# Design of a Propagation Wave Type Microrobot for Moving on the Slippery Surface

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**Abstract**: Animal-like robots are serving an important role as a linkage between biology and engineering. So, in this paper, we aim to develop a biomimetic microrobot that mimics the locomotion mechanism of a gastropod. This microrobot has 3 DOF (x, y translation and rotation), and has small size, unlimited traveling range, high resolution and low cost. Its movement can be made using propagation wave that is generated by the controllable sinusoidal voltage source and piezoelectric effects. This soft motion that can be generated by propagation wave and piezoelectric mechanism would be useful for the motion on the slippery surface. So we modeled the propagation wave mechanism including piezoelectric effect and friction on the contact surface, and could know the velocity of the microrobot is dependent on the driving frequency, input voltage peak, propagation wavelength and surface friction coefficient. With these results we design the microrobot, and accomplish its fabrication and experimentation. The development of this microrobot shall be aimed to design an autonomous moving actuator like animal. Also it can be used from micromanipulation system technology to biology and medicine.

**Keywords: B**iomimetic microrobot, Propagation wave, Slippery surface, Piezoelectric

## 1. INTRODUCTION

Animal-like robots (also known as biomimetic and biomorphic robots) are serving an increasingly important role as a linkage between biology and engineering. So biomechanics is a new multidisciplinary field that encompasses the dual useage of biorobots as tools for biologists studying animal behavior and as testbeds for the study and evaluation of biological algorithms for potential applications to engineering.

It is made to wonder that gastropod transforms a body freely to move on the slippery or soft surface. Such a flexible movement cannot be utterly mimicked by the skeleton muscle type robot like the vertebrate. We aim to develop a biomimetic microrobot that is mimicked the locomotion mechanism of a gastropod.

A main point in the design of microrobot is what kind of actuator we use for locomotion. So many kinds of design methods for microrobots have been presented. Some use MEMs-based techniques. Others have used different special methods like magnetic force mechanism [1]. Often impact drive mechanisms with piezoelectric effect are useful. Many instrument using this mechanism, such as Higuchi et al [2], L.Juhas et al [3], S.Martel [4], and etc. have been appeared. But this mechanism has some problem on slippery surface motion. Propagation wave mechanism reduced this problem. It is generally used in ultrasonic motor mechanism [5-7]. By using propagation wave actuating mechanism, microrobot in this paper enables both highly precise motion and slippery surface motion by controlling sinusoidal wave input voltage.

We modeled the propagation wave mechanism including piezoelectric effect and friction. This model is similar to ultrasonic motor model [8]. Through this model analysis we can know the velocity of the microrobot is dependent on the driving voltage frequency, input voltage peak, propagation wavelength and surface friction coefficient. We designed the biomimetic microrobot and experimented with these results.

In this paper, we present a propagation wave type biomimetic microrobot for slippery surface like intestine. It has three degree of freedom(x, y translation and rotation). We can use this microrobot from biology and medicine to micro-manipulation system technology.

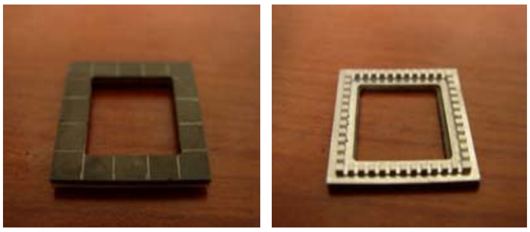
## 2. PIEZOELECTRIC-BASED MICROROBOT DESCRIPTION

There are no optimal actuating systems that can be used for every case. The selection of the most suitable actuator is dependent on many design consideration and environmental factor. Piezoceramic actuator is used in this paper because it has many good characteristics - small size, high precision, and unlimited moving range - to a reasonable price. Micro motion generated by the piezoceramic actuator results in as well high precision as high speed from high operating frequency. And piezoceramic actuator is suitable to making wave motion that will be a operating strategy of the microrobot in this paper.

The wave motion takes advantage of slippery surface than other motion like stick-slip. Example a gastropod makes wave motion in a part of the surface of the body that contacts to the ground and moves a body by moving the wave. It moves on the slippery surface like the branch of the leaf. So we use this wave motion for movement of the robot.

### 2.1 Design

After analysis and simulation about the dynamic model of microrobot that includes the piezoelectric effect, we finally decide the construction of the microrobot base for slippery surface. Its top view and bottom view are shown in Fig. 2. It has four couple of motion generating part that arrayed 4×1 array etched piezoceramic and elastic medium (aluminum). The role of the elastic medium is to transmit a flexural propagation wave from the piezoceramic disk to the ground for driving the microrobot.

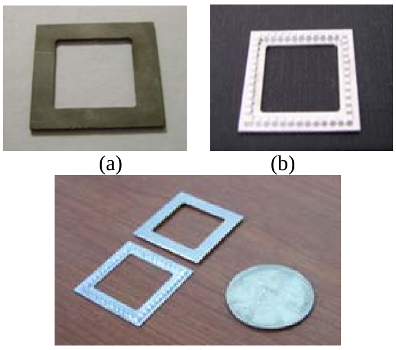


(a) (b)

Fig. 1 Basic construction of the biomimetic microrobot base

The selection of materials greatly affects the performance of motion. Aluminum was selected due to its moderate anti-abrasion properties as well as a nearly uniform Young's modulus insensitive to temperature changes. The second reason is its elasticity. Other possible candidates are brass, copper, steel and so on.

The aluminum base is consists of the holed square plate and comb tooth shape. Its design is shown in Fig. 2 and its parameter is in the Table. 1



(a) (b)

(c)

Fig. 2 Design of the etched piezoceramic and aluminum base (a) Piezoceramic part, (b) Aluminum part, (c) Comparison of size with the coin

Table. 1 Dimension and specification of the microrobot base.

| | | Dimension (mm) |
|---|---|---|
| Piezoceramic disk | Inner square | 17×16×1 |
| | Outer square | 25×25×1 |
| Aluminum base | Inner square | 17×17×0.5 |
| | Outer square | 25×25×0.5 |
| Teeth | | 1.2×1.2×1 |

**2.2 Operating strategy**

Since the biomimetic microrobot should be able to perform a motion in any direction, it is necessary to define some type of operating strategy related to the choice of voltage signal waveform. The goal is to improve motion performances and optimize the configuration of the voltage signal.

There are two categories in the wave motion: a standing wave and propagation wave. The standing wave can make that the surface contact point generates flat-elliptical movement. But it has lack of control in both clockwise and counterclockwise directions. By comparison, propagation wave combines two standing waves with a 90-degree phase difference between in time and space. Fig. 3 shows the configuration of the propagation wave in elastic media.

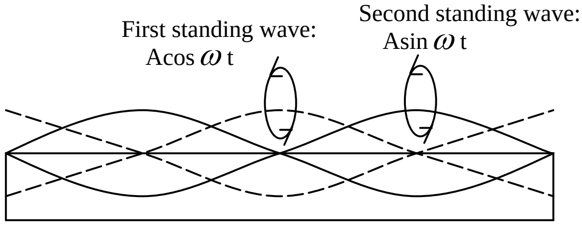



Fig. 3 Propagation wave which is generated by two different standing wave

**2.2.1 Propagation wave**

There is elliptical motion on the surface of the elastic media due to the propagation wave. This motion is consist of sine mode and cosine mode.

Sine/cosine mode solution is

$$w_{\sin}(x,t) = w \sin kx \sin \omega t$$
$$w_{\cos}(x,t) = w \cos kx \cos \omega t \qquad (1)$$

where
$k = 2\pi / \lambda$
$\lambda =$ wave length
$\omega =$ frequency

And then the each mode can make horizontal and vertical displacement. Its equation is

$$w(x,t)_v = w\cos(kx - \omega t)$$
$$w(x,t)_h = -a\frac{\partial}{\partial x}w(x,t)_v = -awk\sin(kx - \omega t) \qquad (2)$$

where
$a =$ distance between the surface and the center of media

Sum of the two displacements motion can make elliptical motion on the surface as shown in Fig. 3. It is derived as following:

$$w_v^{\,2} / w^2 + w_h^{\,2} / (awk)^2 = 1 \qquad (3)$$

This propagation wave motion makes a friction that can generate the movement of microrobot. Then the direction of robot motion is same with that of the propagation wave.

**2.2.2 Operating principles for 3-DOF mechanisms**

As shown in Fig. 4, we need four etched piezoceramic parts to make one period of the propagation wave. It can be replaced by four separated piezoceramic parts. There are two couple of the motion generating parts which are used to make a translation in each direction as shown in Fig. 4(a). We can easily change the directions by changing sine/cosine voltage input each other. And similarly, we can make the rotation of the microrobot by supplying the sine/cosine voltage input as shown in Fig. 4(b)

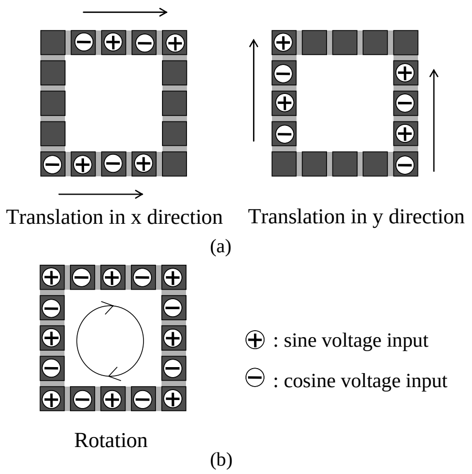



Fig. 4 Schematics of the 3-DOF microrobot operating principle: translation and rotation

It has two key principles that govern the operation. First, there is an elliptical motion of the piezoceramic base at the contact point of the surface. Second, the frictional interface between the robot and surface rectify the micro motion to produce macro-motion. And for more efficient movement on the slippery surface, we would use a special design. It is the comb-tooth shaped groove that is created under aluminum base surface as shown in Fig. 5. These are devised to make the amplitude of the elliptic motion large and to reduce abrasion.

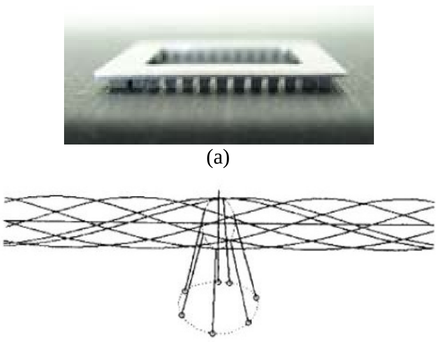



Fig. 5 Design and motion of the comb-tooth: (a) Photograph of the comb-tooth, (b) motion of a comb-tooth.

## 3. ANALYSIS AND SIMULATION

### 3.1 Analytic model

An equivalent mechanical two-mode approximation is given for ultrasonic motor in [7]. We made to assume that the relation of the microrobot and ground is equal to that of the stator and rotor of the motor. This model represents the modal amplitudes, $w_{1t}$, $w_{2t}$ of the sine and cosine-mode of the vibrating system (piezoceramic and aluminum base). As shown in Fig. 6 the parameter $m$ describes the total mass of the piezoceramic and aluminum base, $m = m_a + m_c$, $d_a$ reflects the structural damping and $c_a$ represents the equivalent mechanical stiffness of the aluminum base, whereby the respective piezoceramic stiffness is given $c_c$.

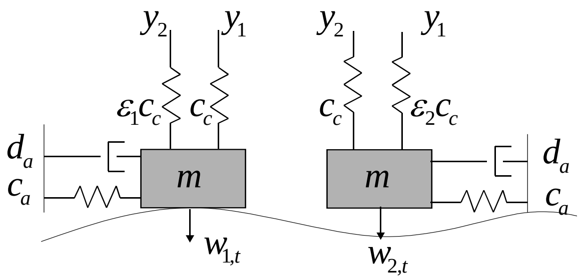



Fig. 6 Discrete mechanical model of piezoceramic and aluminum base

Each piezoceramic part excites this mechanical model via displacement $y_1$ and $y_2$, which are proportional to the phase voltage inputs, $u_1$ and $u_2$. Asymmetries by the construction and manufacturing of the aluminum base are taken into account by adding $\Delta c_a$ in the discrete mechanical model. Since the excitation of the sine and cosine-mode is almost attached, cross excitation occurs between the two modes, which are considered by the small symmetry disturbances $\varepsilon_1, \varepsilon_2$.

The dynamics of the model in Fig. 6 for the piezoceramic motion and its effect on the aluminum base can be described by the following state equations:

$$\begin{bmatrix} m & 0 \\ 0 & m \end{bmatrix}\begin{bmatrix} \ddot{w}_{1,t} \\ \ddot{w}_{2,t} \end{bmatrix} + \begin{bmatrix} d_{s1} & 0 \\ 0 & d_{s2} \end{bmatrix}\begin{bmatrix} \dot{w}_{1,t} \\ \dot{w}_{2,t} \end{bmatrix} + \begin{bmatrix} c_1 & 0 \\ 0 & c_2 \end{bmatrix}\begin{bmatrix} w_{1,t} \\ w_{2,t} \end{bmatrix} = $$

$$= \begin{bmatrix} \hat{A}_1 c_c & \hat{A}_2 \varepsilon_1 c_c \\ \hat{A}_1 \varepsilon_2 c_c & \hat{A}_2 c_c \end{bmatrix}\begin{bmatrix} u_1 \\ u_2 \end{bmatrix} \quad (4)$$

$$\Rightarrow M\ddot{w}_t + D\dot{w}_t + Cw_t = \Theta u \quad (5)$$

with $c_1 = c_a + c_c(1+\varepsilon_1)$, $c_2 = c_a + c_c(1+\varepsilon_2)$

$\hat{A}_1$ and $\hat{A}_2$ represents the elongation factor and yields the relation between the applied voltage input $u$ and displacement $y$ by $y = \hat{A}u$. Because this factor makes the piezoceramic motion amplitude, we must choose the material that has highest $\hat{A}$. That will be most desirable and necessary. $\Theta$ represents the electromechanical coupling matrix considering the cross excitation.

The description of the contact mechanism is assumed to be basically stationary for an ideal propagation wave. So we get the moving force/friction force equation from a normal contact pressure distribution along the contact region, $-x_0 \le x \le x_0$.

The normal contact pressure is

$$p(x) = c_n \Delta w = c_n \cdot \hat{w}(\cos kx - \cos kx_0) \quad (6)$$

Coulomb's friction law is assumed between robot and ground, modeling only slip effects by the coefficient $\mu$, assumed as constant. Thus, the tangential stresses $\tau(x)$ along the contact region are calculated by

$$\tau(x) = \mathrm{sign}(|v_h(x) - v_r|) \cdot \mu \cdot p(x)$$ (7)

where the sign of $\tau(x)$ is related to the horizontal velocity of the tooth $v_h$ and the velocity of the robot $v_r$. The driving force of the robot per wave hill $F_n$ is determined by integrating $\tau(x)$ over the contact zone of the hill.

$$F_n = \int_{-x_0}^{x_0} \tau(x)dx = 2\mu\int_{-x_0}^{x_0} \mathrm{sign}(|v_h(x)| - |v_r|) \cdot p(x)dx$$ (8)

Therefore, the motion equation of the microrobot is calculated by

$$M_r \dot{v} = n \cdot F_n \qquad (9)$$

where $M_r$ is the mass of microrobot and $n$ is the number of wave hill.

### 3.2 Simulation

Based on the model, simulation is accomplished by using MATLAB/SIMULINK to design the control strategy and shape of the input signal. And this simulation can be used to evaluate the effect of the parameter such as the driving frequency, input voltage peak, propagation wavelength and surface friction coefficient.

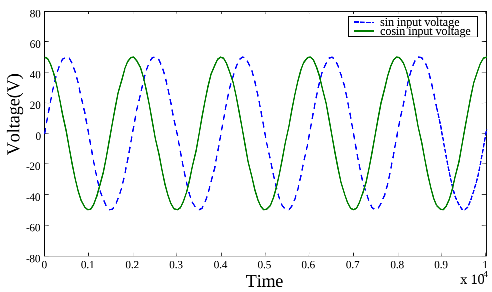



Fig. 7 Input signal voltage for propagation wave

Figure. 7 shows the input signal voltage for propagation wave. It consists of sinusoidal signal. Figure. 8 shows the simulation result for the microrobot. 10khz, 50volt peak sinusoidal input voltage and 10mm propagation wavelength and 0.1 surface friction coefficient is assumed in this simulation. We assume that the slippery surface friction coefficient is 0.1. Displacements which is generated by sinusoidal voltage input is in the Fig. 8(a) and Fig. 8(b). These two displacements make the elliptical motion of comb-teeth. And the horizontal velocity of this elliptical motion and robot's velocity is shown in Fig. 8(c) and Fig. 8(d). Figure. 9 shows the variation of the velocity according to the frequency of the sinusoidal voltage input. The assumption for simulation is that robot's mass is 50g.

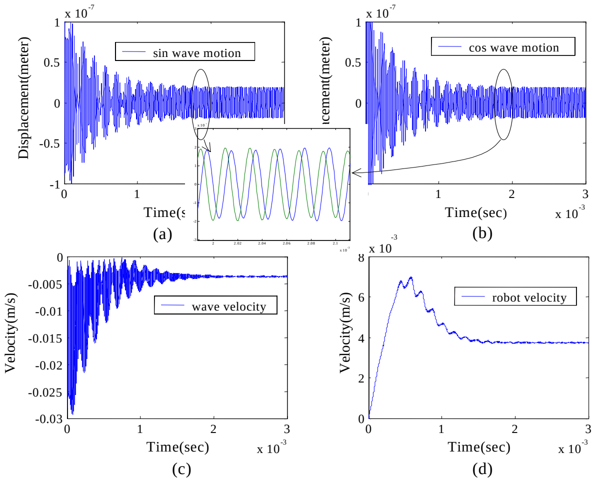



Fig. 8 Displacement and velocity of the piezoceramic and microrobot, (a) sine wave motion, (b) cosine wave motion, (c) wave velocity, (d) robot velocity.

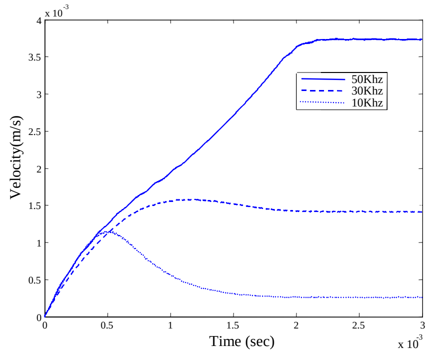



Fig. 9 Variation of the velocity according to the frequency of the sinusoidal voltage input

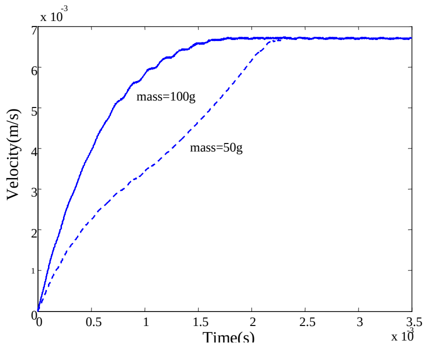



Fig. 10 Variation of the velocity according to the robot mass

Figure. 10 shows the variation of the velocity according to the robot mass. The assumption is that the frequency of the sinusoidal voltage input is 100khz.

But piezoceramic has maximum displacement when it is applied by the resonant frequency. Piezoceramic has many resonant frequencies. So, it is also important that we find resonant frequencies.

## 4. FABRICATIONS AND EXPERIMENTATION

### 4.1 Fabrications and Experimental Setup.

Once from the analysis, we can decide on the location of the teeth projection and subsequent mechanical design of the microrobot according to the space constraint requirement. We used 74.5×74.5×1mm single layer piezoceramic for wave generation and aluminum for the base. Microrobot assembly process is shown Fig. 11.

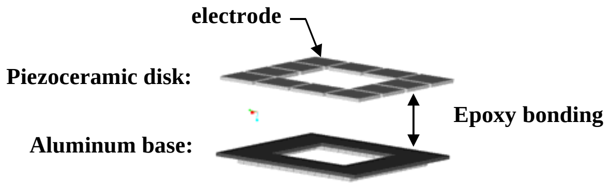



Fig. 11 Microrobot fabrication process

First, we must cut up the piezoceramic into the shape we want. Piezoceramic is best cut using a special diamond saw. Second, aluminum base is manufactured with high precision, because the surface related effects, e.g. adhesive forces, become more important. Third, we bond the piezoceramic part to the aluminum base with epoxy bond. Bonding process is one of the most crucial steps in the assembly of the microrobot. Sanding the surface of the bonding layer with abrasives helps to create better bond. Fig. 12 shows the photograph of fabricated microrobot.

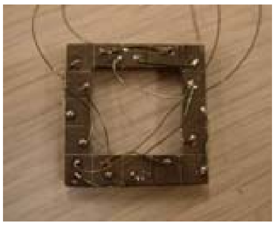


Fig. 12 Photograph of the microrobot

Figure. 13 shows the experimental setup for the microrobot. Function generator and op-amp make the sinusoidal input. So frequency is easily controlled by function generator.

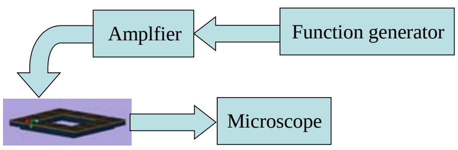
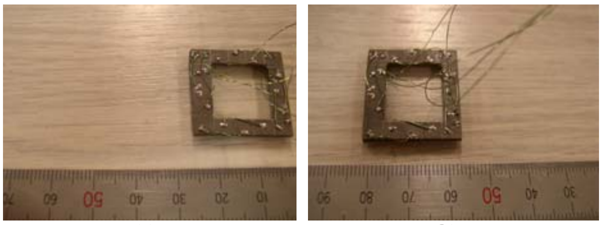



Fig. 13 View of the experimental system

### 4.2 Experimentation

Our microrobot has several resonant frequencies. Through the trial and error, we found the resonant frequency at 6.3, 10.7khz. So, we applied the driving voltage inputs that have a 6.3khz and 10.7khz and 50voltage peak for maximum displacement of microrobot.



(a) (b)

Fig. 14 Photograph of the microrobot's movement

Figure. 14 shows the photographs about movement of the microrobot. Fig. 14(a) shows the initial state. And after several seconds, its state changes in Fig. 14(b). Its velocity measured by the microscope is 5mm/s.

## 5. CONCLUSOIN

In this paper, a biomimetic microrobot is proposed for mimicking the gastropod's locomotion mechanism and studying the biological algorithm for potential applications to engineering. It has 3 DOF (x, y translation and rotation), and has a simple and compact shape and mechanism that can be realized with low cost. This microrobot can have both highly precise motion and slippery surface motion by using propagation wave actuating mechanism that is made by controlling sinusoidal wave input voltage.

To estimate the operating condition and performance, modeling of the system is derived. Base on the model, simulation is accomplished to design the control strategy and shape of the input signal. Experimentation is also accomplished to check the system performance.

The development of this microrobot shall be aimed to design an autonomous moving actuator like animal. For the more close to the gastropod's locomotion, to make the actuator the more soft structure is also important.

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