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Control of a Micro-Organism as a Prototype Micro-Robot

R.S. Fearing
Dept. of EE&CS
Univ. of California
Berkeley, CA 94720, USA

Abstract

Mobile devices built on a sub-millimeter scale working in a fluid medium could be useful for manipulation and testing of small biological or electrical components. Complete self-powered mobile systems on this scale already exist, in the form of simple single-celled animals. By applying external control signals, trajectories of these animals can be specified. Protozooans such as *Paramecium* provide a good example mechanism to begin exploring issues of control, sensing and planning for this environment and size. Path planning using an electric potential has been used to allow these mobile devices to solve a simple maze, using only intrinsic behavior. Using visual sensing of device position, primitive closed-loop trajectory following in the plane has been shown. Based on simple mechanical models [Roberts, 1970], force and velocity limitations for these devices can be estimated.

1. Introduction

There are many problems with manipulation of very small objects for assembly or testing in electronic, mechanical or biological systems. Traditionally, these manipulation systems have been precise, slow, expensive, and likely to damage tiny parts. If it were possible to build micro-robots with a maximum dimension less than one millimeter, many new capabilities would be available for assembly, testing, probing, and machining of electronic, mechanical, or biological systems. As robot systems are reduced in size, absolute accuracy improves for a constant proportional error, forces due to collision are reduced, and costs are potentially much lower. (See for example [Trimmer and Jebens, 1989].) In addition, inaccessible workspaces can be reached. For example, Fukuda et al [1989] built a 32 mm diameter by 90 mm long mobile robot for inspecting the interior of pipes, and a smaller, wireless version [Fukuda et al 1991].

A key to building very small robots is building microactuators. In the last few years, there have been many advances in building very small actuators, in particular, taking advantage of integrated circuit processes for micromachining. Electrostatic rotary motors on the order of 100 μm diameter have been demonstrated by Fan et al [1989]. A wide assortment of actuators including superconducting levitated, and harmonic drive devices are currently being pursued (see for example [Fujita, 1989]).

Recently, there has been some progress in integrating microactuators into robot systems. Some example systems are a plan for a planar manipulator platform on an air bearing [Pister et al, 1990], a magnetically levitated transport system [Busch-Vishniac et al, 1990], a force-reflecting micro-telerobot for single cell manipulations [Hunter et al 1989ab], and a force-reflecting telerobot for atomic manipulations [Hollis, 1990].

In the future, autonomous microbots could function independently without centralized remote control or planning, and may have many applications in exploration, cleaning, or repair. Potential uses for these devices have been explored by Flynn [1987], Flynn et al [1989], and Brooks and Flynn [1989]. In the near term, it may be easier to explore manipulation and planning issues with already fabricated remotely controlled microbots as is proposed in this paper.

Friction creates many problems at the micro-scale, and the best approach is to avoid friction problems by using fluid bearings, levitation, or flexures. For low static friction, and to handle the most delicate parts gently, a liquid medium is ideal. As resistance is small at slow speeds, power requirements favor using a neutral density robot in a liquid medium. A swimming robot seems to be the vehicle of choice at this size range for ease of fabrication. While the ideal microbot is probably still some years away, it should eventually be possible to integrate actuators, power sources and computers onto a single silicon platform.

If a swimming microorganism can be computer controlled, it can be considered as an "at scale" prototype of a micro mobile robot. A large single celled ciliate *Paramecium multimicronucleatum* (Carolina Biological Supply Co.) was chosen as the prototype species. As shown in Fig. 1, Paramecium is covered with hundreds of individual cilia which beat together in a coordinated fashion to propel it through a fresh water medium. (Cilia work very well for fluid propulsion in the sub-millimeter regime, and arrays of cilia like structures can be fabricated using micromachining techniques [Furuhata et al, 1991].) The organism rotates about its longitudinal axis as it swims along a helical path. Paramecium is a predator which preys on a smaller flagellate *Chilomonas*, which in turn feeds on cellulose degrading bacteria. It replicates by cell fission with a generation time of about 24 hours.

1.1. Behavior of *Paramecium*

Paramecium in a current carrying medium tends to swim towards the cathode, in what is called a galvanotactic response. Paramecium is propelled through water by beating cilia which cover its entire surface. In response to a change in membrane potential, the cilia beating direction reverses on some of the cell surface. This reversed beating area creates a torque on the paramecium which reorients the swimming direction [Roberts, 1970]. Machemer and Eckert [1975] have shown that voltage thresholds on the order of 10 mV are sufficient to obtain reversed beating. With a typical length of 0.3 mm, a potential difference of 1 V/cm in a conducting medium would give 30 mV across the paramecium. This low voltage can be used to externally control the paramecium behavior.

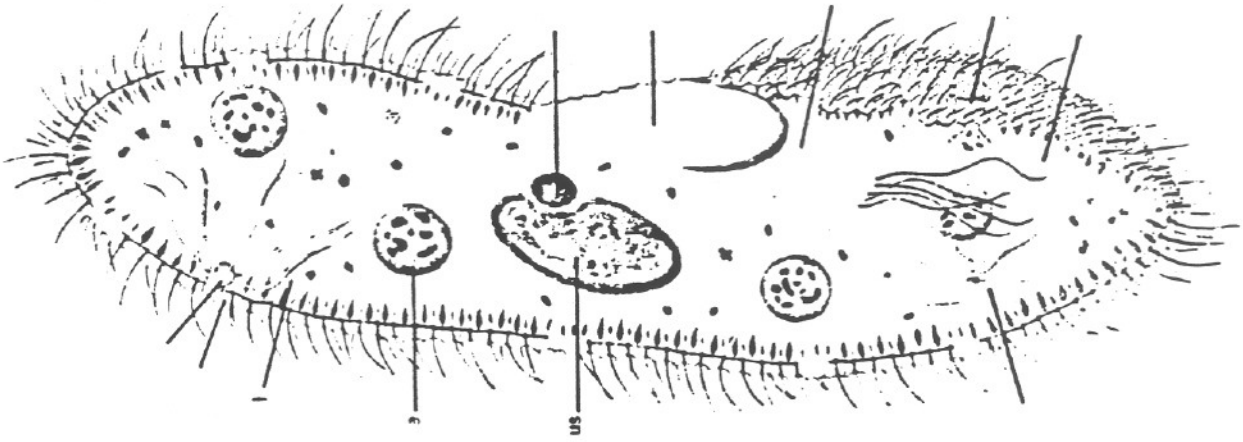

Figure 1. Drawing of Paramecium (from Carolina Biological Supply, 1980)

It should be noted that the electric fields used here do not measurably accelerate the paramecium, instead, they function as a signalling mechanism. Electric fields on the order of $10^5 Vm^{-1}$ have been used directly to manipulate microscopic objects in a dielectric fluid [Washizu, 1990; Fuhr et al, 1991]. Here, the power source for locomotion is contained in the prototype micro-robot.

A microorgranism is not the ideal microbot, but it does allow exploration of the micro-bot system issues of control, manipulation, planning and coordination of multiple robots with little fabrication difficulty. The advantages and disadvantages of using Paramecium as a micro-robot are now examined.

1.2. Advantages to Paramecia as Microrobot Research Tool

The best current advantage of micro-organisms over micro-machined robots is the complete packaging of control system, actuators, and power supply in a very small package. Paramecium is one of the larger single-celled animals, about 300 μm long × 50 μm diameter. *Chilomonas* also exhibits galvanotactic response, and is less than 30 μm in length. Because they can be controlled by an external current through the water medium, no umbilicals are necessary. They can "recharge" on ambient food, and do not need to return to a charging station as a battery powered device might.

Paramecium is basically a fluid filled sack, which is inherently compliant, and should not damage fragile objects by collision. This fluid filled sack moves very fast for its body size, about 5 body lengths per second maximum. (The comparable speed for a human would be a running speed of about 30 Km/hr).

The incremental cost of an organism is remarkably small. $\$10^{-4}$ of food and water will (after several days) yield 10^6 paramecium, for an approximate cost of 1 n$ (nano-dollar) per robot. With this cost, single-time-use and disposable microbots are feasible. The robot hardware cost for massive parallelism is also small. (Of course, external computers and control circuitry will still have significant cost). Another feature is that these microbots are inherently biodegradable.

1.3. Disadvantages of Paramecia as Microrobot Research Tool

As with all living things, they will eventually die, and they emit waste products which can contaminate their environment. They are susceptible to infection, and non-sterile. Moderate environmental changes, such as temperature, pH, and metal ions, can all kill paramecia. They need a water medium to live. In addition, their individual behavior has a large random component. However, a controlled environment at room temperature can be achieved in which they thrive.

2. Potential Method Path Planning

Because Paramecium will tend to move along the gradient of a potential, it can autonomously solve the point motion planning problem in 3D. By applying a negative potential at the goal, and a positive potential at the start location, the microbot can swim around insulating obstacles to eventually reach the goal. (Planning methods using Laplace's equation have been used successfully to find a path through a cluttered workspace [Connolly, et al 1990]). Laplace's equation is physically realized in a conducting solution, thus no computation is necessary. A problem with potential field methods is the chance for the robot to get stuck in local minima. However, Paramecium cooperates by adding a random swimming component which generally prevents it from remaining indefinitely in local minima. Interestingly, Barraquand and Latombe [1989] have shown solutions to planning problems in higher dimensions by superimposing brownian motion on a potential function to avoid local minima and achieve the global optimal solution.

To test the planar paramecium path planning behavior, a simple maze was machined out of acrylic as shown in Fig. 2. The maze has a solution path length of about 35 mm, channel width of 3 mm, and depth 3 mm. The water/paramecia medium is added, and a potential of about 3 V was applied between the two ends of the maze. Many paramecia near the center of the solution channel reorient themselves and swim towards the goal. However, they are likely to swim straight by and miss turns in the solution channel- they seem to not sense the change in current direction. When in a side channel, there is no potential gradient, and the paramecia will swim freely and randomly. Eventually, their random swimming will take them out into the solution channel and they will again swim towards the goal. After about 5 minutes, approximately one half of the animals have reached the goal. Once at the goal, the animals are unlikely to leave the proximity of the cathode.

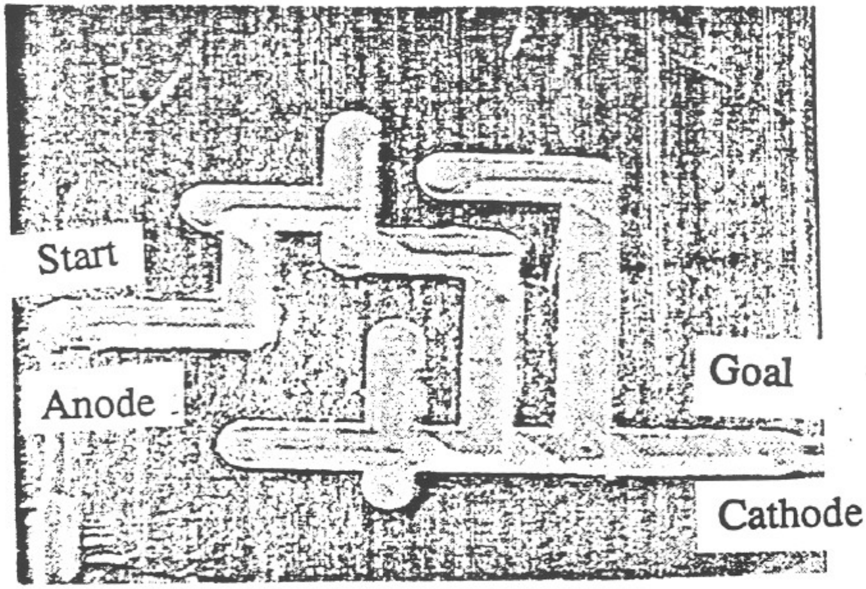

Figure 2. Maze Machined from Acrylic

3. Closed Loop Position Control

For manipulation and probing tasks, one needs to control the position or velocity of the microbots. By determining appropriate electric conduction fields in the medium, the paramecia motion can be controlled. A vision system can be used to track paramecium position, and a voltage proportional to paramecium position error can be applied to the liquid medium.

The initial apparatus is shown in Fig. 3. A glass depression slide has 4 tinned electrodes attached 90° apart on 13 mm diameters. Water covers an area 17 mm in diameter and (with meniscus) a thickness of about 1 mm. When full, the slide contains about 200 mm^3 of water. The depression slide is set on a camcorder with macro lens, and lighting can be adjusted for best contrast (white paramecia on dark background). A background image frame is stored, and paramecia are readily detected by their motion. The figure shows a large square where the image is rapidly scanned for paramecia to track, and two small squares of tracked paramecia. The tracking algorithm handles up to 10 paramecia simultaneously at the image acquisition rate of 15 Hz.

To specify direction and magnitude of the planar electric fields, 3 electrodes are necessary. To simplify computations, a fourth electrode has been added. Eventually, it should be possible to specify the field at any one point in the tank. Initially, only the field in the center of the tank will be of concern, and grossly simplistic assumptions will be made. It is assumed that the tank is relatively flat, and the medium is isotropic and infinite in extent. It is also assumed that the missing insulating boundary conditions ($\hat{n} \cdot \nabla\Phi = 0$ on boundary of region) will not have much effect in the central region.

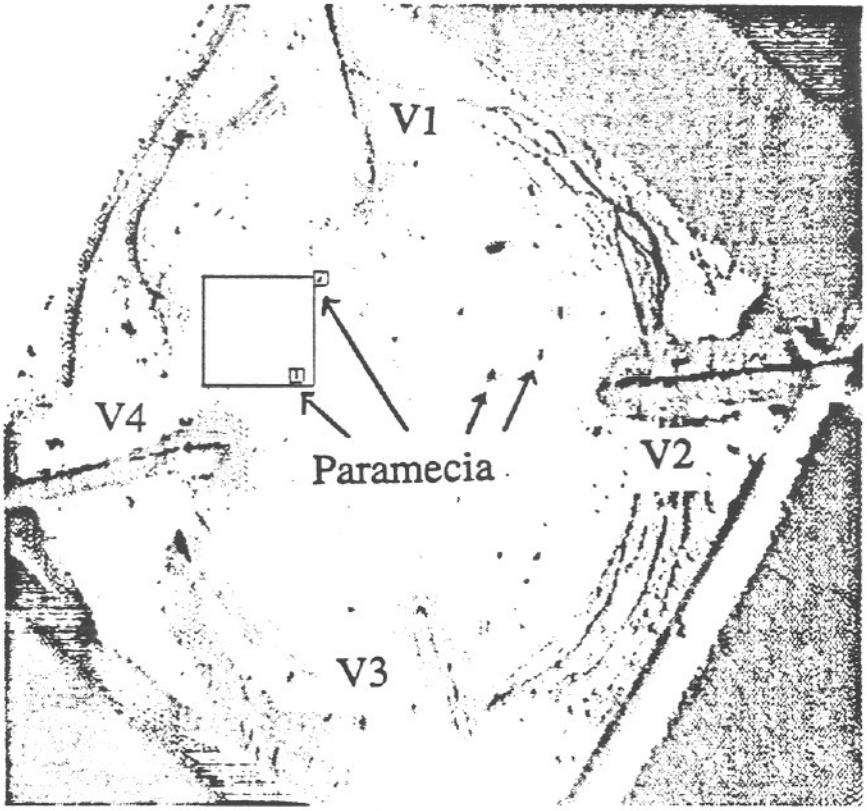

Figure 3. Control Electrodes and Paramecia Tank

Modelling each electrode as a point, we get the total electric potential Φ from:

$$\Phi = \sum_{i=0}^{3} \lambda_i \log|\vec{r}_i| \tag{1}$$

where λ_i is a scaling term proportional to voltage at electrode i, $\vec{r}_i$ is the distance vector to electrode i, and we assumed that the potential is planar. The electric field is obtained by:

$$\vec{E} = -\vec{\nabla}\Phi = -\sum_{i=0}^{3} \frac{\lambda_i \hat{r}_i}{|\vec{r}_i|}. \tag{2}$$

For the fluid medium, we get the conduction current $\vec{J}$ from $\vec{J} = \sigma\vec{E}$ where σ is the conductivity of the water.

To obtain a particular field direction in the central region, the following approximation works well. Consider a potential plane defined by a consistent set of four electrode potentials. The normal of this plane (the gradient direction) defines the direction of the field. The potential at each electrode as a function of the azimuth angle is then

$$v_i = V_o(x_i \cos\theta + y_i \sin\theta) \tag{3}$$

where x_i and y_i are the electrode positions in the plane. The E field in the central region for $\theta = 45°$ is seen to be is the desired direction as shown in Fig. 4 (This field corresponds to $V_1 = 0, V_2 = -1V, V_3 = 0, V_4 = 1V$). For more accurate control, it is possible to do a linearization of the fields and a least-squares inverse to determine the potentials at each electrode required to obtain the desired field.

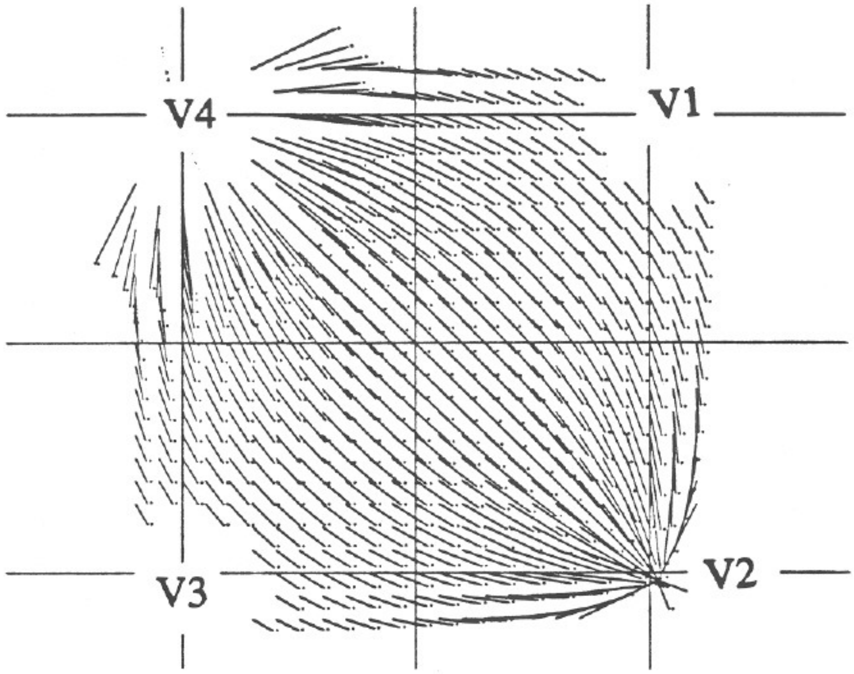

Figure 4. Example Field For Electrode Configuration in Tank

For a position control loop, the angle θ is given by $\tan^{-1}\frac{\Delta y}{\Delta x}$, where Δy and Δx are the position errors in y and x. The potential applied should be proportional to the magnitude of the position error:

$$V_o = k|\Delta\vec{x}| + V_{electrode} \tag{4}$$

where $|\Delta\vec{x}| = |\Delta x\hat{x} + \Delta y\hat{y}|$, and k is the position gain in V/mm. The $V_{electrode}$ term needs to be added to compensate for the half-cell potential for the electrode-electrolyte interface [Ragheb and Geddes, 1990]. It is important to limit the maximum V_o, as potentials much greater than 100 mV across the paramecium considerably reduces its lifetime. One possible explanation for the reduced life of the animal at high potentials is the electrically-induced formation of pores in the cell membrane, leading to rupture [Toner et al, 1990].

A paramecia swimming freely with no applied voltage is shown in Fig. 5. Note the projection of the helical trajectory onto the image plane. Also note that the path is almost straight, until the paramecium changes directions, which occurs at discrete times, rather than continuously.

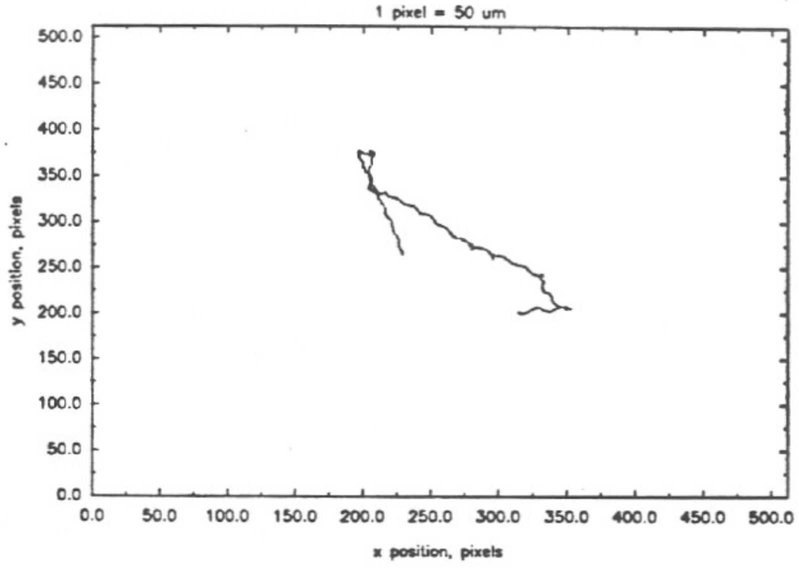

Figure 5. Free Running Paramecia

Two position control experiments are reported here. First is a simple fixed endpoint control system, and second is a trajectory following experiment. In the first experiment (see Fig. 6) a paramecia is tracked from initial pixel location of (x=226, y=123) and commanded to position of (x=200, y=200). The position gain applied is 1.2 V/mm.

There are two interesting features of the response. The first is the bias in the response direction. This may be due to a calibration error in electrode position. (Due to fabrication variability, the electrodes may only be aligned within ±5°). The more interesting feature is the "orbit" of the paramecia about the goal position. It appears as if the paramecium has a limited turning radius, and can not turn sharply enough to intersect the "0" at (200,200). Alternatively, the electric field direction may have a constant bias due to other calibration errors. With accurate electric field control, it should be possible to have the paramecia stop swimming and just rotate about its own axis.

The ability of the simple proportional position controller to track a curve was tested on a square path of 5 mm on a side. The commanded velocity along the square was 0.4 mm s^{-1}, much less than the typical free swimming velocity of 1 mm s^{-1}. The gain was again 1.2V/mm. Two representative experiments (with different animals) are shown here in Fig. 7 and Fig. 8. The first corner is at (200,150), and the trajectory goes counterclockwise around the square. Both animals had deviation from path of < 0.8 mm, but the faster animal (Fig. 8) had a more oscillatory response.

The control applied here is a constant potential. A pulsed orientation control may work a lot better, as the time constant for ciliary reversal is on the order of 20 seconds. [Machemer and Eckert, 1975]. As the animals tend to swim straight without external control, it should

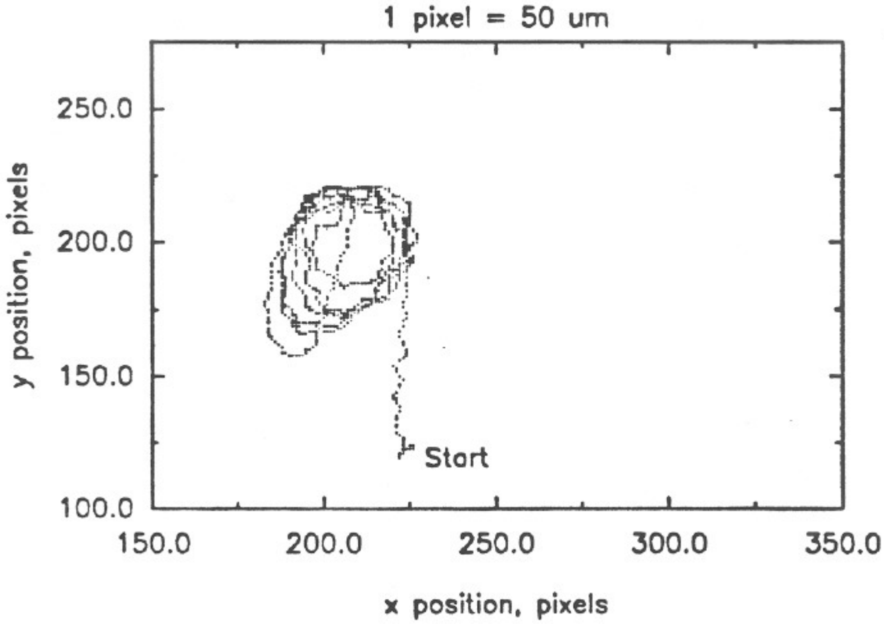

Figure 6. Fixed Point Experiment

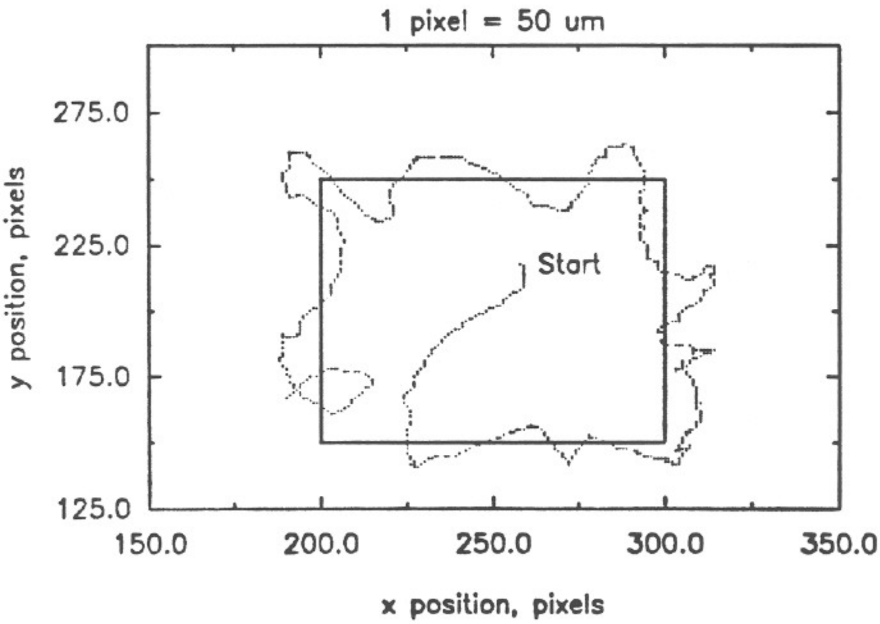

Figure 7. Square Following Experiment with Slow Paramecium

be possible to control them intermittently. This would lead to less stress on the animals from electrode electrolytic products and thermal effects.

The paramecium may be modeled as a system with one control input, the steering angle, and two outputs, the *xy* position in the plane. This problem is similar to an automobile with steering control, but no acceleration control. An interesting possibility is applying steering algorithms for non-holonomic systems, e.g. [Murray and Sastry, 1990], to command

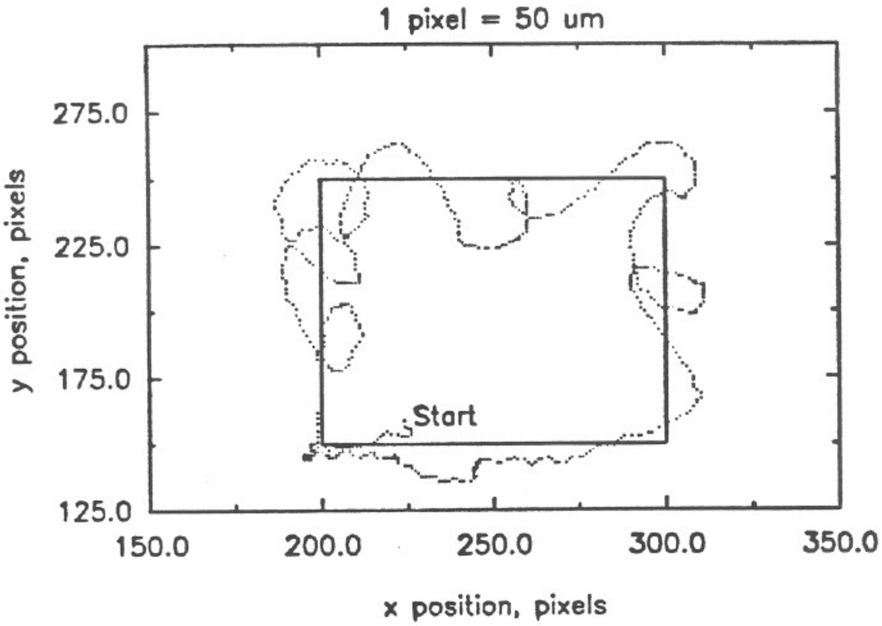

Figure 8. Square following Experiment with Fast Paramecium

point-to-point trajectories for the paramecium.

3.1. Power Requirements

Power requirements for controlling the paramecium are modest. At 3 volts potential, the electrodes only required 6 mA from the supply. Of this 18 mW, a large fraction went into electrolytic reactions at the cathode and anode, and a smaller fraction was dissipated in the water resistance, perhaps 5 mW. Assuming that the paramecium conductivity is the same as the surrounding medium, the fraction of power that is dissipated in the paramecium is given by:

$$\frac{\text{volume paramecium}}{\text{volume medium}} = \frac{6\times10^{-4} mm^3}{2\times10^{2} mm^3} = 3\times10^{-6}.$$

Then the maximum electric heating power in the paramecium is $(5mW)(3\times10^{-6}) = 2\times10^{-8}W$. This heating power does no useful work, and is larger than the mechanical power required to propel the paramecium in a viscous medium. It is interesting to note that using direct electrical stimulation (with embedded micro-electrodes) required $10mV\times10^{-9}A = 10^{-11}W$ (with some loss of power in the micro-electrode) to get full cilial reversal [Machemer and Eckert, 1975].

The propulsion power required in a paramecium can be calculated from its drag forces. The Reynolds number for *Paramecium* is about 10^{-1}, and for cilium 10^{-4} [Sleigh, 1984], thus we have laminar flow, and viscous drag will be the most significant resistance force. As a crude approximation of the paramecium shape, we will consider the drag force on a sphere of 60 μm diameter. Viscous drag on a 60 μm diameter sphere (where η is the viscosity of water), is given by Stoke's Law [Prandtl and Tietjens, 1934]:

$$F = 6\pi r \eta v = 6\pi(30^{-6}m)(10^{-3}Nsm^{-2})(10^{-3}ms^{-1}) < 10^{-9}N. \quad (5)$$

Thus the resistance forces will be on the order of $10^{-9}N$, and the mechanical power required $P = vF = 10^{-12}W$.

4. Future Work and Conclusions

As it seems difficult to attach meaningful grippers to microbots only 300 μm long, it may be better to think about moving objects using multiple microbots as individual "fingers". In the same way in which ants can cooperatively carry objects larger than themselves, groups of microbots could push large neutral density material around. By proper construction of the electric fields, dozens of microbots could be moving an object cooperatively towards the goal. Fig. 8 illustrates how this scheme could work in the plane, with four paramecia pushing an object to the left. An array of electrodes, closer than paramecia size, could be used to construct local fields for each paramecia, and control its direction independently. This method would work best with non-insulating objects, as the conduction field lines will be repelled by insulating objects.

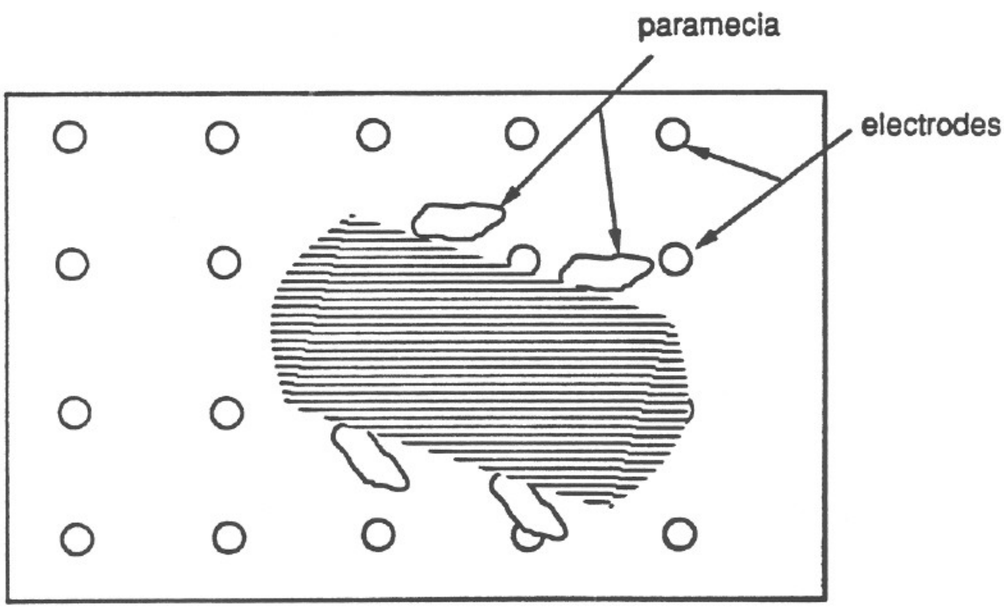

Figure 9. Massively Parallel Grasping with Microbots

The prototype mobile micro-robot described here is intended as a research tool, but future microbots may have practical value, in particular for manipulating small and very fragile parts. The extremely small forces available on this scale are sufficient for slow motion of neutral density objects in a liquid medium. This situation is ideal for small fragile parts, because of the inherent low friction, and very low inertia of paramecium. Many units could be used in parallel if needed for greater speed.

Table 0. Paramecium Microbot Specifications

Parameter	Value
Speed	2 $mm\ s^{-1}$
Power required	10^{-12} watt to overcome drag
Power supply	external control, cellulose food chain
Accuracy	achieved ±1.5mm
range	lifetime (10^4 sec ?) × velocity = 10 m
dimensions	300 μm length × 50 μm diam.
max. force	order 10^{-11} N ?
mass	6×10^{-7} gram
incremental cost	$\$10^{-9}$

Paramecium makes a good test vehicle for exploring mobile micro-robotic systems. (Its basic specifications are summarized in Table 1). Closed-loop position control has been demonstrated, and with refinements of calibration and control, consistent sub-millimeter accuracy should be achieved. While the performance is not exceptional, the cost effectiveness of a single celled animal as a microbot is hard to beat.

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