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Magnetic Actuator with Multiple Vibration Components Arranged at Eccentric Positions for Use in Complex Piping

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Abstract: This paper proposes a magnetic actuator using multiple vibration components to perform locomotion in a complex pipe with a 25 mm inner diameter. Due to the desire to increase the turning moment in a T-junction pipe, two vibration components were attached off-center to an acrylic plate with an eccentricity of 2 mm. The experimental results show that the magnetic actuator was able to move at 40.6 mm/s while pulling a load mass of 20 g in a pipe with an inner diameter of 25 mm. In addition, this magnetic actuator was able to move stably in U-junction and T-junction pipes. If a micro-camera is implemented in the future, the inspection of small complex pipes can be enabled. The possibility of inspection in pipes with a 25 mm inner diameter was shown by equipping the pipe with a micro-camera.

Keywords: magnetic actuator; pipe inside mover; eccentric position; complex pipe; multiple vibration components

1. Introduction

There are several pipes in power generating units and chemical plants. The inspection of existing corrosion and cracks is conducted in a pipe to check the soundness of these pipes. When inspecting from the outside of a pipe by using techniques such as an ultrasonic test method [1,2] or eddy current testing [3,4], it is impossible to estimate minute internal cracks. Therefore, a tool capable of inspecting the condition of a pipe surface is required for safety reasons. In general, a large-diameter-type pipe with a 450 mm internal diameter is used in a power generating unit and is connected to a small pipe with an inner diameter ranging from 25 to 35 mm.

Accordingly, a tool capable of inspecting the interior of a 25-mm-internal-diameter pipe is required. Several studies have investigated mechanisms for a robot capable of inspecting such pipes. The mechanisms include devices using piezoelectric elements [5,6], shape-memory alloys [7,8], external magnetic fields [9–11], and electromagnetic motors [12–14]. An actuator combined with an electromagnetic force and mechanical vibration was previously proposed by the authors [15–19]. However, robots capable of inspection in a pipe with an inner diameter of 25 mm have not yet been developed except in a small study [20]. It should be possible to create a micro-motor which generates torque and then transforms it into movement through the complex pipe in the same way as standard actuators, but the torque produced by micro-motors is quite small. This propulsion scheme would therefore require a geared motor with a very complex structure.

This paper proposes a new type of magnetic actuator capable of locomotion in a small complex pipe with a U-junction and a T-junction. For movement in a pipe with an inner diameter of less than 25 mm, two vibration components were not attached to the center; this differs from methods in previous papers [18,19] proposed by the authors. It was confirmed that this magnetic actuator is able to move in the complex pipe system by using only two amplifiers, one signal generator, and a DC power supply without control units.

2. Structure of a Magnetic Actuator and Vibration Components

Figure 1 shows the vibration components of the proposed magnetic actuator. Vibration components 1 and 2 were attached to an acrylic frame. Vibration component 3 was attached at a right angle to vibration components 1 and 2. Vibration components 1 and 2 had permanent magnets and springs with the same properties. The magnets and springs in vibration component 3 were slightly different compared with those in vibration components 1 and 2. Due to the desire to increase the turning moment in a T-junction pipe, vibration components 1 and 2 were attached off-center on the acrylic plate with an eccentricity of 2 mm. Previous testing showed that the eccentric position hardly influences the straight motion of the actuator. Since a Charge-Coupled Device (CCD) micro-camera was not available, the actuator was not equipped with a CCD camera, although a previous study [19] used a CCD camera with a cube shape, a side length of 8.5 mm and a total mass of 1.2 g.

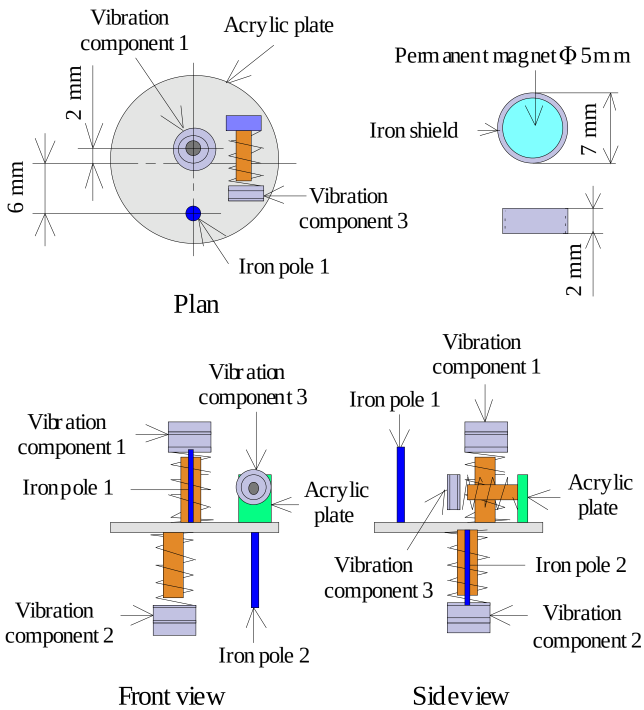


Figure 1. Vibration components of the magnetic actuator.

Each vibration component was composed of a permanent magnet and a translational spring was adhered to the acrylic frame. An electromagnet was inserted in the translational spring. The translational spring of vibration components 1 and 2 was constructed from stainless steel and had an outer diameter of 6.5 mm, a free length of 8 mm, and a spring constant of k = 1491 N/m. Vibration component 3 was constructed from stainless steel and had an outer diameter of 4.5 mm, a free length of 6.5 mm, and a spring constant of k = 1231 N/m. The permanent magnets of vibration components 1 and 2 were cylindrical NdFeB magnetized in the axial direction. The magnets were 5 mm in diameter and 2 mm in height. That of vibration component 3 was cylindrical NdFeB magnetized in the axial direction. The magnets were 5 mm in diameter and 2 mm in height. That of the vibration component 3 was cylindrical NdFeB magnetized in the axial direction and measured 4 mm in diameter and 2 mm in height. The surface magnetic flux density written in the data sheet for vibration components 1 and 3 was 360 and 340 mT, respectively. The permanent magnets were shielded with iron to prevent interference with each other when the vibration components as shown in Figure 1 were vibrated.

For vibration components 1 and 2, the electromagnet consisted of an iron core with a diameter of 2.5 mm and a length of 7 mm with 350 turns of 0.1-mm-diameter copper wire. For vibration component 3, the electromagnet consisted of an iron core with a diameter of 2 mm and a length of 8 mm with 360 turns of 0.1-mm-diameter copper wire. The gap between the electromagnet and the permanent magnet in the static condition was 3 mm. An iron pole was attached to a location 6 mm from the center of the acrylic plate. This iron pole had an outer diameter of 2.3 mm and a free length of 8.5 mm. As shown in Figure 2, by using an iron plate with a thickness of 1.5 mm, electromagnets 1 and 2 were magnetically combined. When a direct current of 0.2 A was inputted to electromagnets 1 and 2, the surface magnetic flux density with the iron plate was 16.69 mT, whereas that without the iron plate was 10.93 mT.

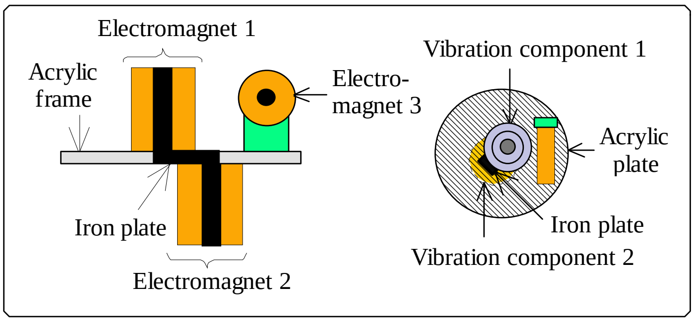


Figure 2. Coupling of the electromagnet by an iron plate.

As shown in Figure 3, the magnetic actuator was composed of the three vibration components, four shape-memory-alloy (SMA) (TOKI Corporations, Tokyo, Japan, Trademark: BioMetal) coils labeled A, B, C, and D, two-layer compound materials labeled A, B, C, and D, eight copper conductors, and an acrylic cap and frame. The compound materials A and B were also attached to vibration components 1 and 2. The compound materials C and D were also attached to iron poles 1 and 2. The compound materials A and B, which support the actuator in the pipe, were composed of natural rubber and silicone rubber. The compound materials measured 50 mm in length, while the thickness of the natural rubber was 1.5 mm and that of the silicone rubber was 1 mm. Compound materials C and D, which turn the actuator in a T-junction pipe, had the same thickness as that of compound materials A and B, but had a total length of 45 mm. When a direct current is applied to the SMA coil by connection to a DC power supply or a battery, the temperature of the SMA coil becomes higher than the transition temperature. Accordingly, the SMA coil contracts. This action causes compound materials A, B, C, and D to completely close. Reverse movement is enabled by using the opening and closing of compound materials A and B, as shown in a previous study [15]. This actuator performs a reciprocating movement in a straight pipe using vibration components 1 and 2. By combining vibration components 1 or 2 and 3, this actuator can perform rotary movement in a pipe. In opening and closing compound material C or D, the iron pole becomes a supporting point of the turning movement in a complex pipe. Table 1 shows the properties of the SMA coil.

Figure 4 shows the complete structure of the proposed magnetic actuator. The actuator was 31 mm in length, and the total mass was 7.34 g. The length of the compound material changed from 22 mm to 30 mm. The actuator can move inside the pipe from 23 mm to 27 mm by the flexibility of the compound material. Figure 5 shows a photograph of the magnetic actuator.

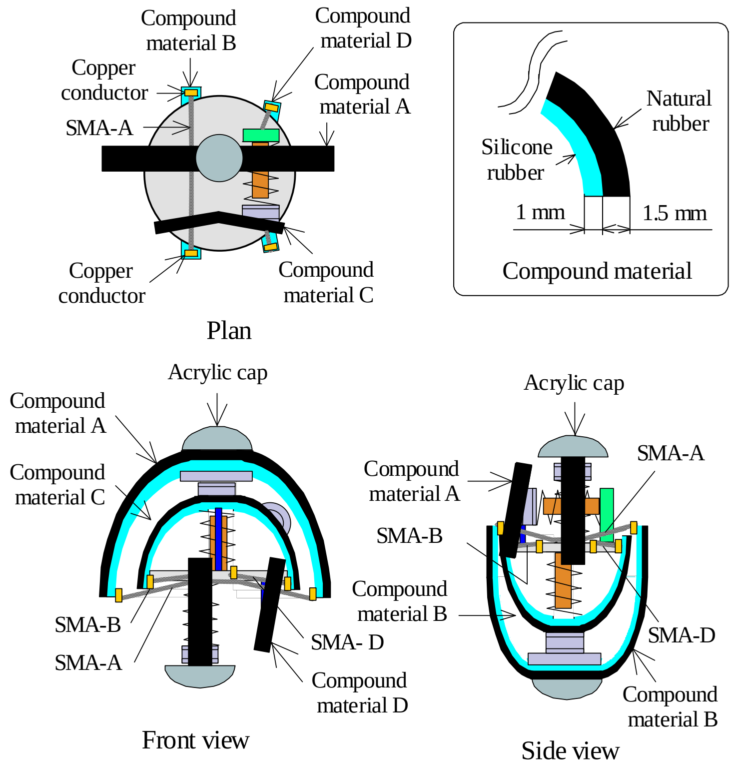


Figure 3. Structure of the magnetic actuator.

Table 1. Properties of the shape-memory-alloy (SMA) coil.

	Outer Diameter	Diameter of Wire	Transformation Point	Resistance Per Meter
SMA coil	0.62 mm	150 µm	60–65 °C	400 Ω

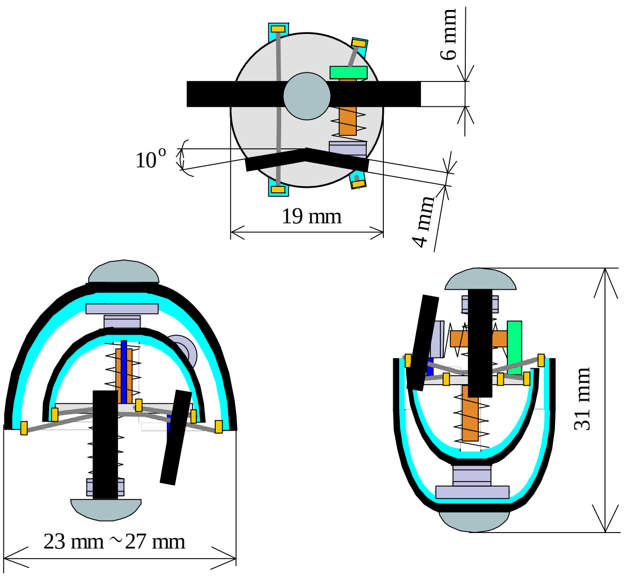


Figure 4. Size of the magnetic actuator.

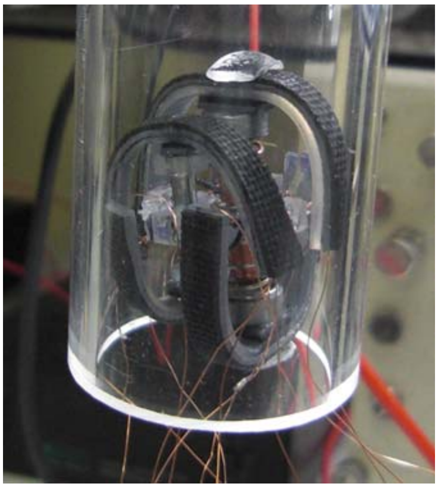


Figure 5. Photograph of magnetic actuator.

3. Principle of Linear and Rotational Motion

It is assumed that SMA coils B, C, and D contract, compound materials B, C, and D are completely closed, and only compound material A is open, as shown in Figure 6. The principle of linear locomotion for this magnetic actuator was demonstrated in a previous study [16]. The frictional force between the compound material and the pipe wall changes alternately during one period of vibration, as shown in Figure 6a,b.

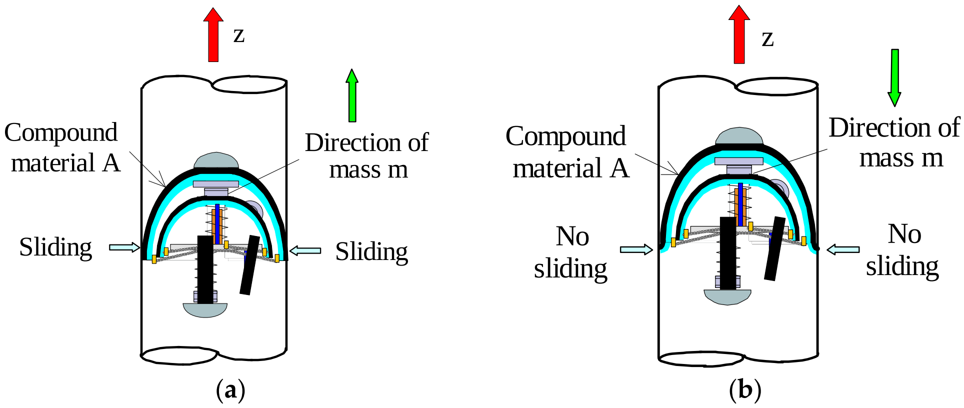


Figure 6. Principle of linear locomotion. (**a**) Linear movement; (**b**) No linear movement.

All vibration components were driven at the same frequency. When a sinusoidal electric current was applied to the electromagnet, the displacement of the vibration component synchronized in the current waveform. Figure 7 shows the displacements of vibration components 1, 2, and 3 when an electric current is applied to electromagnets 1, 2, and 3, respectively. This figure shows the results when the displacements of vibration components 1, 2, and 3 were synchronized. In this condition, the actuator rotated in a clockwise direction, as shown in Figure 7. This actuator can turn in a counter-clockwise direction by changing the phase between vibration components by 180°, as shown in a previous study [16]. Thus, the magnetic actuator undergoes linear and rotational movement based on the difference in frictional force between the forward and backward movement of the compound material.

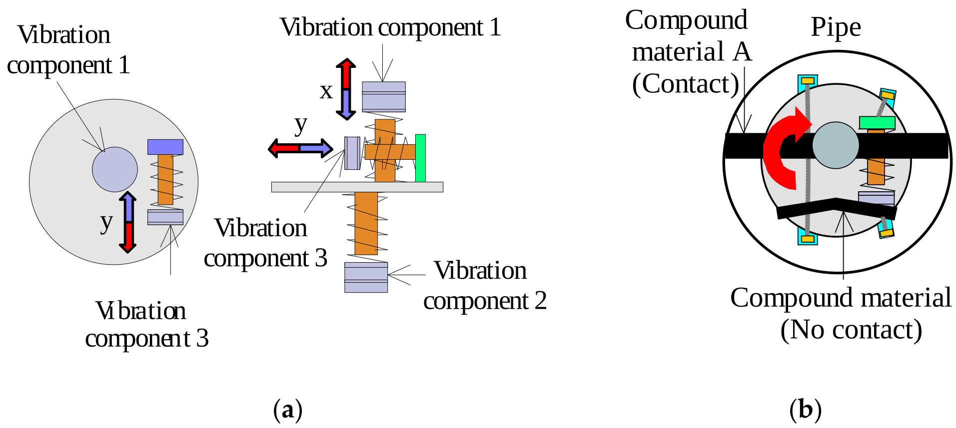


Figure 7. Principle of rotational motion. (**a**) Vibration of components; (**b**) Production of moment by vibration.

In summary, this magnetic actuator can move with straight movement if vibration components 1 and 2 are driven. The actuator is able to rotate in the pipe by changing the phase difference of the displacement between vibration component 3 and vibration components 1 and 2. The compound materials convert the force generated by the vibration components into one-way movement. By the use of flexible materials, this actuator can move in the pipe with different diameters of 23 mm to 27 mm. Reversible movement is enabled by using the opening and closing of compound materials A and B, as shown in a previous study [15].

4. Basic Locomotive Characteristics of Magnetic Actuator

An experimental test was conducted by using the apparatus shown in Figure 8. The resonant frequency of the magnetic actuator was 140 Hz as measured by the experimental apparatus. In this measurement, 12 electric cables (four cables to three electromagnets and eight cables to four SMA wires) were used. A photograph of the experimental setup is shown in Figure 9. A CCD micro-camera with an outer diameter of 8 mm and a length of 10 mm was not available, as mentioned previously. Instead, an additional mass of 2 g was loaded in the actuator to represent two micro-cameras, and measurements were carried out.

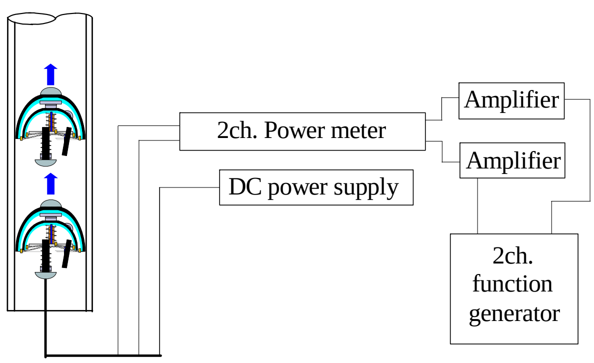


Figure 8. Experimental apparatus.

Figure 10 shows the relationship between the load mass and the vertical upward speed for a straight pipe with an inner diameter of 24 and 26 mm when the input current into the electromagnet of vibration components 1 and 2 was 0.3 A. In this actuator, the maximum electric current capable of input is 0.3 A. After this, the speed of the actuator was measured with an electric current of 0.3 A. This figure indicates that the magnetic actuator was able to climb at 40.5 mm/s when pulling a load mass of 20 g through an inner diameter of 26 mm. The speed of the actuator for the case of no load was 70.2 mm/s. Since vibration components 1 and 2 were not attached to the center of the acrylic plate, this magnetic actuator demonstrated moderately high performance.

Figure 9. Photograph of experimental apparatus.

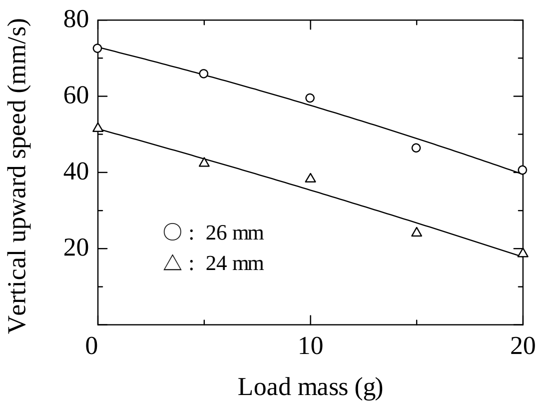


Figure 10. Relationship between load mass and vertical upward speed.

Figure 11 shows the relationship between the tilt angle α of the straight pipe and the speed with regard to a straight pipe with inner diameters of 24 and 26 mm when the actuator had no load mass. The tilt angle α was varied from $-90°$ (straight down) to $90°$ (straight up). In this figure, the vertical upward speed was 51.6 mm/s when the inner diameter of the pipe was 24 mm and the input current was 0.3 A. For the pipe with an inner diameter of 24 mm, the speed when moving straight down was about 2.16 times that when moving straight up.

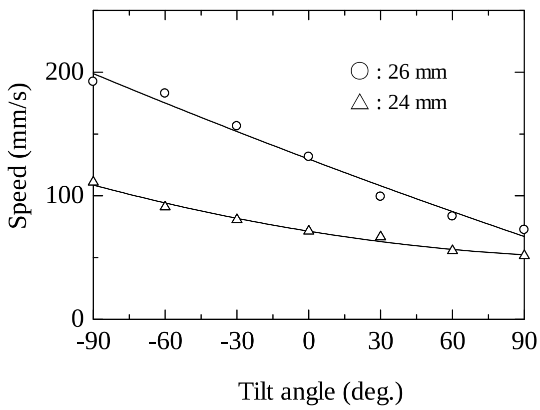


Figure 11. Relationship between tilt angle and speed.

Figure 12 shows the relationship between the input current and the vertical upward speed for the straight pipe with an inner diameter of 24 mm when the input current into the electromagnet of vibration components 1 and 2 was changed. The vertical upward speed was 19.2 mm/s when the input current was 0.2 A. On the other hand, it was 38.1 mm/s when the input current was 0.25 A. The vertical upward speed of the actuator increases proportionally to the value of the input current. When the input current into the electromagnet is low, such as 0.2 A, this magnetic actuator can hardly pull the load mass.

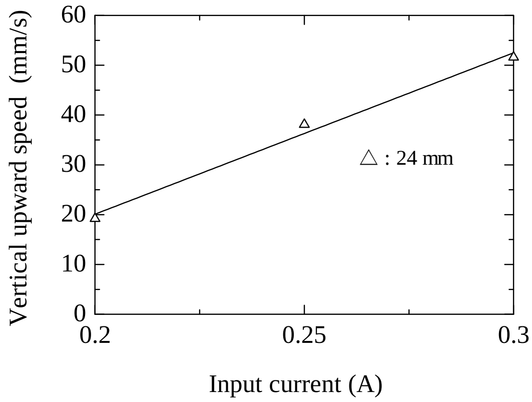


Figure 12. Relationship between tilt angle and speed.

5. Movement in a Complex Pipe

Figure 13 shows details of a curved pipe with a curved part and step parts of 1 mm in the pipe. In addition, the diameters of the curved part and that of an entrance part for this pipe were different.

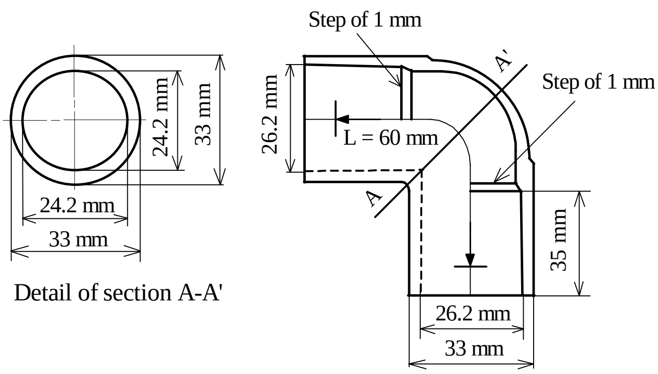
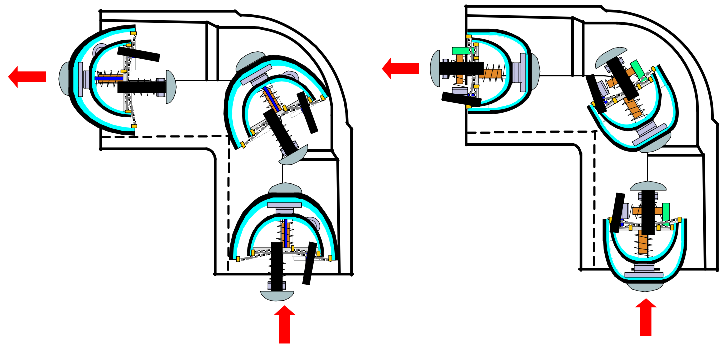


Figure 13. Detail of a curved pipe.

This actuator required movement ability over a wide range of inner diameters ranging from 24.2 to 26.2 mm. This complex pipe was made of polyvinyl chloride. The coefficient of friction between the two rubber arms and the inner wall of the pipe was 0.6. The distance of the measurement was set as 60 mm for one curved part and two straight parts. The measurements of the average speeds were carried out for two moving patterns in the horizontal and vertical directions as shown in Figure 14. In the case of pattern II compared with pattern I, the body of the magnetic actuator in the pipe was turned 90°. Because the coefficient of friction between the two rubber arms and the inner wall of the pipe do not change, this actuator can move underwater if all vibration components are packing possibility. In this case, it is expected that the speed of the actuator hardly changes as compared with air when the same electric current was input into the electromagnet of the vibration components. However, the actuator cannot move in oil because the coefficient of friction is very small. In the future, we have to discuss the frictional force to realize movement in oil.



(**a**) (**b**)

Figure 14. Two moving patterns in the curved pipe. (**a**) Pattern I; (**b**) Pattern II.

Table 2 shows the average speed for the two movement patterns for the actuator measured in the horizontal and vertical directions. The experimental results show that for both patterns, the average speed of the magnetic actuator exceeded 60 mm/s.

Table 2. Average speed for two patterns of movement.

	Upward	**Updown**	**Left**	**Right**
Pattern I (mm/s)	43.8	88.8	63.5	70.8
Pattern II (mm/s)	42.2	67.5	57.3	53.1

Figure 15 shows a schematic of a complex pipe with a T-junction, an inner diameter of 26 mm, and steps of 1 mm. As mentioned above, compound material A only opened in the pipe. Before the actuator moves into the T-junction, the actuator must be rotated in the pipe by controlling the phase difference between the three vibration components and it must be placed in the initial condition, as shown in Figure 15. The supply of direct current into SMA coil C attached on iron pole 1 was first stopped. After a few seconds, compound material C opened due to the elastic restoring force of the material itself. Accordingly, the tip of compound material C made contact with the inner wall of the pipe. In this initial condition, vibration component 1 (compound material A) was driven, and a rotational torque acted on the main body of the actuator, because the supporting point was compound material C. Consequently, the actuator can turn in the left direction in the T-junction pipe as shown in Figure 15. By changing the initial condition due to the rotation of the actuator as mentioned above, this actuator can turn in the right direction.

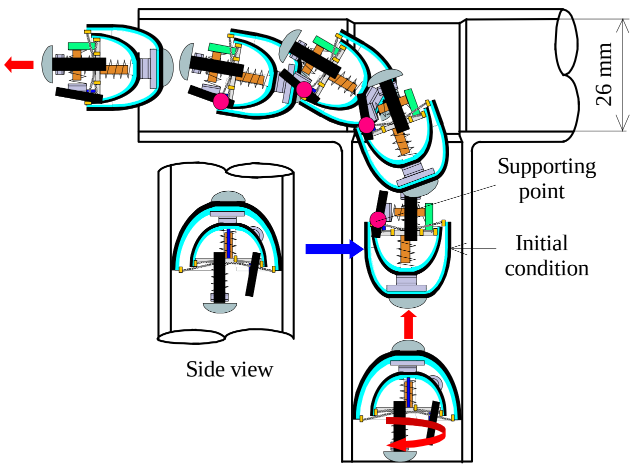


Figure 15. Actuator moving in a T-junction.

As shown in Figure 16, the movement speed in the horizontal and vertical directions in the pipe with a T-junction was measured when the input current to vibration components 1 and 2 was 0.3 A. Table 3 shows the average speeds for the eight movement patterns. Since the distance between the center of vibration component 1 or 2 and the center of iron pole 1 or 2 was 8 mm, the magnetic actuator could turn smoothly in the small complex pipe.

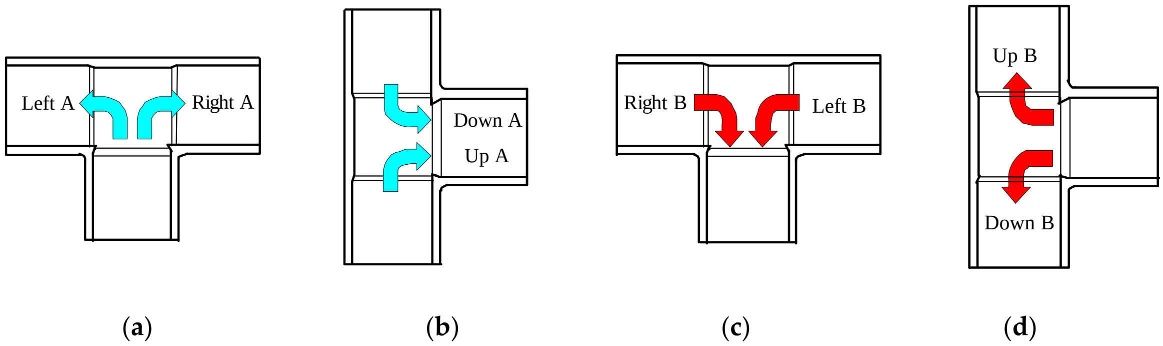


Figure 16. Eight movement patterns of the actuator. (**a**) Horizontal direction; (**b**) Vertical direction; (**c**) Horizontal direction; (**d**) Vertical direction.

Table 3. Average speeds for the eight patterns considered.

	Speed (mm/s)		**Speed (mm/s)**
Left A	32.97	Up A	17.08
Right A	33.71	Down A	29.41
Left B	25.2	Up B	20.13
Right B	27.27	Down B	38.4

6. Conclusions

A new type of magnetic actuator is proposed that is capable of locomotion in a complex pipe with an inner diameter of 25 mm. Due to the desire to increase the turning moment in a T-junction pipe, vibration components were attached off-center on an acrylic plate with an eccentricity of 2 mm. The experimental results show that the magnetic actuator was able to move at 40.6 mm/s while pulling a load mass of 20 g in a pipe with an inner diameter of 26 mm. In addition, by using the three vibration components of the magnetic actuator, the magnetic actuator was able to turn in a small complex pipe with a T-junction. If a micro-camera with an outer diameter of 8 mm and a length of 10 mm is available in the future, inspection of a small complex pipe can be enabled.

Author Contributions: Hiroyuki Yaguchi initiated and supervised the development of the magnetic actuator and wrote the paper, Kazushige Kamata and Hiroshi Sugawara performed the design, assembly and integration of the prototype.

Conflicts of Interest: The authors declare no conflict of interest.

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