A novel hybrid wireless microrobot

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Abstract: In this paper, we propose a hybrid microrobot concept to increase dynamic efficiency and adapt these systems for use in various working environments. The microrobot consists of a head capable of spiral motion, legs capable of paddling motion, and fish-like fins. We developed a prototype with a rotatable head and a body that has legs and fins. Additionally, we developed a control system and carried out experiments to evaluate its characteristics. The experimental results indicated that the head of the microrobot with spiral motion can achieve a movement speed of 58 mm/s and rotation speed of 87 rad/s, respectively, and the prototype of the leg has a maximum displacement of 3.7 cm. The experimental results also demonstrated a number of advantages of the microrobot, such as rapid response, movement stability, and wireless operability. This type of hybrid microrobot may be useful in both industrial and medical applications, such as microsurgery.

Keywords: micromechanism; hybrid microrobot; spiral motion; rotating motion; wireless microrobot.

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1 Introduction

As wireless microrobots controlled by a magnetic field are both safe and reliable, and can be carried deep within the tissues of living organisms in the body fluids, they have many potential applications in the field of medical engineering. For example, they may be used for microsurgery in blood vessels, which is expected to become an increasingly widely adopted medical procedure in the near future. With advances in precision processing technology, several types of microrobot have been developed for various applications and further progress in this field is expected. Microrobots may be used in very small spaces, and in medical practice, their use can obviate the need to open and close a surgical field. Fukuda et al. (1995) developed the underwater micro mobile robot, Guo et al. (2002, 2003a, 2003b), Ye et al. (2006) and Zhang et al. (2006) developed several types of swimming microrobot using an IPMC actuator and cable, which can move forward, float up and down, and steer to the left and right.

Implementation of wireless drive for microrobots is the key to enhancing the feasibility and reliability of their use. Honda et al. (2001; Sudo et al., 2003, 2006) developed a new type of wireless swimming robot with a tail fin that can swim in one direction. Subsequently, Mei et al. (2002) developed another type of wireless drive swimming microrobot, using a new intelligent magnetic material, FMP that showed good experimental results. Additionally, Guo et al. (2005, 2008; Guo and Pan, 2007a) have developed a novel type of wireless swimming robot that can move not only horizontally but also vertically; it can turn right and left, Khamesee et al. (2002) designed a microrobotic system, they are both controlled by the external magnetic field. Yesin et al. (2006), Nelson (2006) and Chigasaki et al. (2005) developed an untethered biomedical microrobot with a number of potential applications, including sensing, diagnosis, and surgical procedures, which can be guided within the human body using external magnetic fields. Previously, we developed and evaluated the characteristics of wireless microrobots that can swim within pipes (Sendoh et al., 2000; Pan and Guo, 2007; Guo and Pan, 2007b). The findings of these studies will allow us to improve the microrobot by making it more compact and optimising its functions. As mentioned above, over the last decade, several groups have developed wireless microrobots with applications in many fields, such as observation of aquatic life and medical diagnosis. Biomimetic swimming microrobots are of great interest in exploring unstructured underwater environments and in microsurgery within blood vessels for minimally invasive medicine.

In this paper, we focus on the development of a hybrid wireless microrobot with the following properties:

1 functional in multiple working environments
2 good stability
3 rapid response
4 high propulsion force
5 several types of locomotion.

This paper is structured as follows. First, we introduce the structure of the hybrid microrobot. Second, we analyse the mechanism of spiral motion, paddling motion, and the driving fin. Third, we discuss the prototype design for spiral motion and paddling motion, describe experiments, and present the characteristics of the microrobot. The final part of the paper presents our conclusions.

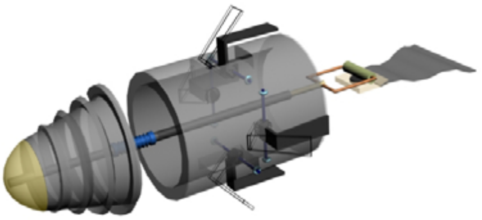
2 Proposed hybrid microrobot

2.1 Concept of the hybrid microrobot

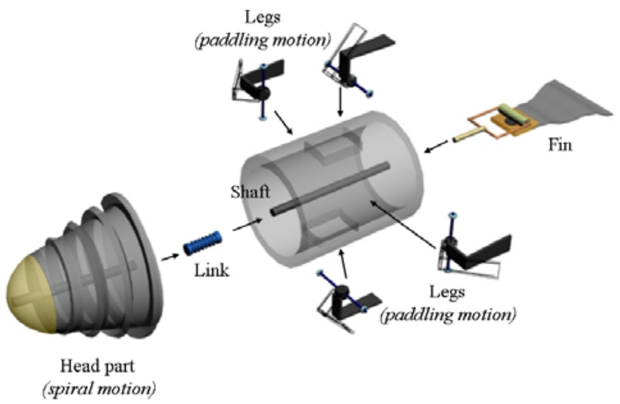
We propose a novel type of hybrid microrobot consisting of a head capable of spiral motion, legs capable of paddling motion, and a driving fin (Figure 1). The head with spiral motion generates power for cleaning application and increases stability. The legs are used for crawling and for support. The fin generates propulsion for swimming.

Several types of microrobot for use within pipes have been developed (Berk et al., 2006; Park et al., 2007). In previous study, most of the wireless microrobots have been proposed, we almost imitated them with the fish called fish-like (Rosen, 1959; Pan and Guo, 2006, 2008) with the undulatory motion (Laurent and Piat, 2001) which can obtain much more propulsive force demonstrated by Laurent. But, the power is not enough to propel the microrobot when it moves against with obstruction. So, we propose the microrobot with rotating motion in order to obtain the big power. By applying a rotational magnetic field, Sendoh et al. (2000, 2003) developed a rotating machine that can move through the intestine. This type of microrobot can move forward with propulsive force from the inner wall while rotating (Barret et al., 1999; Behkam and Sitti, 2005). In this paper, we will introduce a small-scale microrobot that can be propelled by low voltage and has a rapid response time. This type of microrobot has the significant advantage that it can remove obstructions in the intestine or blood vessels within the human body.

Figure 1 The proposed hybrid microrobot, (a) concept of the hybrid microrobot (b) structure of the hybrid microrobot (see online version for colours)



(a)



(b)

2.2 Structure of the hybrid microrobot

A Structure of the head part with spiral locomotion

1 Structure of the head part with four-magnetic actuators: The head of the microrobot has a drill bit-like structure. It can supply a propulsive force while the body is rotating, and can destroy obstructions in the pipe, intestine, or blood vessel, and continue to move forward. This is important for biomedical applications, and can also be used in a wide range of pathological conditions related to thrombi and aneurisms.

   Based on magnetic theory, rotation of the microrobot in a magnetic field requires at least a pair of forces in opposite directions, and a moment should also be generated. Thus, we set four-permanent magnets at the top, bottom, front, and back of the body; the magnets are not set in the same line, so as to generate rotational motion (Table 1). The prototype microrobot is shown in Figure 2, and the dimensions of the head part are shown in Figure 3.

Table 1 Parameters of the magnets

Size	*Magnetic field*	*Weight*	*Magnetism*
$\phi 4 \times 2$ mm	330 mT	0.19 g	0.35 kg

Figure 2 The structure of the head part (see online version for colours)

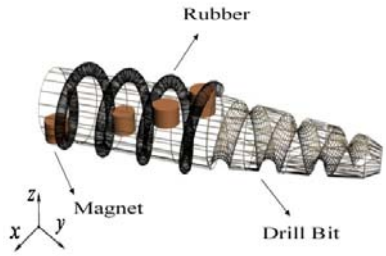
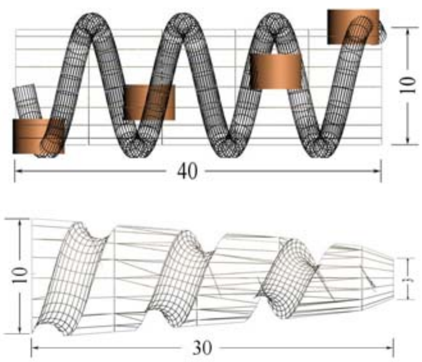


Figure 3 The measurement of the head part (unit: mm) (see online version for colours)



2 Optimise the structure of the head part with one magnetic actuator: We attempted to optimise the size and weight of the microrobot to allow the development of a more compact system while retaining the advantageous structural characteristics of the head with four-magnets and spiral locomotion. To realise this concept, we should reduce the number of magnets and change the magnetic field.

   In our previous studies, we simply drove the microrobot using an alternating magnetic field in only the horizontal direction. Due to the structural design limitations of the microrobot, we designed a new external superposition magnetic field with horizontal and vertical directions (Figure 4). With analysis of the superposition magnetic field, we improved the structure of the head part of the microrobot, using only a single magnet to achieve rotational locomotion. A prototype of the head part has been designed with a propeller and one magnet embedded in the main body of the head part (Figure 5).

Figure 4 The superposition magnetic field (see online version for colours)

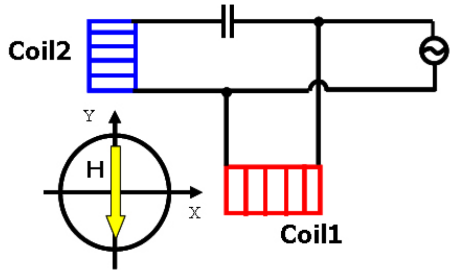
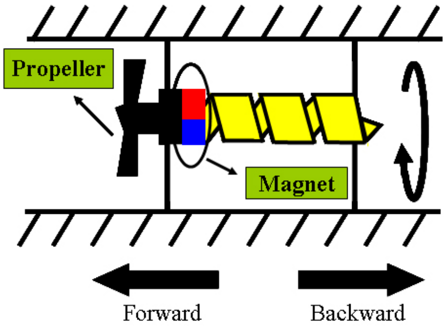


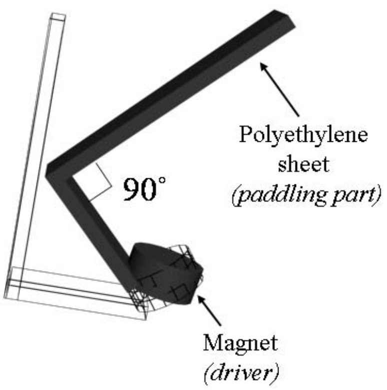
Figure 5 The optimised structure (see online version for colours)



B Structure of legs with paddling motion

To obtain balance and power, we designed a body with four-legs 4 mm wide and 1 cm long at 90° to each other (Figure 6). The leg consists of a paddling part made from polyethylene sheet 0.5 mm thick and a magnet that acts as a driver to allow control of the paddling part by the magnetic field. The paddling part can be rotated from 0 to 90° according to the angle of rotation generated by the magnet.

Figure 6 The structure of the leg



C Structure of the fin

The tail consists of a holder, magnet and polyethylene sheet. The magnet is inserted into the holder, which has a thin plastic pipe through which a thin aluminium rod is passed as a shaft (Figure 7)

Figure 7 The sketch of the fin (see online version for colours)

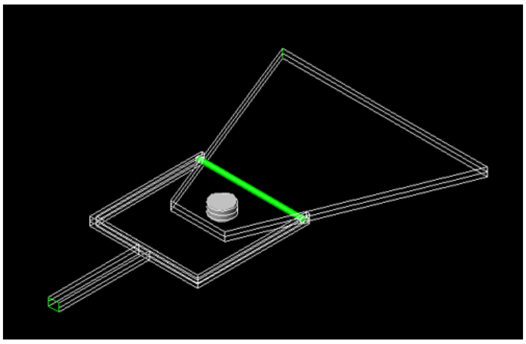
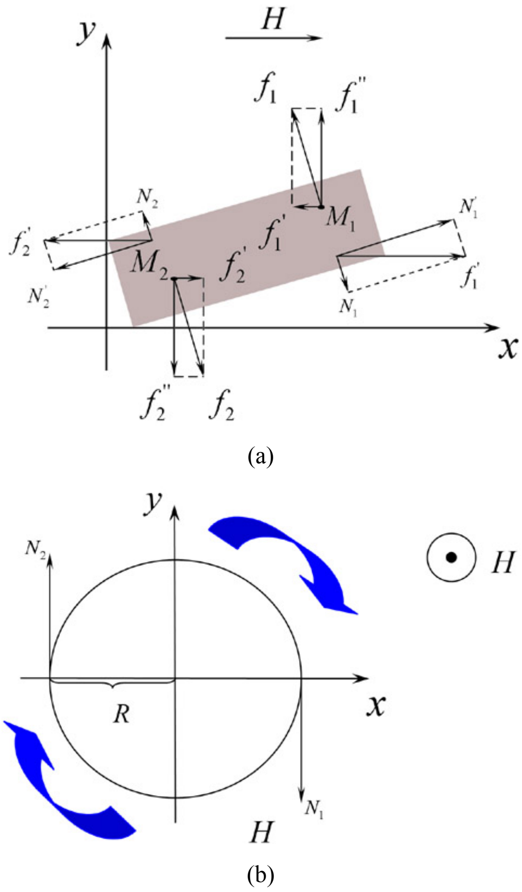


Figure 8 The mechanism of the spiral motion, (a) the force analysis of the microrobot (b) the sectional view of the microrobot (see online version for colours)



3 Motion mechanism of the hybrid microrobot

3.1 Mechanism of spiral motion

A Spiral motion with four-magnetic actuators

We can explain how the microrobot can obtain rotation locomotion, based on the mechanism of motion described previously. Figure 8 shows the mechanism of the spiral motion. We set four-magnets on the body of the microrobot: two on the front and two on the back. They are not aligned on the same line, so as to provide rotary torque *m*. Here, we only analysed two of the four-magnets in the centre of the body, as M_1 and M_2 in Figure 8(a). f_1 and f_2 are the magnetic field directions of M_1 and M_2, respectively. We resolved the force f_1 to f_1' and f_1''. The force N_1 can be generated in the vertical direction relative to the body, and we can also obtain N_2 in different directions. As N_1 and N_2 are not in the same line, rotary torque will be generated, as shown in equations (1) and (2), and rotation locomotion can be realised, as shown in Figure 8(b).

$$m_1 = N_1 \times 2R \tag{1}$$

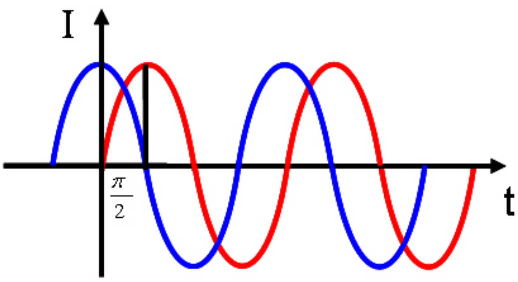
$$m_2 = N_2 \times 2R \tag{2}$$

where M is the magnet, f is the magnetic force of the magnet, N is force in the direction of the tangent line and R is the distance of the magnets from the axis of rotation.

B Mechanism of motion for structure optimisation

To optimise the structure with one magnet, we have designed a superposition magnetic field, as described above. We used two-pairs of coils: one to generate the horizontal magnetic field, and the other to generate the vertical magnetic field. A magnetic field will be generated when a current flows in the coil. Figure 9 shows the magnetic fields in two-directions with a 90° phase difference. By adjusting the frequency of the input current, the spiral locomotion of the optimised structure can be controlled freely.

Figure 9 The signals of superposition magnetic field (see online version for colours)



3.2 Mechanism of legs with paddling locomotion

Previously, we reported several types of fish-like microrobot with a magnet actuator composed of one magnet for propulsive force (Guo et al., 2008). Considering the locomotion of the fish body and fin, we designed a structure for the developed microrobot. Here, we focus on the mechanism of locomotion of the microrobot. The magnetic field is shown in Figure 10 and the mechanism of the permanent magnet is shown in Figure 11. Thus, when current flows through the coil, an alternating magnetic field will be generated:

$$\vec{B} = \mu_0 \vec{H} = \mu_0 n \vec{I} \tag{3}$$

where B is the magnetic flux density, H is the magnetic field strength, μ_0 is the permeability of a vacuum, n is the number of turns in unit length and I is the current in the coil.

Figure 10 The alternating magnetic field (see online version for colours)

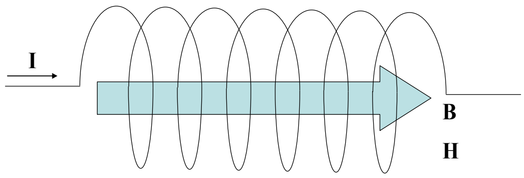
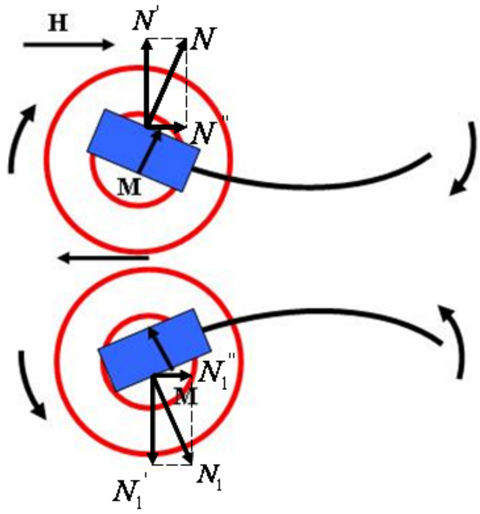


Figure 11 The mechanism of the permanent magnet in magnetic field (see online version for colours)



Additionally, the magnetic torque T acting on the permanent magnet in the external magnetic field H is given by:

$$T = M \times H \tag{4}$$

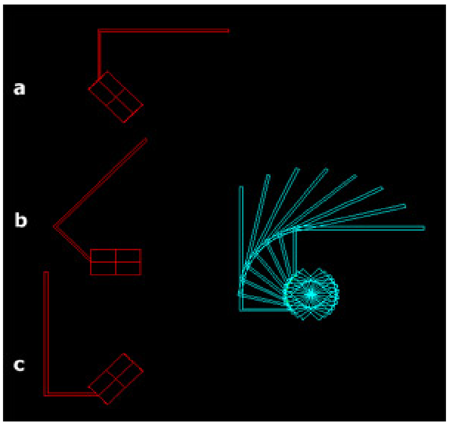
where M is the magnetic moment of the permanent magnet. Due to the torque of the magnet, the rotational oscillation of the permanent magnet induces bending motion at the tail of the robot. Additionally, the fin is connected to the head, so it undergoes the same movement as the head. During bending motions of the tail film, the tail of the robot pushes backwards against the medium (water or glycerol), thus generating a propelling force, and the robot can be moved forward by adjusting the frequency of the input current. The proposed structure allows the robot to be moved wirelessly.

In this study, the proposed locomotion mechanism of the leg originates from the paddle (Figure 12). Here, the legs and by the magnets replace the paddle and the canoeist, respectively. Figure 13 shows one step cycle of paddling forward, which can be divided into three-periods.

1 In period A (from a to b), the leg begins rotating to the position where the magnet lies in horizontal position.
2 In period B (from b to c), the magnet rotates to maximum downward position.
3 In period C (from c to a), the magnet will rotate to the initial position, so the leg pushes the water backward because of the reaction force. This generates a propulsive force, and the body will be pushed forward.

Figure 12 Paddle a boat (Paddle.(RSF).png)

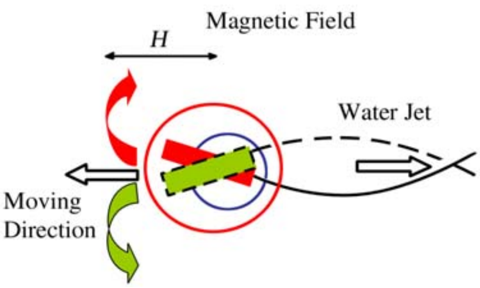
Figure 13 One step cycle of the leg (see online version for colours)



3.3 Mechanism of motion of the fin

A magnetic field is generated when current flows through a solenoid. When an alternating magnetic field parallel to the direction of advance is applied, movement due to an impelling force arising from the permanent magnet causing rotation and vibration of the connected fin (Figure 14).

Figure 14 Motion mechanism of the fin (see online version for colours)

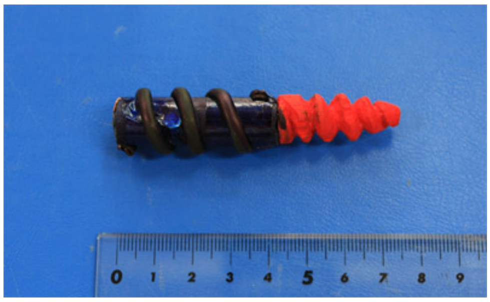


4 Characteristics and experimental results

4.1 Characteristics of spiral locomotion (four-actuators)

The structure of the head part was inspired by a drill bit, and consists of four-magnets to generate rotary torque (Figure 15). To reduce friction, it is wrapped in rubber tubing.

Figure 15 Prototype of the head part (four-magnets) (see online version for colours)



The main equipment used for measurement is the coil and the high-speed camera. We used two-DC power supplies to obtain the input current. We can control the speed of the robot's spiral locomotion by adjusting the output signals from the functional generator. One end of the body was fixed on a tripod with half of the body in the coil. A magnetic field is generated when an alternating current flows in the coil, and the robot can rotate. We drew a straight line on the body, and then we can count the number of turns using a high-speed camera. The measurement system for the rotation speed is shown in Figure 16.

The following characteristics of the rotation speed were determined using the measurement system shown in Figure 16. We carried out this experiment by changing the frequency of the input current from 0 to 20 Hz. Figure 17 shows the experimental results of the rotation speed according to the frequency of the input current. The maximum rotation speed was obtained at a frequency of 10 Hz with a current of 0.7 A. The natural frequency of the rotation can be obtained from the experimental results, and the characteristics of the rotation motion can be evaluated.

Figure 16 Measurement system of the spiral motion (four-magnets) (see online version for colours)

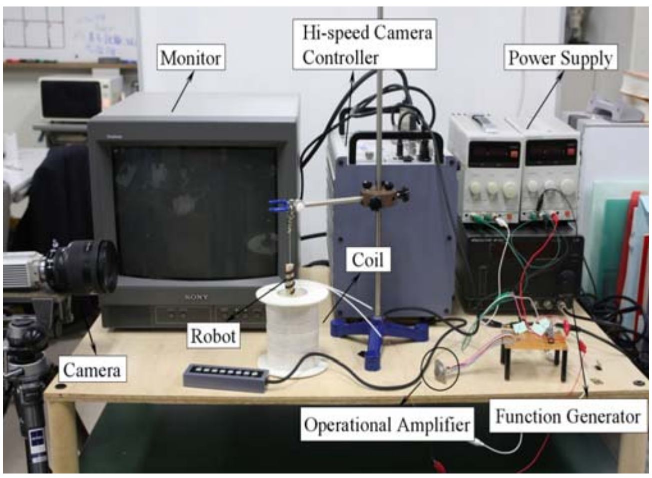
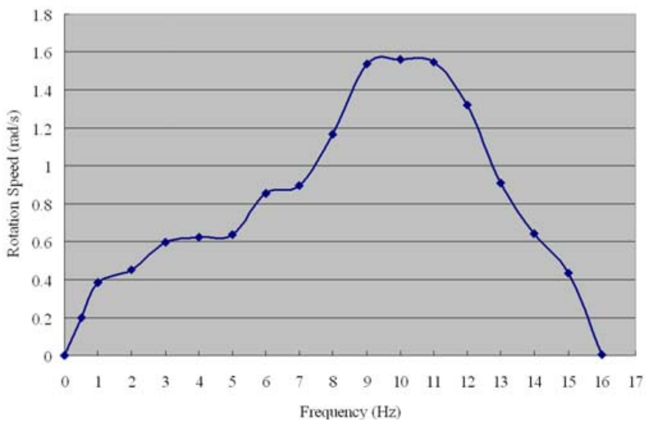


Figure 17 Experimental results of the rotation speed (see online version for colours)



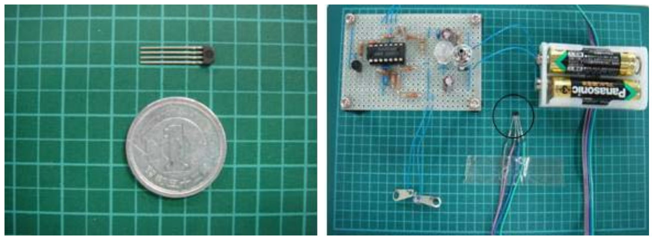
4.2 *Characteristic of spiral locomotion (one-actuator)*

We have developed a prototype of the head part with one actuator (Figure 18). The prototype is about 31 mm in length and 6 mm in diameter, and has a permanent magnet 4 mm thick and 3 mm in diameter, with a magnetic strength of 0.3 T.

Figure 18 The prototype of the optimised head part (one magnet) (see online version for colours)

For spiral locomotion with one actuator, we carried out experiments to measure the rotation speed as well as the speeds of forward and backward movement. To measure the rotation speed, a Hall element was used as an induction element [Figure 19(a)]. As shown in Figure 19(b), the electrical circuit can be developed into a magnetic sensor. We set one magnetic sensor on the pipe (Figure 20). If the object rotates in the pipe, the magnetic sensor can be induced by the magnet. When the object rotates one cycle, we can monitor the peak of the sine wave that will appear twice using an oscillograph. Thus, applying signals with different voltages and frequencies, we read the time from the oscillograph and the calculated rotation speeds are shown in Figure 21. As shown in Figure 20, we set two-pairs of magnetic fields onto the pipe over a short distance. We recorded the time for object to move forward and backward, and the calculated motion is shown in Figure 22.

Figure 19 Magnetic sensor system, (a) hall elements (b) electric circuit (see online version for colours)



(a) (b)

Figure 20 Measurement system for the optimised structure (see online version for colours)

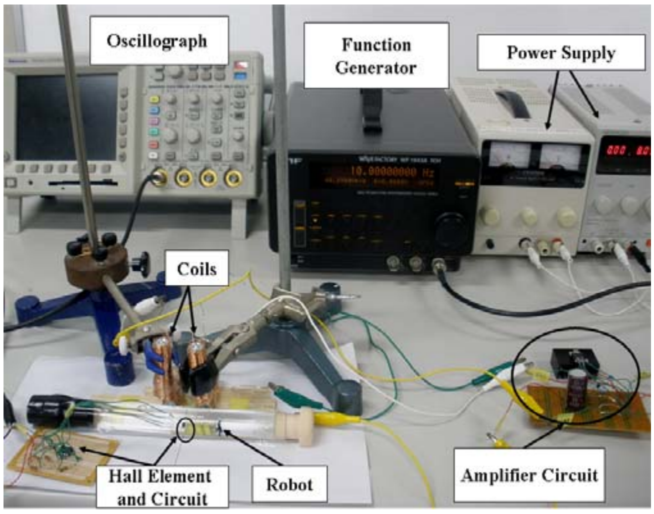
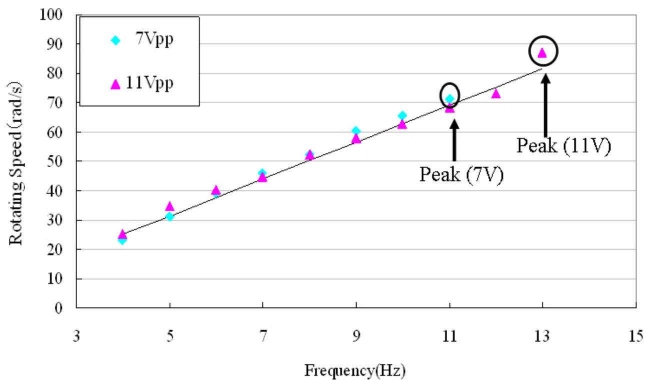


Figure 21 The speed of rotating motion with different voltage (see online version for colours)



4.3 *Characteristics of the paddling motion*

A Displacement measurement system

The displacement measurement system is shown in Figure 23. To measure the displacement of the tail, we constructed a motion controller that needs a power supply. Using the motion controller, we can control the vibration speed and displacement of the tail by adjusting the frequency of the input current. Additionally, a laser displacement sensor (KEYENCE Corp.) was used to measure displacement of the tail, and the displacement can be read on the oscillograph.

Figure 22 The speed of moving motion with different voltage (see online version for colours)

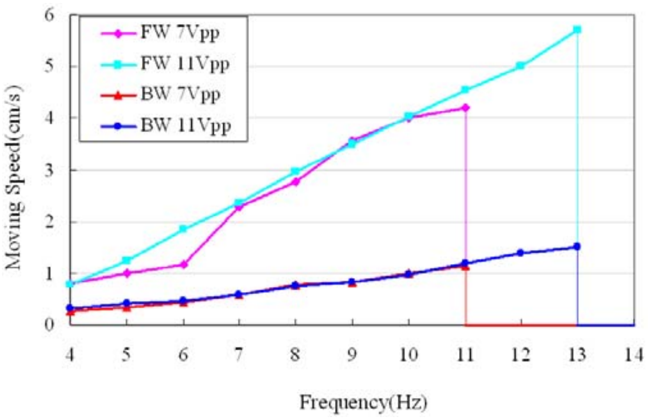
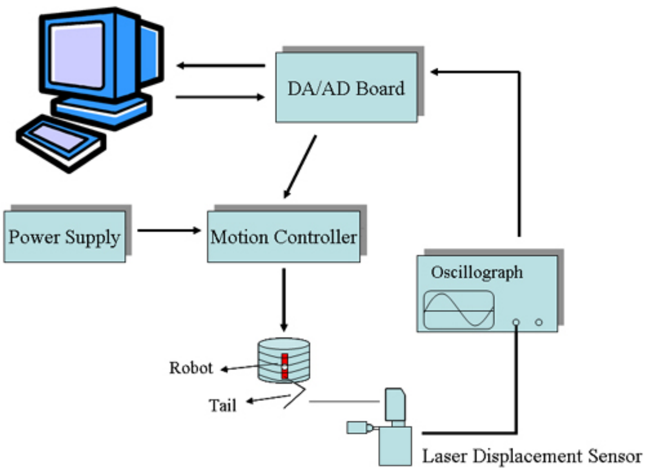


Figure 23 The sketch of displacement measure system (see online version for colours)



B Evaluation of displacement measurement

Displacement of the leg was measured using the measurement system shown in Figure 24. This experiment was performed by changing the frequency of the input current from 0 to 15 Hz. To evaluate the characteristics of the leg, displacement was measured at different voltages. The experimental results demonstrated the relationship between frequency and displacement at different voltages (Figure 25). The maximum displacement was obtained at frequencies around 5 Hz and 12 Hz. Thus, the motion of the leg appears to be a second-order system. The frequency of the leg motion can be determined based on pickup points in the experimental results. We evaluated the leg based on a cantilever model, and the movement equation for horizontal vibration of a cantilever beam is:

$$EI\frac{\partial^4 \omega}{\partial \chi^4} + \rho A \frac{\partial^2 \omega}{\partial t^2} = 0 \tag{5}$$

If the conditions of fixed-freedom are substituted for the general solution of equation (5), equation (6) can be obtained:

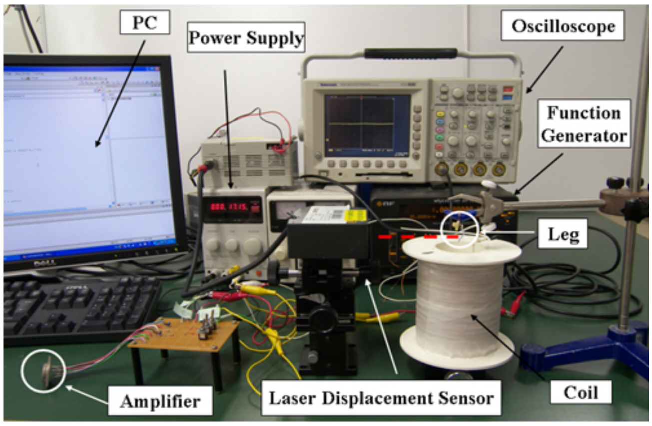
$$1 + \cos\ \alpha \cdot \cosh\ \alpha = 0 \tag{6}$$

In this formula, α is the characteristic value. Using equation (7), the frequency of the leg can be calculated as follows:

$$f_i = \frac{\alpha_i}{2\pi} \cdot \frac{1}{l^2} \cdot \sqrt{\frac{EI}{\rho A}} \tag{7}$$

where f_i is the frequency of the driving leg, E is the Young's modulus of the leg, I is the secondary section moment, ρ is the density of the leg, A is the cross-sectional area, l is the length of the leg, and α_i is the characteristic value of the leg.

Figure 24 The displacement measurement system (see online version for colours)



4.4 Characteristics of the fin

The following characteristics of the fin were measured. First, we measured the maximum displacement of the thickness in two different types of fin at the front end by changing the frequency of the current from 0 Hz to 60 Hz. Figure 26 shows the experimental results of the driving fins according to frequency of input current. The experiment was performed under different conditions with regard to the thickness of the fin. Maximum displacement was obtained at a frequency of 30 Hz and current of 0.7 A. The selected experimental results indicated that the natural frequency of the driving fin can be obtained. The characteristics of the driving fin can be evaluated using a cantilever model.

Figure 25 The result of the displacement with frequency (see online version for colours)

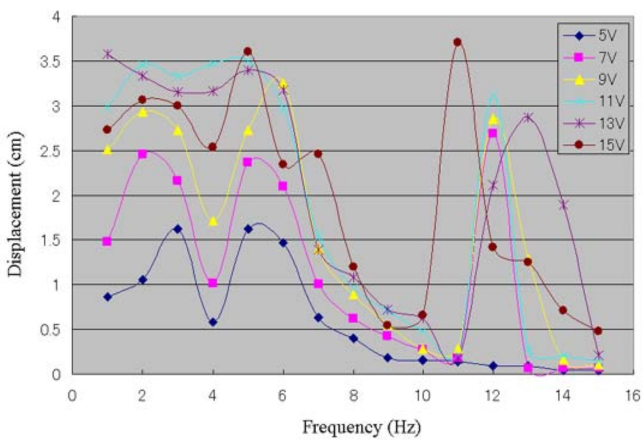
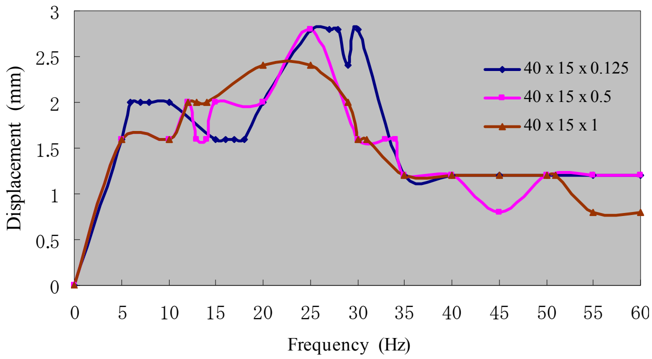


Figure 26 Displacement of fin with frequency (see online version for colours)



5 Conclusions

To develop a novel type of wireless microrobot with swimming, rotating, and stopping motions, we have developed several types of wireless microrobots driven by an external alternating magnetic field. Here, to increase the dynamic efficiency and adapt these systems for use in various working environments, we proposed a concept of a hybrid microrobot with spiral, paddling, and moving motions.

We also analysed the structures and mechanisms of motion, and have developed a head part with spiral motion, legs with paddling motion and fin with fish-like motion. The motion characteristics of the microrobot were also analysed. The experimental results indicated a number of advantages of the hybrid wireless microrobot as:

1 The prototype of the head part with four-actuators can be driven by an external magnetic field in one dimension with a top rotation speed of 1.6 rad/s.

2 The head part has been optimised to be light and small with one actuator. By using a superposition magnetic field, the top rotation speed was increased at 87 rad/s. Additionally, the prototype can move forwards and backwards, with top speeds of 58 mm/s and 16 mm/s, respectively.

3 Experiments showed displacement of the prototype legs and fin of 3.7 cm and 2.8 cm, respectively.

4 3DOF of the head has been realised using a flexible tube as a link to connect with the body. It can carry out not only rotational motion, but can also raise and lower the head, or turn the head to the right and left.

5 The response of the head of rotation and legs with paddling is very rapid.

Future studies will further optimise the design and energy supply of the wireless microrobot. It will be necessary to design and use an electromagnetism sensor to determine the location of the microrobot in a pipe and for accurate control of speed and position of the microrobot. Additionally, the magnetic field generator must be driven following the microrobot. This type of hybrid wireless microrobot may be useful in industrial and medical applications.

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