all the while having a specific system in mind, so that once these are optimized, we can quickly put a system together.

We propose the *six-legged walker* of figure 13 as our showcase system because it exemplifies a system with a large number of degrees of freedom which plays well to the advantages of small direct drive motors. A walking robot also fits in nicely with our present walking robot project in the Mobot Lab, which has vastly changed the way people think (not only in terms of space exploration but even more generally just in terms of how large a useful robot needs to be). Scaling down such a six-legged walker to one-inch would be a head-turning feat. Imagine now carrying this little creatue in the palm of your hand when marketing to potential customers.

5 Complete Systems

After building a robot from bulk motors, we incorporate the lessons we learned and the mistakes we have made into a very well thought out design for a microfabrication motor run. With PZT 500 times thinner, we can achieve very large electric fields at low voltages. This will allow us to drive the motors from simple logic gates. When we put thin film motors into a small robot, we can carry the controlling logic onboard in small surface mount chips, a step which would be much more difficult with the bulk ceramic motors. This makes our system an impressive demonstration and the tight loop reinforces and steers the research directly towards gnat robots.

Once micromotors reach the useful stage and are reliable enough to be routinely incorporated into mechanical systems, we can begin to think about sensors and the other components needed to create artificial microcreatures. [**Angle and Brooks 90**] describes a shoe-box sized six-legged robot, Attila, with 150 sensors, 11 computers and 25 motors in a package weighing roughly $2kg$. Many of the sensors onboard are already commercially available microsensors and would fit well in our targeted microrobots. And while large robots today usually require bulky batteries, [**Munshi andOwens 89**] relate progress on new thin-film batteries which could be integrated into microsystems.

The software organizing the intelligence and instantiating the networks of behaviors in Attila is written in the Behavior Language [**Brooks 90**], which is built on top of a subsumption architecture [**Brooks 86**]. By

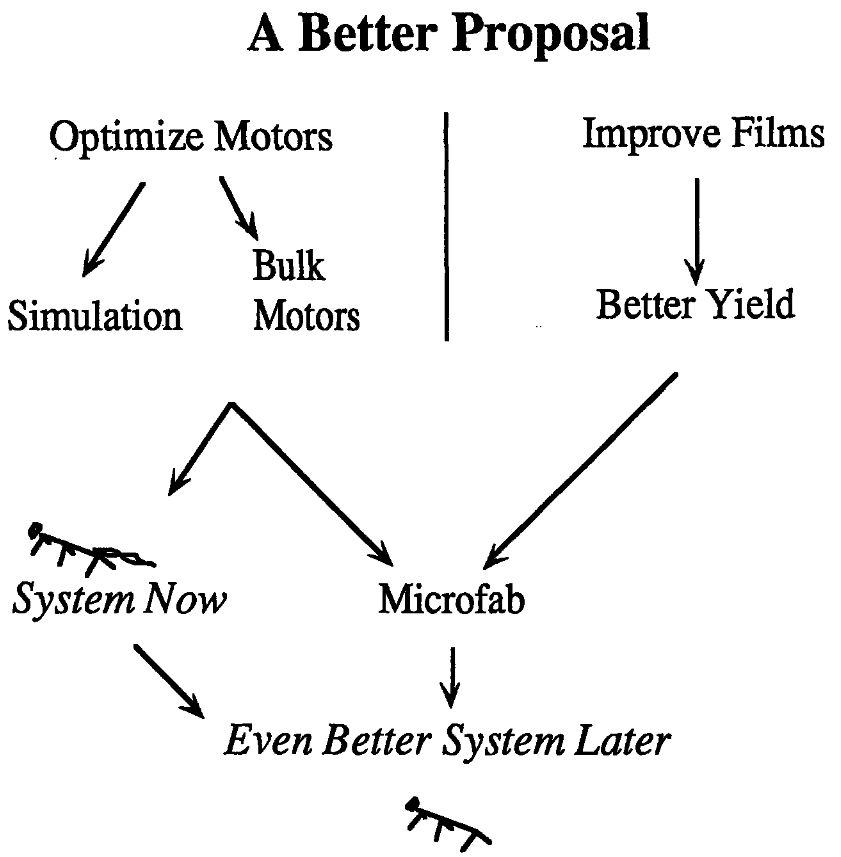


Figure 25: We can take the act of building a macro-motor via watchmaking technology to the next step and build a *system*, such as a one-inch long six-legged walker. A tight coupling of complete systems to the real world is effective in making sure device and technology research progress along the most appropriate path.

putting together many simple behaviors in an appropriate way, more sophisticated behaviors are seen to emerge, such as rough terrain locomotion and people following [**Brooks 89**]. One interesting ramification of a subsumption architecture organization for the intelligence is that it can compile very leanly to a small number of gates. That is, the same algorithms and behavioral networks that control Attila can control a microbug. In a similar way, we envision that by putting many independent agents into a task scenerio, through interaction of simple behaviors, complex societal properties can emerge. [**Brooks and Flynn 89**] describes how such a collection of Attila-sized robots together with gnat robots will change our approach to space exploration.

5.1 A New Industrial Revolution

Changing the world involves changing the way people think. It involves changing the way we use technology.

It is not just space exploration and walking bugs that we are proposing here. What we are promoting is a whole new viewpoint on solving problems. *Fine grained robotics* might be a proper label. Just as ants and termites can cooperate to build communal structures despite very little direct communciation, we can apply simple machines acting in concert to create results greater than the sum of individual efforts. The idea of collective intelligence, using many simple machines organized such that complex behaviors emerge, matched with a set of technologies for manufacturing at low cost, will lead to a rich set of solutions which will change our way of life. From robot scrubbing bubbles to microants aerating contaminated soil, this technology will forge a new industrial revolution.

6 Converging to a Plan

While swarms of integrated robots are a long way off, thinking explicitly and out loud has helped us converge to a plan for the next first best steps.

First of all, we will analyze and simulate a variety of motor geometries trying to gain insight into critical parameters. At the same time, the Penn State materials experts will lead a focused investigation for improving film integrity and overcoming shorting problems. They will also experiment with substrates other than silicon, look into effects of dopants for improved piezoelectric traits and investigate techniques for patterning PZT.

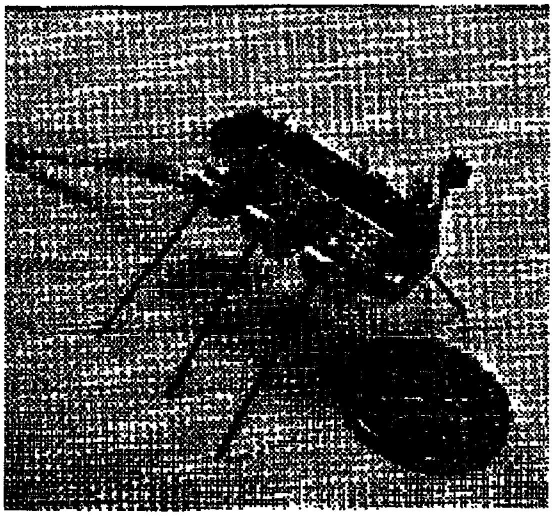


Figure 26: This is a full scale model (one inch long) of the six-legged walker we plan to build with twelve bulk ceramic piezoelectric motors. Wires for power and control for the motors will tether offboard.

We will simultaneously undertake a program to validate micromotor designs by manufacturing a spectrum of models from bulk ceramic. Using photoetching techniques for patterning electrodes and fine watchmaker's craft for turning bearings and rotors, we will test a variety of parameters on motors of the scale of $5mm$ in diameter. Characterizing the torque–speed curves for these motors will necessitate investment in creating the infrastructure for testing. A device for visualizing traveling waves on the stator would be helpful. We will also build a dynamometer for measuring very small torques.

In order to prevent the trap of building a device with all the wrong abstraction barriers and interfaces, we plan to design for and immediately build a target system. Specifically, our aim is to fabricate a six-legged walking robot with two rotary joint motors per leg. A tether for power and control will run to offboard electronics. A full scale model is shown in figure 26.

While designing and testing the bulk ceramic piezoelectric motors, we will constantly be thinking about process sequences for fabricating micromotors using thin films. Before merging improved films with optimal motor designs into a microfabricated motor, we will begin the legwork required to flush out a viable processing sequence, addressing a variety of issues. This work will be carried out at Lincoln Labs, in parallel with the motor optimization and film improvement efforts, on existing or slightly modified stator designs in order to have a debugged microfabrication process developed in time to batch fabricate a cheap motor. Specifically, it will highlight process step interactions and work arounds for problems such as high temperature PZT annealing and electrode adhesion. Methods for etching, as opposed to lifting-off, the top gold electrodes and for making contact to the bottom platinum layer will be determined (via laser or plasma etching of PZT). Inserting other new materials if required, such as rotor/stator contact materials will also be looked into.

By the end of the year we hope to establish a viable process for manufacturing thin-film piezoelectric motors, backed up by prototype bulk motors and bulk systems, and thorough results in PZT film studies. The next step after that will be microfabrication of a thin-film motor for improved performace over the bulk motors, and finally incorporation into small robots.

The solar system is ours for the taking. Let's pluck it!

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