MASSACHUSETTS INSTITUTE OF TECHNOLOGY
ARTIFICIAL INTELLIGENCE LABORATORY

Working Paper 295 June, 1987

Gnat Robots
(And How They Will Change Robotics)

A.M. Flynn

Abstract

A new concept in mobile robots is proposed, namely that of a gnat-sized autonomous robot with on-board sensors, brains, actuators and power supplies, all fabricated on a single piece of silicon. Recent breakthroughs in computer architectures for intelligent robots, sensor integration algorithms and micromachining techniques for building on-chip micromotors, combined with the ever decreasing size of integrated logic, sensors and power circuitry have led to the possibility of a new generation of mobile robots which will vastly change the way we think about robotics.

Forget about today's first generation robots: costly, bulky machines with parts acquired from many different vendors. What will appear will be cheap, mass produced, slimmed down, integrated robots that need no maintenance, no spare parts and no special care. The cost advantages of these robots will create new worlds of applications.

Gnat robots will offer a new approach in using automation technology. We will begin to think in terms of massive parallelism: using millions of simple, cheap, gnat robots in place of one large complicated robot. Furthermore, disposable robots will even become realistic.

This paper outlines how to build gnat robots. It discusses the technology thrusts that will be required for developing such machines and sets forth some strategies for design. A close look is taken at the tradeoffs involved in choosing components of the system: locomotion options, power sources, types of sensors and architectures for intelligence.

---

1 Where Did All The Robots Go?

If you've been keeping up with your reading of *Time* magazine or watching of the Saturday morning cartoons, you were probably disappointed last Christmas when you didn't get a robot that did the dishes, washed the windows and swept the floors. Where did all the robots go? We've become conditioned to believe that soon robot-helpers would be permeating our society, but it hasn't turned out that way. Why don't we see more robots in everyday life?

The main reason is money. Robot technology is very expensive for the level of intelligence attainable. Many hard problems need to be solved in sensory perception and intelligent control before robots will achieve higher levels of competence. No market exists today for such costly machines of limited capabilities. Therefore I propose that we work on building very cheap robots with the capabilities we can produce now and then see what happens later, much the same way as when microprocessors were first introduced (as video games, etc.).

What makes robots expensive? Mobile robots today contain mostly motors and batteries while all the sensors and computers come in a very tiny package. The battery-motor system has a certain runaway characteristic. Big motors tend to need big batteries which weigh down the chassis, so larger motors are called for, which require heftier batteries ... and on and on it goes. Meanwhile, all the intelligence and sensing mechanisms fit onto a few square inches of silicon. Mobile robots that are used as sensor platforms, exploration robots or sentries, as opposed to heavy lift arm-type robots, pay especially heavy penalties for carrying around large loads of motors and batteries.

If mobile robots are half motors and batteries, what takes up the other half of the physical space? The answer is connectors: power connectors, signal connectors, bus interfaces - whatever it takes to hook up one vendor's computer to another vendor's motor to another vendor's sensor to yet another vendor's battery. All these interfaces between parts from various suppliers mean added cost and complexity and the assurance of the necessity of planning for spare parts and maintenance during the lifetime of the robot.

Due to mass production and integrated circuit technology, processors and many types of sensors have declined in both price and size over the past few years while motors and batteries have enjoyed no such benefits and remain the most costly and bulky components of a robot system. In order to minimize the size and cost of a robot, we propose to use ever smaller and lighter motors and batteries until we find a limit for building the smallest robots possible. Recent advances in silicon micromachining technology have brought about the appearance of micromechanical motors. These motors are on the order of a few hundreds of microns in diameter and are actually etched on-chip [2,30]. One might question the usefulness of such tiny motors, but if all we wanted to do was to locomote the chip on which they were fabricated, then we would have a system in which the motors were of the same scale as the sensors and processors. Putting an entire robot system on-chip would allow for mass production using IC fabrication technology and costs would plummet.

2 Applications of Gnat Robots

Our concept of mobile robots centers around applications that we can imagine for our traditional model of a mobile robot - usually some large, klunky, heavy, slow, dumb machine. However, if we imagine one-chip robots with sensors, computers, actuators and power supplies all on one chip, our concept of robotics becomes completely different.

At present, we probably never think of building any machine at a size smaller than our thumb. This is because we can't build a machine smaller than the motor we have in it and the smallest motors we've ever seen might be about as big as our thumb knuckle. The problem is that our thinking has been constrained by our implementation options.

There are many useful tasks which can be carried out by robots in entirely different implementation ways than what we think of now. Furthermore, many tasks which we would never consider automating could be automated if we had completely orthogonal implementations of robots to what we presently have. We roboticists often seem to fall into the trap of thinking too anthropomorphically, i.e. of having robots on the same scale as ourselves and of having sensors and actuators similar to our own.

Imagine a one-chip robot the size of a gnat which is totally autonomous. It flies, crawls or swims like a boat. It has microsensors on-board which allow it to see, smell or feel. What could we do with such machines?

First of all, gnat robots can be used as small autonomous sensors able to get into hazardous or hard to reach places. Have a suspicious O-ring on your favorite Space Shuttle? Send a little crawling robot laden with sensors back to check it out.

Microrobots can be used to fix things too. Imagine a break in an electrical conduit somewhere underground. The robot crawls along it, measuring the conductivity between legs on each step. When one leg steps on nothing, the open circuit is found. Then it extends that leg further until it steps over the break and reconnects the circuit. Then it can just stay there forever, having fixed the problem - as an autonomous piece of wire.

Another application is farming. Gnat robots fly over fields with their moisture sensors or infrared sensors [25] and determine exactly which sections of the crop need water. Then they swoop down onto a smart valve which controls the irrigation system and tap a message into the touch sensor on the top of the valve. Such precision control of limited water reserves could turn deserts into bread baskets.

Space applications are another appealing realm for cheap lightweight robots. Gnat robots could be used to inspect the outside of the Space Station, be employed as forward scouts for a Mars rover, or be used as atmospheric probes for planetary exploration. Their small size and light weight would enable hundreds to be taken along on any shuttle flight for very little cost.

Gnat robots would also make excellent sentries. Mobile sensor platforms could fly around a warehouse checking for any strange disturbances. Their low cost would allow many to be used, increasing coverage and effectiveness.

We can imagine reconnaissance operations. Nat the Gnat goes flying down the hallway (he has a map of the floor stored away), turns left into your friend's office, grabs a snapshot into his CCD array and flies back to your office where you do a core dump to see what your friend was up to.

We can also imagine little messenger robots, cheap enough that every outdoorsman carries a handful of them in his pockets. Next time you're stuck on Mt. Everest in an avalanche you send a few a these on their way to get you some help. They deliver little electronic messages which you programmed in from your pocket calculator.

A huge variety of applications for gnat robots can be found if we don't let our creativity become inhibited by preconceived notions of what a mobile robot should look like or how it should act. There are plenty of applications more interesting than sweeping the floor.

Gnat robots fall into two basic categories of usage. First, they can be used as *autonomous sensors*, in which case we want to see what it sees, but we can't get into the places it can. It brings back or transmits back the information we desire. The explorer robots and sentry robots fall into this category. The other way that gnat robots can be used is actually as *autonomous robots.* Here, we don't care to see what it sees, but rather that it just carries out the correct action based upon what it sees. It fixes whatever's broken and man is out of the loop. The advantage is that we don't have to retrieve the robot to retrieve data. The electrical conduit fixer and the irrigation robot fall into this category.

3 Technology To Exploit

Is building a gnat robot feasible? Bringing gnat robots out of the realm of science fiction and into reality can be accomplished if we exploit recent breakthroughs in technology in five major areas: microsensors, control systems, actuators, power sources and systems integration.

Microsensors are needed so that the gnat robot can perceive its surroundings and react accordingly. In order to build an integrated robot, we need to be able to manufacture sensors in a manner compatible with traditional IC processes. This ensures low cost of mass production and the ability to put computational circuitry on the same chip as the sensor. Integrating sensors and circuitry provides greater sensitivity since it removes the possibility of introducing noise or parasitic capacitances which would otherwise occur in chip to chip wiring. The elimination of this interconnect also facilitates smaller packaging. Many types of microsensors are already available. Solid state imaging devices such as black and white CCD cameras have been on the market for some time with color cameras beginning to emerge. Research in computer vision has led to algorithms appropriate for mobile robot navigation using these types of sensors, such as one-line stereo [26]. The military has been using thermal imaging devices for years and they have active research programs ongoing in infrared focal plane arrays [20]. Recently, silicon micromachining techniques, in which actual physical structures are etched on chip, have produced a host of new sensors [23]. Chemical sensors [18], pressure sensors [10] and thermopile infrared sensors [9] are just a few of the types of sensors being developed in this rapidly expanding field.

How a robot manages to survive and carry out useful tasks is the responsibility of the control system. Taking sensory input and converting it to appropriate actuator commands is an active area of research, and the MIT mobile robot group has been developing a control system with some new and innovative approaches [6]. The idea is to build a system based on lots of simple finite state machine modules sending messages to each other. This distributed control system, called the subsumption architecture, is built in layers with each succeeding layer incorporating more complex behavior. Lower layers which are built first and debugged, continue to work should higher levels break, granting robustness to the system. These lower level behaviors mimic insect level intelligence, incorporating behaviors such as running away, following, etc. Studies of insect control systems have shown a remarkably similar architecture [8]. A central tenet of the subsumption architecture is that there is no central control; no one module acts as a master keeping a representation of the environment and doing planning from a global map. Thus no single processor can create a bottleneck. The idea is to achieve intelligence without representation [5]. Indeed, much of the intelligence resides in the peripherals. This too, is similar to insect control systems [19]. The beauty of this approach is that each module is very simple and in fact can be compiled down to chip level. A silicon compiler is presently being developed to do just that [29].

Whatever form of locomotion the gnat robot utilizes, whether it be flying, crawling, swimming or rolling, it will need actuators. Fabricating motors on chip is an area where technological breakthroughs are right around the corner. Although silicon's electrical properties have been well known and developed, the mechanical properties of silicon are just now beginning to be exploited. Surprisingly, silicon has a tensile yield strength three times higher than that of stainless steel wire (although it yields by fracturing instead of deforming plastically like most metals) [23]. High resolution planar lithography for defining circuit layouts can be used to create precisely defined miniature mechanisms. Chemical etching can then sculpt three-dimensional features. A wide variety of devices utilizing mechanisms such as cantilever beams and thin membranes have been developed to create vapor and pressure sensors [1,22,16]. Now however, people are going one step further and building miniature mechanisms such as gears and motors to do mechanical work [30,2]. It turns out that at the very small feature sizes achievable with micromachining, electrostatic fields can develop gap energy densities of the same order of magnitude as the gap energy densities in macroscopic, conventional magnetic motors. Such an electrostatic motor has been conceived that incorporates a freely rotating disk etched in place between two stators [2]. A synchronous variable capacitance motor with a $300\mu m$ radius, its no-load power output has been calculated to be $1.8mW$ with a maximum angular velocity of $600,000rpm$. A power transmission system for this motor has yet to be designed, however.

Coupling enough power to the gnat robot to drive the motors and circuitry and yet requiring small size and low weight poses some significant challenges. Total capacitance available on chip is extremely small and very little power can be stored on-board. Battery technology has never scaled in the way microelectronics has and piggy backing an off-the-shelf battery to a gnat robot would cost far more in terms of weight than the rest of the system. Laying down batteries on chip might be one possibility, eliminating the weight of the package. Another possible alternative is to radiate power and not store any on-board, but use it up continuously. Some work in this area has been done with magnetic power coupling but requires the magnets to be within a few millimeters of the chip [26]. Solar cells seem promising because they can be made from single crystal silicon and therefore would be low weight and compatible with an IC process. Solar cells have problems with leakage currents when placed in series however, and in addition are typically inefficient, running in the 10% range. Recently, double-sided cells have yielded improved performance [17] and single-sided cells have been reported with efficiencies of 22% [27]. Further improvements in solar cell technology have yielded 24% efficiency[28].

Finally, system integration issues have to be addressed and myriads of tradeoffs made. Putting all the subsystems together and coming up with appropriate sensor technology to match a useful means of locomotion is an intriguing problem. Tradeoffs will have to be made between available real estate on-board chip, power usage and degrees of complexity of behavior attainable. Of course, building a large scale mobile robot involves many of these same constraints and we've gained a lot of experience in this area of putting systems together [7].

4 Design Strategies for Gnat Robots

Scaling down all the way to chip level, however, adds a new world of constraints. How will the constraints of small size and low weight affect our design choices? There are two major guiding considerations. The first is that we want to *minimize power consumption.* Very little power consumption means not only that we can use a smaller power source, but that alternative power sources might become feasible. For instance, some digital watches are made to run on such low power these days that they are actually powered by water batteries [14]. The second guiding consideration is that we want to *save chip real estate.* If we maximize on-chip integration we will need less interconnect and the resulting package will become smaller and lighter.

The problems associated with integrating all the necessary subsystems into a gnat robot lead to a set of design strategies that will most effectively deal with the constraints of minimizing power consumption and maximizing level of integration.

The first strategy is to use all *passive sensing* in order to conserve power. Right now on the MIT mobots we use sonar, infrared and light-striping for ranging and proximity sensing. Laser rangefinders are another commonly used sensor for mobile robots. All of these sensors radiate energy and detect a return signal. However with our low-power gnat robot, we don't have the luxury of throwing away power in this way. What we can use instead are passive imaging devices such as cameras and thermal sensors. Additionally, we can experiment with other passive sensors such as electrostatic or capacitive proximity sensors, compasses, autofocus mechanisms and chemical sensors.

The second strategy is to be clever about using sensors so that *one sensor can be used to sense more than one physical phenomenon.* This is motivated by the necessity to conserve chip real estate. Presently the MIT mobots use a different sensor to sense each different type of physical phenomenon needed. Sometimes multiple sensors are used to improve the accuracy of a single type of reading [13]. These strategies are fine for a macroscopic robot but unworkable for an integrated gnat. Researchers at the MIT Biomedical Engineering Center have developed a sensor array that uses one sensor to measure more than one thing and uses two sensors in combination to measure parameters that neither sensor alone could measure [11]. They have a tumor probe with an array of ten oxygen-temperature sensor pairs along it. The temperature sensors not only give an indication of the thermal gradient but also blood flow and the thermal properties of diffusivity and conductivity. The oxygen sensor, in conjunction with the temperature sensor, provides a measure of the partial pressure of oxygen. This very interesting scheme can be carried over to a sensor system appropriate for a gnat robot. On our gnat, we can combine an infrared sensor array with ranging techniques normally used with CCD cameras, such as stereo and motion algorithms. In this way we get both heat signatures and range data from one piece of hardware. This enables us to perform tasks such as obstacle avoidance and warm-body tracking with the same amount of physical hardware that we would have previously used to do just stereo.

The third strategy is to carry the idea of doubling up sensors one step further and actually *use actuators as sensors.* The micromotors will be sensitive to changes in air pressure and so can be used as pressure sensors. Furthermore, the motor control system that keeps the micromotor's rotor spinning level deals with counteracting the torques generated on the rotor as the gnat changes its orientation. Thus these motors can be used as gyroscopes and provide heading and orientation information. These gyroscopes hold the possibility of becoming as accurate as optical or mechanical gyros while costing orders of magnitude less.

Finally, in order to minimize power consumption, we'll have to *use the most efficient power transmission system possible.* Gearing down these motors to provide useful torque output will be one of the most formidable problems and large losses here could wipe out gains made by other strategies. Very little is known about power transmission systems at such small scales and what the effects of friction, viscosity, small size and high speeds will have on transmission efficiencies.

5 Details of a Proposed Implementation

Where should we start in our quest to build a gnat robot? Certainly there are many technical issues that have to be tackled. What we need is a design for a first prototype, based on sound engineering choices, which can demonstrate the feasibility of the general concept. Can we show that the numbers we obtain for motor and power supply output are in the ballpark of the locomotion requirements of the gnat robot? What would be the best choices for the first chassis, sensor system, power supply and control system?

Let's start with locomotion options. For a swimming, crawling or rolling robot just about everything is a big obstacle compared to a gnat. Furthermore, crawling robots would require all the problems of legged locomotion to be solved first. The resulting complex control system with the ensuing large number of motors necessary to run all the joints is a major research project in itself. A swimming locomotion system for a gnat robot also provides problems. As a body is scaled down in size, viscous forces have relatively more effect than inertial forces since viscous forces are proportional to the surface area of a body and fall as the square, whereas inertial forces are proportional to the mass of a body and fall as the cube. This is why amoebas are often said to effectively swim through asphalt. Flying too, has its problems with viscosity. Small airplanes have low Reynold's numbers - the ratio of inertial to viscous forces. Tiny insects do manage to fly however, and so by existence proof we should be able to make a gnat robot fly. Flying has advantages because it overcomes many of the obstacle avoidance and complex control systems issues but very little is known about flight at low

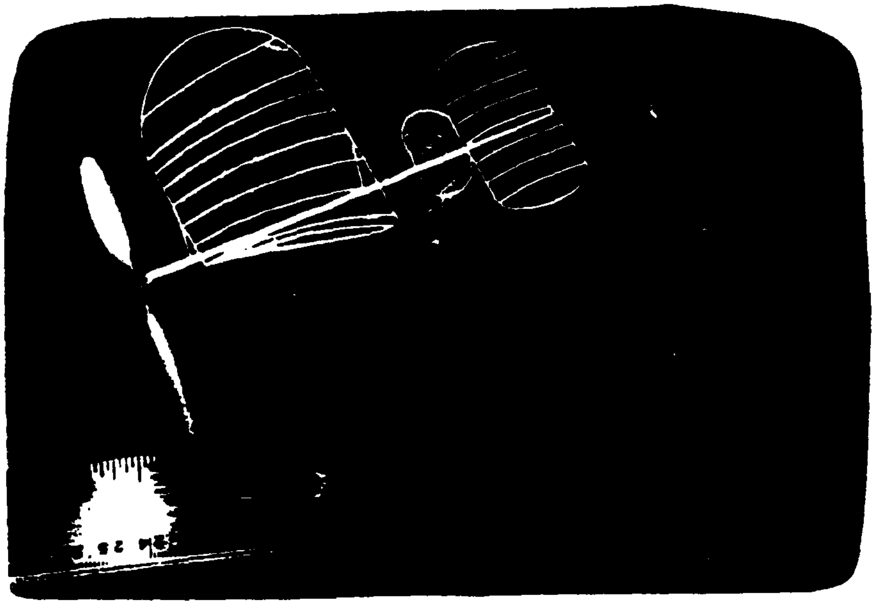

Figure 1: A rubber powered airplane with a $50mg$ airframe and $30mg$ rubber band - Mark Drela.

Reynold's numbers, especially flapping flight.

Rather than try and solve the mysteries of insect flight right now, I propose we find the smallest and lightest known aircraft available today and see if we can make it autonomous; powered by onboard motors and power supply and controlled by onboard sensors and control systems. This way, we can work on the scaling issues involved in the propulsion system and intelligence areas without having to break new frontiers in aerodynamics.

Probably the record for such an aircraft is held by Professor Mark Drela of the MIT Aeronautics and Astronautics Department. His rubber band powered craft which is approximately five inches long, is shown in Figure 1. It weighs $80mg$ including the $30mg$ rubber band.

This remarkable airplane, which can stay aloft for six minutes, has an airframe made out of splinters of balsa wood and a wing composed of a film $1\mu m$ thick [12]. The plane is inherently stable and a slight twist of the wing causes it to fly in circles. The upswept wingtips keep the plane level while turning, alleviating the need for ailerons. This feature means that if we were to automate this airplane, only one additional actuator would be needed for control - an actuator to steer a rudder. Climbing is accomplished by increasing the speed of the propeller. Some of the characteristics of the

Table 1: Flight parameters of 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	$19\mu Nm$
Reynold's number	800 - 1000
Lift:drag	2.5
Energy density of the rubber band	$15\frac{W}{kg}$

airplane are shown in Table 1.

What's intriguing here, is that the power supplied by the rubber band, $.4mW$, is less than the no-load power output, $1.8mW$, of the MIT micromotor mentioned earlier. Clearly it seems plausible then, that micromotors of this type might be adequate to power this aircraft. With the addition of high efficiency solar cells to supply power, and passive sensors and a control system for obstacle avoidance, we just might be able to build a very small airplane that could fly autonomously.

The MIT micromotor, shown in Figure 2 (from [2]), has another characteristic that makes the feasibility of powering the plane with this motor look more promising. Because of its extremely small size, its mass is very low. A silicon micromotor approximately $700\mu m$ in diameter on a $500\mu m$ thick wafer would weigh $.4mg$, roughly two orders of magnitude less than the weight of the rubber band.

The airplane's propeller requires an applied torque of $19\mu Nm$ at an angular velocity of $200rpm$, equivalent to $.4mW$ of power. The corresponding no-load figures for the micromotor [2] are shown in Table 2.

Since at the present time, the design has no provision for attaching a load, the maximum angular velocity, ω_{max}, is determined by setting the electric drive torque, τ_e, equal to the viscous torque, τ_v, where all the power

Figure 2: The synchronous variable capacitance rotary micromotor [2].

Table 2: Performance of the MIT micromotor under no load [2].

τ_e	Drive torque	$2.9 \times 10^{-8} Nm$
τ_v	Viscous torque at max velocity	$2.9 \times 10^{-8} Nm$
ω_{max}	Max angular velocity	$6.2 \times 10^{4} \frac{rads}{s} = 600,000 rpm$
$P_d = \tau_v \omega_{max}$	Power delivered	$1.8 mW$

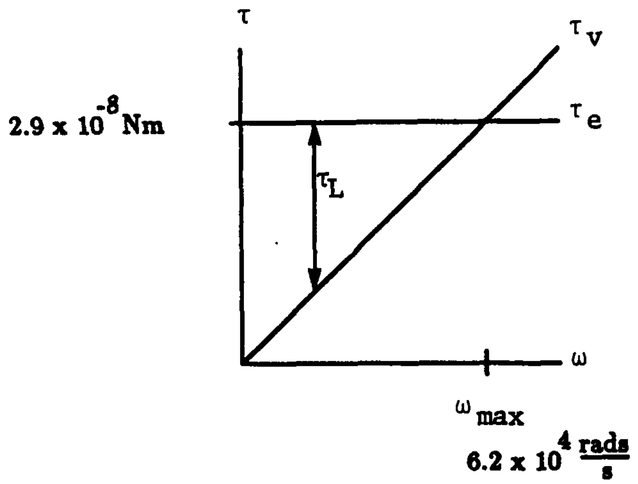

Figure 3: Electric drive torque and viscous torque.

is dissipated by the rotor churning up the air. The drive electronics would then have to also switch at this speed in order for the motor to work.

What we need to know however, is what speed we'll have to operate at in order to get useful torque output. It turns out that this type of motor has a constant τ_e for all values of ω [3,4,31]. Since τ_v increases linearly with ω, the useful torque, τ_L, is the difference between these two curves and decreases linearly with omega as shown in Figures 3 and 4.

Since the power delivered to the load, P_L, is equal to the product $\tau_L\omega$, maximum efficiency is derived from the motor when it is operated at $\omega_{op} = \frac{\omega_{max}}{2}$ and $\tau_{op} = \frac{\tau_e}{2}$. These values are shown in Table 3. Note that the power output is still roughly equal to that of the rubber band. The torque-velocity relationship however, is clearly in the wrong ratio. We need to increase the motor's torque 1,270 times and decrease its speed by a factor of 1500 in order to drive the propeller. A very efficient gearing system is needed since we don't have much power to spare.

Assuming some transmission system can be developed, we turn now to the question of providing power. Probably the highest power density solar cell developed so far is a double sided design which utilizes photons captured by reflection from a surface below the cell to boost the specific power to $700\frac{W}{kg}$ [17,15]. Thus the $.5mW$ of power necessary to drive the motor at its operating point can be achieved with $.7mg$ of silicon. For an $80\mu m$ thick cell and $\rho_{si} = 2300\frac{kg}{m^3}$, this takes up only $3.5mm^2$ of space. The micromotor

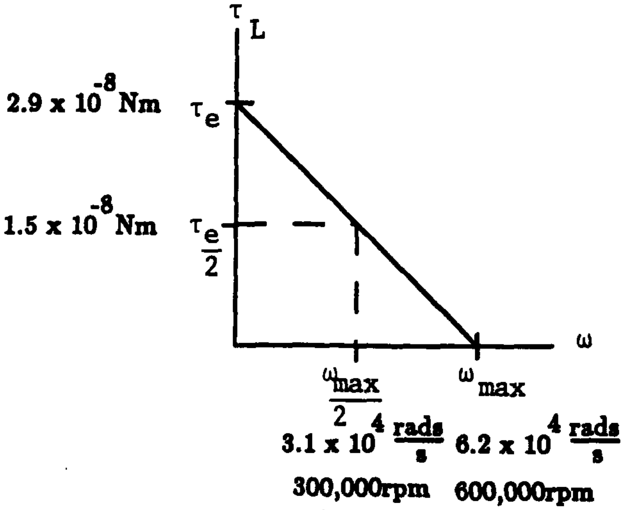

Figure 4: Useful torque that can be delivered to a load.

Table 3: Operating Point for the MIT micromotor.

$\frac{\tau_e}{2}$	Torque available for the load	$1.5 \times 10^{-8} Nm$
$\frac{\omega_{max}}{2}$	Operating velocity	$3.1 \times 10^{4} \frac{rads}{s} = 300{,}000 rpm$
P_L	Power delivered to the load	$.46 mW$

needs 100V applied across the capacitors formed between the stators and the rotor. At 0.6V per solar cell, 167 cells need to be run in series to provide 100V. Each cell would then be $0.02mm^2$. The total weight of the propulsion system, motor plus solar cell, is only $1.1mg$. This is still more than an order of magnitude less than the weight of the rubber band.

It seems plausible then, that continuous flight can be achieved and we need not be constrained by the finite energy of a rubber band. However, this example of powering the airplane by a micromotor of the type being worked on at MIT is not intended to give the impression that these motors are widely available or even that this particular design is the right choice. The MIT micromotor work described here is, at this time, still at the design stage and no motors have yet been fabricated or tested. The numbers used in this paper for maximum torque and maximum angular velocity are theoretical limits and are not meant to imply actual working values. Their inclusion in this paper is merely to show that calculated power outputs of these types of motors are in the same ballpark as those needed to propel a small vehicle.

What sort of sensors and control system can we put onboard to automate this plane? We are presently developing a sensor system based on a pair of single scanline CCD cameras to implement obstacle avoidance algorithms using stereo and motion techniques. Some novel ideas regarding automatic calibration of the cameras allow the algorithms to work without initialization, which usually requires the use of a test pattern. Thus robustness is provided should the cameras become misaligned while in use. Stereo provides information regarding bearing and range to a target. This is accomplished by matching vertical edges in two images and then triangulating. This assumes however, that the optical axes of the two cameras are perpendicular. Errors here can be calibrated out if a few initial distances are known, and that information can be provided by motion algorithms which match feature points from one camera that has moved in position over time. This type of passive sensor system can be implemented on chip and incorporated into a very small package. Several such systems can be used to provide both forward and peripheral vision and enable the airplane to discern placement of obstacles.

Converting stereo and motion information to appropriate rudder and propeller commands can be accomplished through a subsumption architecture control system very similar to the ones presently running the MIT mobile robots [6]. Figure 5 shows a level zero version of a control system for a miniature airplane. The camera module provides a local map in robot-centered polar coordinates of bearing and range to obstacles and sends this

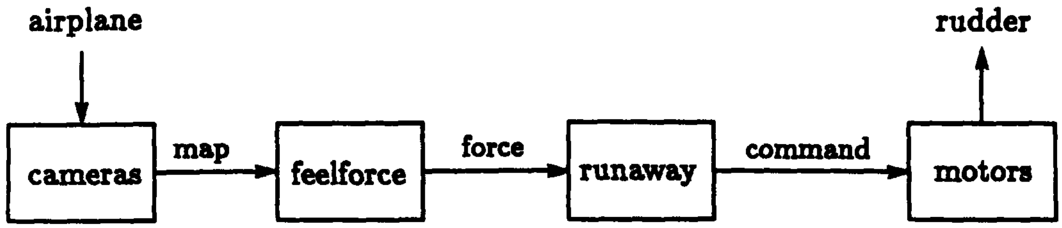

Figure 5: Runaway behavior. Level 0 control system for an airplane.

map to the feelforce module. The feelforce module does a vector sum on this map, treating distant obstacles as weakly repulsive forces and close obstacles as strongly repulsive forces and produces one resultant vector that signifies the path of least resistance. The runaway module monitors this force and when it becomes significant it sends a command to the rudder, directing the airplane to turn left or right. The overall behavior achieved here is that the airplane will fly in a straight line and turn before it collides with an obstacle.

A slightly more sophisticated behavior can be achieved by developing a level 1 control system. Level 0 is left unchanged, but augmented by new modules that sometimes supersede level 0 modules. Different levels are combined by means of a suppressor mechanism in which outputs from higher level modules can suppress outputs from modules in lower levels. A time constant is associated with each suppressor node so that suppression occurs for a fixed period of time after the higher level module fires. Figure 6 shows the level 1 control system which implements a behavior in which the airplane will randomly change direction, and in addition, will avoid obstacles. The wander module provides new headings at discrete increments in time and sends them to the avoid module. The avoid module receives both the resultant force vector and the heading command, and if necessary, computes a slightly perturbed heading so as to avoid any obstacles. It supplies this result to the rudder and propeller, directing the airplane to turn left or right, climb or dive. The output of the runaway module is suppressed for the amount of time set at the suppressor node. Each module in this control system is a simple finite state machine and can be compiled into silicon directly.

The example of automating the miniature airplane here, is not an abandonment of the goal to build a gnat-sized robot, but rather is intended to

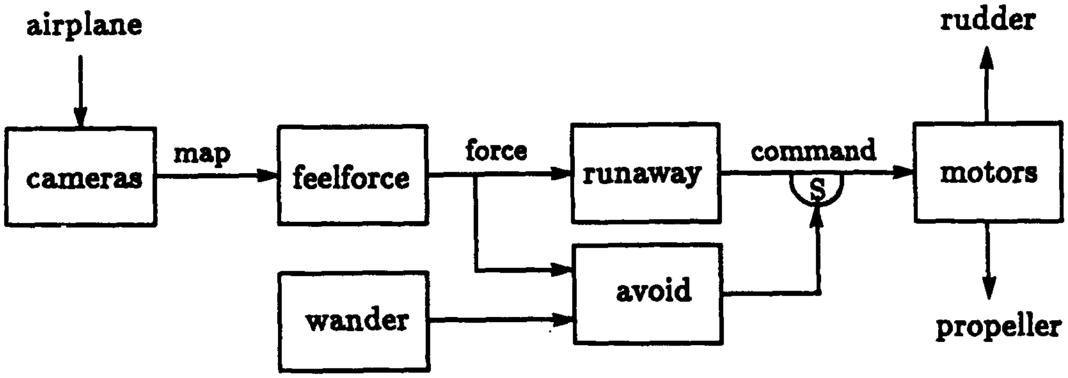

Figure 6: Wander behavior. Level 1 control system.

give concrete evidence of feasibility of integrating a miniature propulsion system with a sensor suite and a subsumption architecture control system, while temporarily alleviating the need for addressing the problem of aerodynamic flight at low Reynold's numbers. The driving issue is cost. If all these things could be integrated and mass produced, then the price of robot systems would drop drastically and open up new areas of application.

What this example has tried to show is that it is worthwhile to take a different course than that which is typically taken in mobile robotics today. That is, it is worthwhile to pursue the idea of using ever smaller and lighter motors and power supplies with the aim of developing cheaper robots, which then hopefully will make robotics more useful to society.

6 What We Need From Micromachining Technology

We've highlighted a specific set of technologies that fit together appropriately to implement a microrobotic system. Obviously, some elements are farther along in development than others. What are the biggest problems and where do we need to concentrate research so that we can actually build such systems in the near future?

Micromotor development is probably the primary concern. Methods for transmitting power need to be studied. A single-stage gear to achieve the torque reduction required for the airplane would be two meters in diameter. Clearly there are better solutions. Harmonic drives, multi-stage gears or perhaps even fluid gears might be appropriate. Very little is known about fluid dynamics in the scenarios presented by micromotors: boundary layer domains, high ratios of viscous to inertial forces and incredibly high rotor speeds. Alternative designs for micromotors could possibly eliminate the need for gearing altogether. Miniaturization of surface acoustic wave motors, which have a high torque to mass ratio, may be the answer.

Interfacing micromotors to macroscopic loads is another problem area. If attaching a propeller to a micromotor requires hand assembly with a very tiny drop of epoxy, then all the advantages of low cost, mass production are lost. Etching propeller mounts or building small robots to do micro assembly may be necessary.

Another technology area that requires research is solar power. Isolation between cells is very important when putting cells in series on the same chip. Improved process technology to yield lower leakage currents is needed. An alternative solution might be to use chemical etching to increase isolation.

Finally, we need research in micro-aerodynamics, a field relatively untouched. It's possible that although we don't know how to make a gnat-sized robot fly today, development of micromotor technology may be a useful tool in studying insect flight.

7 How Gnat Robots Will Change Robotics

The low cost of gnat robots will change the way we think about using robotics in two major ways. First of all, we can begin to think in terms of *massive parallelism.* Instead of large machines which have parts from many vendors and need many interfaces, we use millions of very simple robots to carry out massively parallel work. Take for example, the job of cleaning barnacles off the side of a ship. We could use one large, crane-like robot to lean over the side of the ship and scrub or we could imagine throwing millions of little gnat robots at the side of the ship and have them munch away in parallel. The idea is analogous to the use of a Cray vs. a Connection Machine in terms of sequential vs. parallel processing. The crane robot would also be large and costly and require spare parts and trained personnel to maintain it. The gnat robot on the other hand, would be small, cheap and thrown away when it breaks.

This brings us to the second way in which low-cost gnat robots will change the way we use robot technology. We will see the emergence of *cheap disposable robots.* Once designed, gnat robots are produced in one fabrication process and can be very cheaply manufactured. They can be thrown away or left behind when they finish their task or run out of power. Presently, a sentry robot guarding a warehouse just might be the most expensive thing in that warehouse and we might tend to worry more about somebody stealing our robot than any merchandise. Gnat robots will come to be regarded like ball point pens. They'll be cheap enough that we just toss them out and buy new ones when the old ones break.

8 Conclusion

A new direction in robotics is needed in order to reduce costs so that robots can become more useful to society. Integration of an entire robotic system onto a single piece of silicon is the avenue we need to pursue. By integrating propulsion systems, sensors and intelligent control, mass production and low cost can be achieved, opening up a new range of applications. Instead of spending energy on large, mainframe robots which will never be cheaply mass produced, we should focus research on microrobots. Just as declining costs enabled personal computers to become widely available, so too will declining costs enable robot technology to become a part of everyday life.

This paper has argued that such machines are not science fiction, but are in fact, well within the realm of feasibility. We've outlined which technology areas and problems need to be addressed and have outlined some strategies for design that will enable this technology to come to fruition in the fastest possible manner.

The example of automating the miniature airplane was designed to illustrate specifically how the appropriate pieces could be combined to realize a microrobotic system. The framework of a lightweight airplane was chosen because it provides the simplest scenario for implementing a complete system, due to the fact that it requires very little power input and can be automated with a straightforward control system. The point of this example was not to imply that the micromotors mentioned would be the right choice for design of a propulsion system, or that an airplane of a macroscopic scale would be acceptable. Rather the goal was to put all the pieces in the concrete context of a system in order to demonstrate feasibility, to show that this direction is worthy of pursuit, and to pinpoint which problems need to be solved.

For instance, although the micromotors discussed in this paper have a calculated power output roughly equivalent to that necessary to power a small airplane, we know that higher torque and lower speed are required, and we can begin to concentrate on those issues. Whether the solution is a mechanical or hydraulic gearing system, or a totally different kind of motor altogether, the exercise of putting the problem in the context of an entire system has been helpful.

All of this is not an abandonment of the ultimate goal of building a truly gnat-sized robot either, but merely good engineering use of abstraction, i.e. isolating tough problems. By separating the problem of microaerodynamics from integration of miniature propulsion, sensor and control systems, it might be possible to solve them iteratively. Advances in one area may provide tools for research in the other. Hopefully in this way, we can make steady progress in solving the many problems involved in building gnat robots.

9 Acknowledgments

Discussions with numerous people spawned many of the ideas in this paper. The author would especially like to thank Stephen Bart and Jeff Lang of the MIT Laboratory of Electromagnetic and Electronic Systems; Roger Howe and Martin Schlecht of the MIT Microsystems Technology Laboratories; Mark Drela, Steve Bussolari, Juan Cruz, Harold Youngren and Steve Finberg from the MIT Daedalus Project; David Staelin and Greg Wornell, MIT Research Laboratory of Electronics; Mike Curley, MIT Biomedical Engineering Center; Harry West, MIT Mechanical Engineering Design Center and Ken Salisbury, Ken Pasch, Al Ward, Mike Caine, Carl Ullrich, Steve Eppinger, Eric Vaaler and Rod Brooks of the MIT Artificial Intelligence Laboratory.

References

[1] James B. Angell, Stephen C. Terry, and Phillip W. Barth. Silicon micromechanical devices. *Scientific American*, 44–55, April 1983.

[2] Stephen Bart and Jeff Lang, MIT Laboratory of Electromagnetic and Electronic Systems; Martin Schlecht and Roger Howe, MIT Microsystems Technology Laboratories. Personal communication.

[3] Stephen Bart. MIT Laboratory of Electromagnetic and Electronic Systems. Personal communication.

[4] B. Bollée. Electrostatic motors. *Philips Technical Review*, 30(6/7):178–194, 1969.

[5] Rodney A. Brooks. Intelligence without representation. In *Proceedings of the Workshop on The Foundations of AI*, Endicott House, June 1987. Forthcoming.

[6] Rodney A. Brooks. A robust layered control system for a mobile robot. *IEEE Journal of Robotics and Automation*, RA-2(1), April 1986.

[7] Rodney A. Brooks, Jon Connell, and A.M. Flynn. A mobile robot with onboard parallel processor and large workspace arm. In *Proceedings of AAAI*, August 1986.

[8] Jeffrey M. Camhi. The escape system of the cockroach. *Scientific American*, 243(6):169–171, December 1980.

[9] Il Hyun Choi and Kensall D. Wise. A silicon-thermopile based infrared sensing array for use in automated manufacturing. *IEEE Trans. on Electron Devices*, ED-33(1):72–79, 1986.

[10] Samuel K. Clark and K.D. Wise. Pressure sensitivity in anisotropically etched thin-diaphram pressure sensors. *IEEE Trans. on Electron Devices*, ED- 26(12):1887–1896, 1979.

[11] M.G. Curley, L.M. Peznola, J.C. Weaver, D.J. Edell, S.K. Burns, and H.F. Bowman. Multipoint monitoring of temperature, oxygen tension, perfusion and thermal properties. In N.A. Langrana, editor, *Advances in Bioengineering*, 1985. ASME Winter Annual Meeting, Miami, Nov. 1985.

[12] Mark Drela. MIT Aeronautics and Astronautics Department. Personal communication.

[13] A.M. Flynn. *Redundant Sensors For Mobile Robot Navigation*. Technical Report 859, MIT AI Lab, 1985.

[14] Marty Heitner. As time flows by. *IEEE Spectrum*, March 1987.

[15] Rudolf Hezel. Institut für Werkstoffwissenschaften VI, Universität Erlangen-Nürnberg, D-8520 Erlangen, West Germany. Personal communication.

[16] R.T. Howe. Polycrystalline silicon microstructures. In C.D. Fung, P.W. Cheung, W.H. Ko, and D.G. Fleming, editors, *Micromachining and Micropackaging of Transducers*, pages 169–187, Elsevier, 1985.

[17] K. Jaeger and R. Hezel. Bifacial metal insulator semiconductor inversion layer solar cells based on low temperature silicon surface passivation. In *Proceedings of the 19th IEEE Photovoltaic Specialists Conference*, New Orleans, May 1987.

[18] R.G. Kelly and A.E. Owen. Microelectronic ionsensors: a critical survey. *IEE Proc.*, Vol. 132 Pt. 1(5):227–236, 1985.

[19] T. Kleist. Bee navigation: the eyes have it. *Science News*, 130(14):214, October 4, 1986.

[20] M.R. Kruer, D.A. Scribner, and J.M. Killiany. Infrared focal plane array technology development for navy applications. *Optical Engineering*, 26(3):182–190, March 1987.

[21] Kurt E. Petersen. Dynamic micromechanics on silicon: techniques and devices. *IEEE Transactions on Electron Devices*, ED-25, 1978.

[22] Kurt E. Petersen. Silicon as a mechanical material. In *Proc. IEEE*, pages 420–457, 1982.

[23] Kurt E. Petersen. Silicon sensor technologies. In *Technical Digest*, pages 2–7, IEEE International Electron Devices Meeting, Washington, D.C., December 1985.

[24] J. Raloff. Infrared can spy plant stress before eyes do. *Science News*, 127(5):70, February 2, 1985.

[25] Charles W. Selvidge, Adam C. Malamy, and Lance A. Glasser. Power and communication techniques for physically isolated integrated circuits. In *Proceedings of the Stanford Conference on Advanced Research in VLSI*, March 1987.

[26] Bruno Serey and Larry Matthies. Obstacle avoidance using 1-d stereo vision. CMU Technical Report. In preparation.

[27] R.A. Sinton, Y. Kwark, J.Y. Gan, and R.M. Swanson. 27.5-percent silicon concentrator solar cells. *Electron Device Letters*, EDL-7(10):567–569, October 1986.

[28] Richard Swanson. Stanford University. Personal communication.

[29] Markus Toth. *A Design Compiler for the Intelligent Control System of a Mobile Robot.* Master's thesis, MIT AI Lab, August 1987. Forthcoming.

[30] W.S.N. Trimmer and K.J. Gabriel. Design considerations for a practical electrostatic micro motor. *Sensors and Actuators*, 11(2):189–206, 1987.

[31] J.G. Trump. *Vacuum Electrostatic Engineering.* PhD thesis, Massachusetts Institute of Technology, 1933.