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Paper:

Trajectory Planning of Motile Cell for Microrobotic Applications

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Our goal is to use motile microorganisms as smart microscale robots for a variety of applications. As a first step, we have achieved microrobotic control of Paramecium cell movement using galvanotaxis (locomotor response to electrical stimulus). Previous studies based on simple empirical rules that did not consider cell dynamics had only limited control. To control cells more precisely as microrobots, we must deal with Paramecium cells in the standard robotics framework. This paper is, to our knowledge, the first attempt in trajectory planning of Paramecium cells under an electric field using a dynamics model for microrobotic applications. Based on the original dynamics model, we propose trajectory planning for cells using a common well-known Lyapunov-like approach and generate cusp-free trajectories. We discuss how to generate stable streamlined trajectories for living cells in a step toward actual control. Numerical experiments demonstrate the successful stable convergence of cell trajectories to the desired location and attitude, which should prove useful in the advanced guidance of cells.

Keywords: Paramecium, micromachine, galvanotaxis, trajectory planning, Lyapunov-like method

1. Introduction

Recent progress in biotechnology has raised growing interest in and increased demand for micro- and nanoscale measurement and control. This typically requires high-precision automation to avoid the need for highly dextrous experienced human operators, Many problems remain to be solved before application becomes practical. Microsystems usually have only a single function, for example, and no studies have achieved multifunctional programmable systems with internal and external sensors, such as robots, insofar as we know.

Our approach to overcoming these problems is to use microorganisms, which may be thought of as smart naturally occurring microrobots [1] and microsensors [2]. Microorganisms have acquired sophisticated sensors and actuators through their evolution. Developing ways to control them freely may enable us to realize multipurpose programmable microrobotic systems superior to synthetic micromachines. Anticipated applications includes cell manipulation, microscopic transport, smart microsensors, and micromachine assembly (**Fig. 1**).

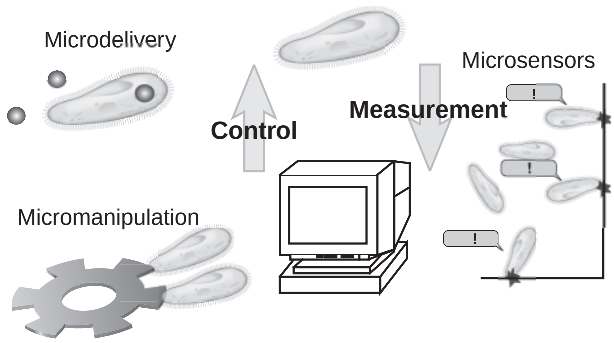

Fig. 1. Our goal: microorganisms as microrobots.

Before we can develop microrobotic applications of microorganisms, however, we must be able to control the navigation of individual cells. One candidate for navigation is galvanotaxis, which is the intrinsic locomotor response of cells to an electrical stimulus, and is noninvasive and noncontact. Using galvanotaxis, recent studies have described simple motion control of *Paramecium caudatum*, a protozoa exhibiting strong galvanotaxis [1, 3–6]. Performance was limited, however, because these studies were based on simple empirical rules without knowledge of the physical properties of cells, i.e., merely experimental control without explicit control laws. To realize more precise control as microrobots, Paramecium cells must be dealt with in the framework of standard robotic methodology. One such standard approach is to construct a dynamics model and derive a control law for planning trajectories. Such an approach has not, to our knowledge, been considered for microorganisms.

We discuss trajectory planning for microrobotic applications of Paramecium cells under an electric field. We previously proposed a basic mathematical model of Paramecium galvanotaxis dynamics [7] that predicted realistic cell behavior, and agreed with actual data. Here, we simplify this nonlinear model to derive a trajectory. Based on the simplified model, we then derive a control law for cells using a well-known Lyapunov-like approach to nonholonomic systems. Given that Paramecium cells cannot swim backward in usual, we designed cusp-free trajectories. Numerical experiments demonstrate the stable convergence of cell trajectories to the desired location and attitude. This should proved useful in microrobotic applications involving Paramecium cells.

We focus on trajectory planning rather than control, on how to generate a stable trajectory rather than on controlling cells along the trajectory.

2. Background

In this section, we discuss the usefulness of microorganisms as micromachines.

The automation of micromanipulation is now essential in biotechnology. Micromachine technology, represented by microelectromechanical systems (MEMS), is one of the hopes for microscale automation. It is difficult, however, to integrate internal sensors that measure the state of MEMS themselves, so most MEMS have only a single function. No study appears to have realized programmable multifunction systems with several internal and external sensors similar to robots. Current affinity of MEMS to bioorganisms is too low for biotechnology applications, because such MEMS are generally too delicate to operate in fluids.

We therefore focus on microorganisms to use as smart autonomous micromachines having the following advantages: (1) highly precise sensors; (2) sophisticated, wireless actuators that operate without an external power supply; (3) easy production – they reproduce themselves; (4) high affinity to bioorganisms; and (5) a size large enough for microscale operation. Future advances in genetic recombination may allow us to design microorganisms with desired functions. Once we can control them, we may realize programmable multipurpose micro-systems superior to MEMS.

Despite numerous studies on MEMS [8] and the development of biosensors using microorganisms [9], very few studies appear to have focused on microorganisms as smart motile machines, not just as tools. Arai manipulated yeast cells freely and dexterously using laser micromanipulation [10]. His concept differs from ours in that he did not use the intrinsic nature of microbes in his work. Fearing and Itoh pioneered using microorganisms as machines and they independently established a firm basis for this possibility [3, 4]. Ogawa et al. improved on their work using high-speed tracking and demonstrated successful motion control with detailed observation in a sufficiently large working area [1]. Yamane et al. analyzed potential distribution in the chamber and realized stable two-dimensional control of a cell by controlling currents [5]. Takahashi et al. succeeded in manipulating small objects by controlling a cluster of Paramecium cells [6]. However, their works were based on empirical rules and not suitable for precise control. We previously proposed a dynamics model of Paramecium galvanotaxis to

Fig. 2. A Paramecium cell.

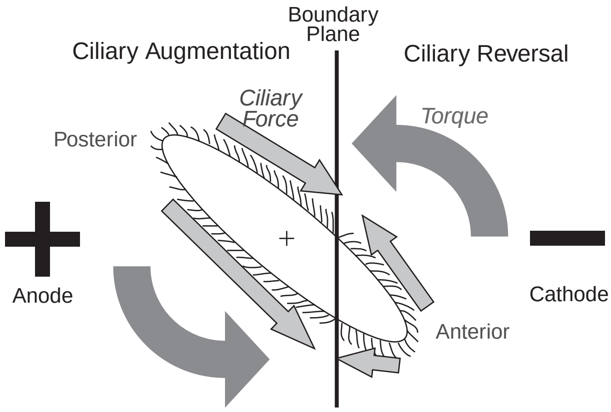

Fig. 3. Qualitative explanation of Paramecium galvanotaxis (Ludloff phenomenon).

introduce robotics methods [7]. Here we derive control laws for Paramecium cells from the dynamics model to realize trajectory planning.

3. Paramecium Galvanotaxis and its Dynamics Model

3.1. Galvanotaxis in Paramecium Cells

We chose Paramecium for our feasibility study, because its strong galvanotaxis is suitable for external control, and it is easily available. *Paramecium caudatum* (**Fig. 2**) is a common unicellular ellipsoidal protozoan 100 to 200 μm long that swims by waving thousands of cilia to move water backward in forward propulsion [11], i.e., these cilia act as tiny actuators.

We use galvanotaxis to navigate Paramecium cells because they exhibit strong negative galvanotaxis [12]. An external electrical stimulus modifies the membrane potential and alters ciliary movement, affecting the cell motion. Viewed macroscopically, the cell is made to swim toward the cathode in a DC electric field. This is done by torque generated by asymmetry in ciliary movement caused by a potential gradient (**Fig. 3**) known as the Ludloff phenomenon [13].

Table 1. Parameters of the proposed model.

Parameters	Values	Comments
Major cell axis $2L$	$100\ \mu$m	our strain
Minor cell axis $2R$	$25\ \mu$m	our strain
Boundary plane offset l	$10\ \mu$m	[23, 24]
Viscosity of water μ	1.00×10^{-3} kg/(ms)	at 20°C
Cell density ρ	$1,000$ kg/m^3	same as water
Increase in beating freq. β	2.00×10^{-3} V^{-1}	[7]
Cell velocity v	$400\ \mu$m	[25]

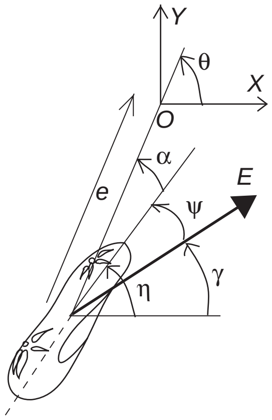

Fig. 4. Definition of coordinates and variables.

3.2. Dynamics Model

To briefly introduce the dynamics model we proposed previously [7], we assume that an ellipsoid cell swims in two-dimensional space. This assumption is valid because, in our past experiments, cells were constrained to move in an almost two-dimensional chamber, necessary to achieve maneuvering using visual feedback because the world viewed through a microscope has a very shallow depth of field. Let (X,Y) be the location of the cell, η the angle of the cell, E the magnitude and γ the angle of the electrical field, and $\psi = \eta - \gamma$ (**Fig. 4**). (Other variables in the figure are introduced later.)

As derived in [7], the physical dynamics of cell attitude and movement are described by

$$\begin{aligned} M\ddot{X} + D\dot{X} &= A\varphi(E)|x_a(\psi)|\cos\eta, \\ M\ddot{Y} + D\dot{Y} &= A\varphi(E)|x_a(\psi)|\sin\eta, \\ I\ddot{\psi} + D'\dot{\psi} &= \tau(\psi,E), \end{aligned} \qquad \text{. . . . (1)}$$

where M is the cell mass, D the viscous friction coefficient for translational movement, $A = 2\kappa n$ a coefficient defined by physical parameters, $\varphi(E) = (1+\beta E)\varphi_0$ ciliary beating frequency for E, and β a coefficient, κ (known as α in [7]) a coefficient between φ and the force generated by a single cilium, n a linear density of cilia, $x_a(\psi) = lL^2\cos\psi/(R^2\sin^2\psi + L^2\cos^2\psi)$ the x-coordinate of the site of action of rotational force on the cell, l the offset of the boundary plane in ciliary motion, L the semimajor cell axis, R the semiminor cell axis, I the moment of inertia, D' the viscous friction coefficient for rotational motion, and $\tau(\psi,E)$ torque generated by the electric field. (See [7] for details.) We confirmed that our model agrees well with actual Paramecium galvanotaxis data using galvanotaxis measurement [7, 14]. Parameter values were obtained from our experimental results or from the literatures (**Table 1**). Actual values are used later in numerical experiments.

3.3. Dynamics Model Simplification

Equation (1) is difficult to evaluate analytically because it contains nonlinearity and acceleration constraints. Here we simplify and linearize the equation based on the assumptions below to derive a suitable control law.

In the micron-scale world of Paramecia, inertia terms are much smaller than viscosity terms because of the small Reynolds number. Reynolds number Re for a Paramecium cell is estimated as

$$Re = 2Lv/\nu = 0.10,$$

using cell length $2L = 100\ \mu$m, velocity under the electrical field $v = 1$ mm/s, and kinematic viscosity of water $\nu = 1.00 \times 10^{-6}$ m^2/s. We conducted simulation without the inertial terms and found that results were almost the same as those obtained with inertial terms used [7]. The equation of motion is thus approximated by ignoring inertial terms as follows:

$$D'\dot{\psi} = \tau(\psi,E) \qquad \text{. . . . . (2)}$$

$$D\dot{X} = A\varphi(E)|x_a(\psi)|\cos\eta \qquad \text{. . . . . (3)}$$

$$D\dot{Y} = A\varphi(E)|x_a(\psi)|\sin\eta. \qquad \text{. . . . . (4)}$$

Next, we assume that forward propulsion is constant and independent of cell attitude. Under this assumption, we treat $x_a(\psi)$ as a constant $x_a(0) = l$, enabling us to rewrite Eqs. (3) and (4) using coefficient $a = A\varphi_0 l$, where $U = U(E) = 1 + \beta E$ is an input-related variable:

$$\begin{aligned} D\dot{X} &= aU\cos\eta, \\ D\dot{Y} &= aU\sin\eta. \end{aligned}$$

The assumption that ψ is less than $\pm\pi/2$ indicates the monotonic decrease in $\tau(\psi,E)$ with respect to ψ [7], leading to the rough approximation that $\tau(\psi,E)$ is proportional to ψ for small ψ. $\tau(\psi,E)$ is thus approximated using the inclination of the tangential line at $\psi = 0$:

$$\tau \simeq \left.\frac{\mathrm{d}\tau}{\mathrm{d}\psi}\right|_{\psi=0} \cdot \psi = -4\frac{R^2 LU f_0 n\sqrt{L^2 - l^2}}{\sqrt{L^4 - L^2 l^2 + R^2 l^2}}\psi,$$

where $f_0 n = \kappa\varphi_0 n = 3\pi\mu R/lv$ is the ciliary force per unit length. By setting $\tau(\psi, U) = bU\psi$ with coefficient b and using relation $\psi = \eta - \gamma$, we obtain a reformulated equation of rotational motion:

$$\dot{\eta} = \frac{bU}{D'}(\eta - \gamma) + \dot{\gamma}.$$

Using the assumptions above, we obtain:

$$\begin{pmatrix} \dot{X} \\ \dot{Y} \\ \dot{\eta} \end{pmatrix} = \begin{pmatrix} \cos\eta & 0 \\ \sin\eta & 0 \\ q(\eta - \gamma) & 1 \end{pmatrix} \begin{pmatrix} u \\ \dot{\gamma} \end{pmatrix} \quad \ldots\ldots (5)$$

where $u = aU/D$ and $q = Db/(D'a)$. This three-state two-input system describes cell movement, where $u = a(1 + \beta E)/D$ and $\dot{\gamma}$ are input variables determined by the electric stimulus. Note that u corresponds to the magnitude of the cell velocity.

Note the similarity between this equation and that for nonholonomic two-wheeled vehicles and autonomous underwater vehicles (AUVs):

$$\begin{pmatrix} \dot{X} \\ \dot{Y} \\ \dot{\eta} \end{pmatrix} = \begin{pmatrix} \cos\eta & 0 \\ \sin\eta & 0 \\ 0 & 1 \end{pmatrix} \begin{pmatrix} v \\ \dot{\phi} \end{pmatrix},$$

where v is velocity and ϕ is the angular velocity of steering. An extra term $q(\eta - \gamma)$ and the restriction that cells cannot swim backward make trajectory planning more difficult than that for common two-wheeled vehicles.

4. Coordinate Transformation

The system (5) derived approximately above is described with a triplet (X, Y, ψ) based on Cartesian coordinates.

We transform coordinates to deal with cusp-free trajectories. This transformation introduces a discontinuity at the equilibrium point in the system. This releases the system from the pessimistic Brockett's theorem asserting the absence of a time-invariant state feedback law to stabilize the system, because the theorem is valid under the condition that state variables are continuous at the equilibrium point [15, 16]. This transformation also realizes cusp-free trajectories, as described later.

We describe this system by a triplet (e, θ, α) based on the following polar coordinates (**Fig. 4**):

$$e = \sqrt{X^2 + Y^2},$$
$$\theta = \mathrm{atan2}(-Y, -X),$$
$$\alpha = \theta - \eta,$$

where e is the radius (for simplicity, e must not be zero), θ the angle, and α the angular displacement of the cell axis from the radial direction. The relationship between velocity vector $(\dot{X}, \dot{Y})$ in Cartesian coordinates and vector $(\dot{e}, \dot{\theta})$ in polar coordinates is:

$$\begin{pmatrix} \dot{e} \\ e\dot{\theta} \end{pmatrix} = \begin{pmatrix} -\cos\theta & -\sin\theta \\ \sin\theta & -\cos\theta \end{pmatrix} \begin{pmatrix} \dot{X} \\ \dot{Y} \end{pmatrix}.$$

The system's state equation is rewritten in (e, θ, α) space as:

$$\dot{e} = -u\cos\alpha \quad \ldots\ldots\ldots\ldots (6)$$
$$\dot{\theta} = \frac{u\sin\alpha}{e} \quad \ldots\ldots\ldots\ldots (7)$$
$$\dot{\alpha} = \frac{u\sin\alpha}{e} - qu(\theta - \alpha - \gamma) - \dot{\gamma}. \quad \ldots\ldots (8)$$

These state equations are defined in the entire state space except the origin.

5. Control Laws

We derive control laws by the following Lyapunov approach; Lyapunov approaches with nonholonomic constraints have been studied in detail by Canudas de Wit, Sordalen, Nakamura etc. [17–22]. Our main originality is in considering the stable trajectory planning of living cells by applying the Lyapunov approach under cell dynamics constraints.

We define the goal of the control task as $(e, \theta, \alpha) \to (0, 0, 0)$, equivalent to the goal that $(X, Y, \eta) \to (0, 0, 0)$. A task with arbitrary goal location and goal attitude is regarded as equivalent to the task defined above by applying suitable transformation. Trajectory planning is defined as the problem of finding a smooth control law for u and $\dot{\gamma}$ so that the above goal is asymptotically achieved for an arbitrary initial condition.

Note that we do not discuss cell behavior around the goal point in our setup because the goal is a singularity and the system is not defined in it. The subtle control of living cells is difficult and the discussion of cell motion in the neighborhood of the goal does not make sense, so here we deal only with the approaching of the goal along its course, or how to navigate the cell toward a distant desired region. We believe that simply the ability to make a cell approach the goal is sufficiently practical.

5.1. Control Law for u

Given that Paramecium cells swim only forward without cusps, we define a control law for u as:

$$u = \xi e \quad : \quad \xi > 0. \quad \ldots\ldots\ldots\ldots (9)$$

Because e is positive by definition, u is invariably positive, satisfying the physical constraint of Paramecium cells, i.e., velocity is invariably positive.

We thus rewrite Eq. (7) as:

$$\dot{e} = -\xi e\cos\alpha \quad \ldots\ldots\ldots\ldots (10)$$
$$\dot{\alpha} = \xi\sin\alpha - \xi qe(\theta - \alpha - \gamma) - \dot{\gamma} \quad \ldots\ldots (11)$$
$$\dot{\theta} = \xi\sin\alpha. \quad \ldots\ldots\ldots\ldots (12)$$

Eq. (10) shows that when $\cos\alpha$ is positive, i.e., the goal is located ahead of the cell, the cell moves to decrease e or to approach the goal. When $\cos\alpha$ is negative, i.e., the goal is located behind the cell, the cell moves to increase e, or to temporarily move away from the goal. α monotonically decreases and $\cos\alpha$ becomes positive. Even if the goal is located behind the cell in the initial state, a U-turn occurs and the goal soon becomes located ahead of the cell. The cell eventually reaches the goal in both cases.

5.2. Control Law for $\dot{\gamma}$

We define a Lyapunov quadratic function:

$$V := \frac{1}{2}(\alpha^2 + h\theta^2),$$

in which h is a positive parameter. Its derivative is:

$$\dot{V} = \alpha\dot{\alpha} + h\theta\dot{\theta} = \xi\alpha\sin\alpha - \xi qe\alpha\theta + \xi qe\alpha^2 + \xi qe\alpha\gamma - \alpha\dot{\gamma} + h\theta\xi\sin\alpha.$$

We choose function $\dot{\gamma}$ with positive coefficient k as:

$$\dot{\gamma} = \xi\sin\alpha - \xi qe\theta + \xi qe\alpha + \xi qe\gamma + h\theta\xi\frac{\sin\alpha}{\alpha} + k\xi\alpha \quad (13)$$

that guarantees a negative time derivative of the Lyapunov function:

$$\dot{V} = -k\xi\alpha^2 \leq 0. \quad (14)$$

From Eq. (14), V approaches a nonnegative finite limit, and α and θ have finite limits $\bar{\alpha}$ and $\bar{\theta}$. These show that V has a finite limit $\frac{1}{2}(\bar{\alpha}^2 + h\bar{\theta}^2)$ as $t \to \infty$ and that $\dot{V}$ is uniformly continuous (because $\ddot{V} = -2\alpha\dot{\alpha}k\xi$ is bounded). If $f(t)$ has a finite limit as $t \to \infty$, and if $\dot{f}$ is uniformly continuous (or $\ddot{f}$ is bounded), then $\dot{f}(t) \to 0$ as $t \to 0$ by Barbalat's Lemma. It is thus proved that $\dot{V}$ converges to zero and that $\bar{\alpha}$ is zero.

By substituting the control law (13) into Eqs. (6) to (8), we obtain

$$\dot{e} = -\xi e\cos\alpha,$$
$$\dot{\alpha} = -h\theta\xi\frac{\sin\alpha}{\alpha} - k\xi\alpha,$$
$$\dot{\theta} = \xi\sin\alpha.$$

The fact that $\alpha \to 0$ and $\theta \to \bar{\theta}$ and the uniform continuity of $\dot{\alpha}$ indicate that

$$\lim_{t\to\infty}\dot{\alpha} = -h\bar{\theta}\xi = 0$$

by using Barbalat's Lemma again, and thus $\bar{\theta} = 0$. These results shows that α, $\dot{\alpha}$, θ, and $\dot{\theta}$ converge to zero. Eq. (6) gives $\dot{e} \to -\xi e$, and thus $e \to 0$.

To summarize, we obtain the following control laws for the cell;

$$u = \xi e,$$
$$\dot{\gamma} = \xi\sin\alpha - \xi qe\theta + \xi qe\alpha + \xi qe\gamma + h\theta\xi\frac{\sin\alpha}{\alpha} + k\xi\alpha,$$

with positive coefficients ξ, h, and k such that the cell should swim toward the origin along a cusp-free path.

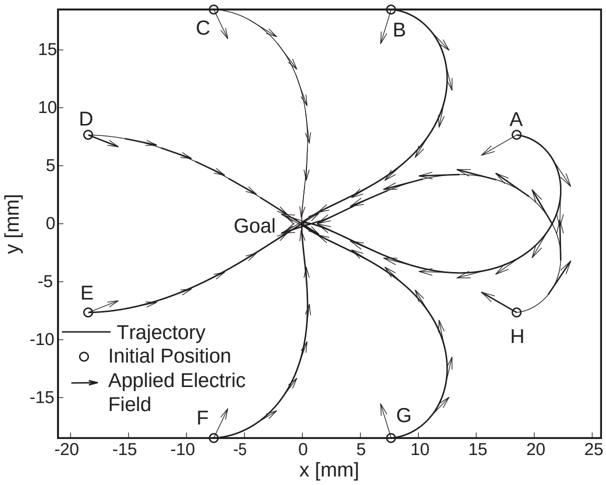

Fig. 5. Trajectories generated by our proposed control law. The eight small circles around the origin indicate the initial points. Arrows along trajectories indicate normalized magnitudes and directions of electrical stimuli input to effect maneuvers at each point.

These laws provide a cell trajectory in which $(e, \theta, \alpha) \to (0, 0, 0)$. We achieve this by adjusting two physical parameters, i.e., electric field magnitude $E = (U - 1)/\beta$ and the derivative of the field direction, $\dot{\gamma}$.

6. Numerical Simulation

6.1. Experimental Setup and Results

We verified the effectiveness of our proposed trajectory planning by numerical simulation, using numerical analysis software (MATLAB, MathWorks Inc.).

We set up a task in which the cell moves toward a goal (origin) from different initial relative attitudes. Initial locations at eight different relative attitudes with 45° intervals were located 20 mm from the origin. In global coordinates, all cells were aligned to initially face in the X direction. We assumed that we could apply an electrical stimulus with an arbitrary magnitude and direction at any point.

Parameters were set by trial and error to $\xi = 1$, $k = 2$, and $h = 0.1$. Other parameters are the same as those used in our previous experiments [7] (**Table 1**). Note that we set the maximum input magnitude to 5 V/cm in the simulation because we have confirmed that stronger electrical fields harm cells. We also aborted the simulation when cell distance e became less than 100 μm in each trial.

Figure 5 shows trajectories obtained as proposed. The eight small circles around the origin indicate initial points. Arrows indicate normalized magnitudes and directions of electrical stimuli input to effect maneuvers at each point. Note that cells approached the goal using only forward movement and rotation, without pivoting or reversing. **Figs. 6**, **7**, and **8** show the time evolution of X, Y, and η cell coordinates. They show the desired stable convergence of (X, Y, η) to the origin. Time evolution plots of control input are shown in **Figs. 9** and **10**.

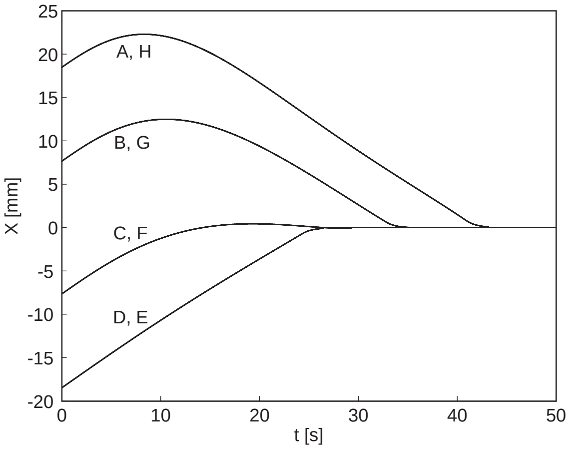

Fig. 6. Time evolution of X position for each initial condition.

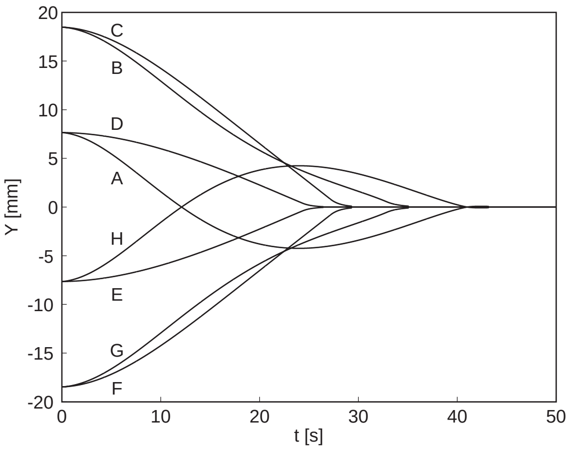

Fig. 7. Time evolution of Y position for each initial condition.

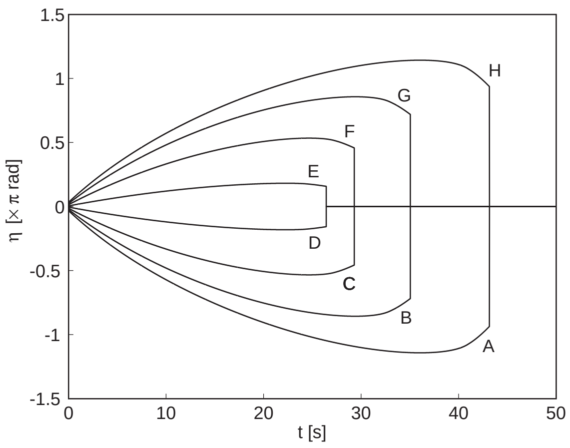

Fig. 8. Time evolution of angle η for each initial condition.

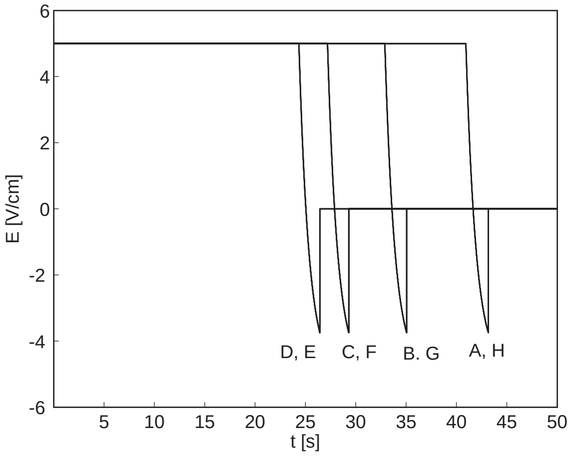

Fig. 9. Time evolution of electrical input magnitude E for each initial condition.

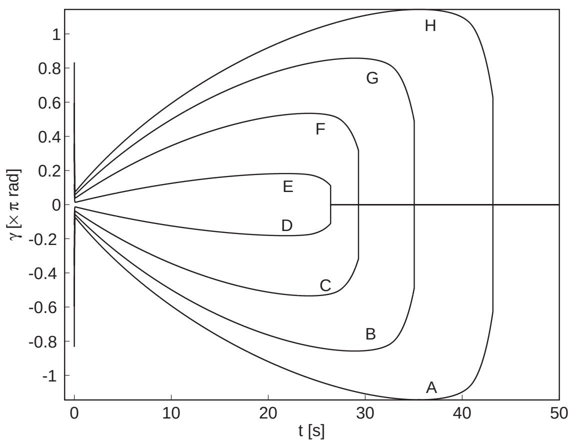

Fig. 10. Time evolution of electrical input direction γ for each initial condition.

6.2. Toward Application to Living Cells

Implementation of the derived control law in an experiment using actual cells is the next main task. We have confirmed that Paramecium cells can be controlled on a two-dimensional plane by manually adjusting the electric field magnitude and direction [1, 5]. We identified the physical parameters of the dynamics model using experimental data [7]. We are now setting up an improved Paramecium control version for model-based control, and wet experiments are now underway at our laboratory. The attitude and the location of a cell is obtained automatically by a high-speed vision, and lock-on tracking to keep the target at the center of view at a 1-kHz frame rate [1, 25]. The number of electrodes is extended to eight, and the system generates the appropriate electrical stimulus in a chamber based on the captured cell image. Details of implementation and experimental results are to be reported elsewhere.

7. Conclusions

We have proposed trajectory planning for Paramecium cells using a Lyapunov approach for microrobotic applications. In numerical experiments, the derived control law successfully demonstrated stable convergence of cusp-free trajectories from different initial points and attitudes in relation to a goal. This work should prove useful in microrobotic applications to Paramecium cells.

References:

[1] N. Ogawa, H. Oku, K. Hashimoto, and M. Ishikawa, "Microrobotic visual control of motile cells using high-speed tracking system," IEEE Trans. Robotics, Vol.21, No.4, pp. 704-712, Aug. 2005.

[2] A. Davies, N. Ogawa, H. Oku, K. Hashimoto, and M. Ishikawa, "Visualization and estimation of contact stimuli using living microorganisms," in Proc. 2006 IEEE Int. Conf. Robotics & Biomimetics (ROBIO 2006), pp. 445-450, Dec. 2006.

[3] R. S. Fearing, "Control of a micro-organism as a prototype microrobot," in Proc. 2nd Int. Symp. Micromachines and Human Sciences, Oct. 1991.

[4] A. Itoh, "Motion control of protozoa for bio MEMS," IEEE/ASME Trans. Mechatronics, Vol.5, No.2, pp. 181-188, Jun. 2000.

[5] J. Yamane, N. Ogawa, H. Oku, K. Hashimoto, and M. Ishikawa, "A current controlled electrostimulation device for the motion control of Paramecia," in Proc. 2004 JSME Conference on Robotics & Mechatronics (Robomec'04), Jun. 2004, pp. 1A1-H-28 (in Japanese).

[6] K. Takahashi, N. Ogawa, H. Oku, and K. Hashimoto, "Organized motion control of a lot of microorganisms using visual feedback," in Proc. 2006 IEEE Int. Conf. Robotics & Automation (ICRA2006), May 2006, pp. 1408-1413.

[7] N. Ogawa, H. Oku, K. Hashimoto, and M. Ishikawa, "A physical model for galvanotaxis of paramecium cell," J. Theoretical Biology, Vol.242, No.2, pp. 314-328, Sep. 2006.

[8] R. S. Muller, "MEMS: Quo Vadis in Century XXI?" Microelectronic Engineering, Vol.53, pp. 47-54, 2000.

[9] S. Daunert, G. Barrett, J. S. Feliciano, R. S. Shetty, S. Shrestha, and W. Smith-Spencer, "Genetically engineered whole-cell sensing systems: Coupling biological recognition with reporter genes," Chemical Reviews, Vol.100, No.7, pp. 2705-2738, Jun. 2000.

[10] F. Arai, "Synchronized laser micromanipulation by high speed laser scanning –dancing yeasts–," in Video Proc. 2003 IEEE Int. Conf. Robotics & Automation (ICRA2003), Sep. 2003.

[11] Y. Naitoh and K. Sugino, "Ciliary movement and its control in *Paramecium*," J. Protozool., Vol.31, No.1, pp. 31-40, 1984.

[12] H. Machemer and J. de Peyer, "Swimming sensory cells: electrical membrane parameters, receptor properties and motor control in ciliated Protozoa," Verhandlungen der Deutschen Zoologischen Gesellschaft, pp. 86-110, 1977.

[13] K. Ludloff, "Untersuchungen über den Galvanotropismus," Archiv fur die Gesamte Physiologie, Vol.59, pp. 525-554, 1895.

[14] N. Ogawa, H. Oku, K. Hashimoto, and M. Ishikawa, "Single-cell level continuous observation of microorganism galvanotaxis using high-speed vision," in Proc. 2004 IEEE Int. Symp. Biomedical Imaging (ISBI 2004), Apr. 2004, pp. 1331-1334.

[15] B. W. Brockett, "Asymptotic stability and feedback stabilization," in Differential Geometric Control Theory, pp. 181-191, Jun. 1982.

[16] M. Aicardi, G. Cannata, G. Casalino, and G. Indiveri, "Guidance of 3D underwater non-holonomic vehicle via projection on holonomic solutions," in Proc. Symposium on Underwater Robotic Technology (SURT 2000), World Automation Congress (WAC 2000), Jun. 2000.

[17] C. Canudas de Wit, A. D. NDoudi-Likoho, and A. Micaelli, "Feedback control for a train-like vehicle," in Proc. 1994 IEEE Int. Conf. Robotics and Automation (ICRA 1994), May 1994, pp. 14-19.

[18] O. J. Sørdalen and O. Egeland, "Exponential stabilization of nonholonomic chained systems," IEEE Trans. Automatic Control, Vol.40, No.1, pp. 35-49, Jan. 1995.

[19] Y. Nakamura and R. Mukherjee, "Nonholonomic path planning of space robots via a bidirectional approach," IEEE Trans. Robotics and Automation, Vol.7, No.4, pp. 500-514, Aug. 1991.

[20] R. T. M'Closkey and R. M. Murray, "Exponential stabilization of driftless nonlinear control systems using homogeneous feedback," IEEE Trans. Automatic Control, Vol.42, No.5, pp. 614-628, May 1997.

[21] J.-M. Godhavn and O. Egeland, "A Lyapunov approach to exponential stabilization of nonholonomic systems in power form," IEEE Trans. Automatic Control, Vol.42, No.7, pp. 1028-1032, Jul. 1997.

[22] K. Tsuchiya, T. Urakubo, and K. Tsujita, "Motion control of a nonholonomic system based on the Lyapunov control method," J. Guidance, Control, and Dynamics, Vol.25, No.2, pp. 285-290, 2002.

[23] H. S. Jennings, "Behavior of the Lower Organisms," Columbia University Press, 1923.

[24] T. Kamada, "Polar effect of electric current on the ciliary movements of Paramecium," J. the Faculty of Science, Imperial University of Tokyo, Sect. IV, Zoology, Vol.2, pp. 285-298, 1931.

[25] H. Oku, N. Ogawa, K. Hashimoto, and M. Ishikawa, "Two-dimensional tracking of a motile micro-organism allowing high-resolution observation with various imaging techniques," Rev. Scientific Instruments, Vol.76, No.3, Mar. 2005.

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- G. Chesi and K. Hashimoto, "A Simple Technique for Improving Camera Displacement Estimation in Eye-in-Hand Visual Servoing," IEEE Trans. Pattern Analysis and Machine Intelligence, Vol.26, No.9, pp. 1239-1242, 2004.

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