A Crawling Based Locomotive Mechanism Using a Tiny Ultrasonic Linear Actuator (TULA)

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Abstract
A crawling based locomotive mechanism for inspection of small sized pipes is developed by using a tiny ultrasonic linear actuator. In case of piezo material based actuators, it is known that they have small displacement with high voltage supply. In order to overcome the limitation of common piezo actuators, the impact based piezo actuator (TULA) has been developed to realize long stroke up to 11 mm. By using TULA, we develop a crawling locomotive mechanism. Previously reported locomotive mechanisms such as earthworm-like and inchworm-like mechanism cannot realize continuous motion but move with step-wise motion since they have clamping and elongation sequence for movement. Therefore, long time loss for movement of one stroke is inevitable. In this crawling mechanism, nearly continuous motion is achieved by using both directions of actuating forces. Owing to the light weight and the simple structure of the actuator, the crawling based locomotive mechanism has simple design with 9mm diameter, 40mm length and 1.1g weight. It shows 9.2mm/s in 18.5mm inside diameter of a pipe regardless of the pipe’s tilting angle.

1. Instruction

The development of modern industries brought about the complexity of machines and devices and they require small-sized in-pipe locomotive mechanisms for inspection and repair. Since large-sized in-pipe locomotive mechanisms [1] using conventional motors are not suitable for the inspection of complex devices, the researches on micro in-pipe moving mechanisms using micro motors [2,3], micro pneumatic actuators [4,5] and smart material based actuators such as piezo actuators [6,7] and SMA (shape memory alloy) actuators [8,9] are carried out. The micro motor is tiny, but it requires additional devices to convert rotating motion into linear motion for actuating of locomotive mechanism. The micro pneumatic actuator has flexibility, compactness and high generative force. But, it always has to connect to pneumatic power source and the pneumatic line causes high friction force between pipe wall and body of locomotive mechanism. On the other hand, SMA has such slow actuating speed since it actuates based on joule heating. In case of the piezo actuator, it generates small displacement although it produces rapid actuating speed and high generative force. Therefore, the novel impact based ultrasonic PZT linear actuator (Tiny Ultrasonic Linear Actuator, TULA) has been developed, which generates larger amounts of displacement compared to conventional piezo actuators. It enables to embody locomotive mechanism with long stroke [10].

The typical locomotive mechanism using the linear actuator is earthworm-like and inchworm-like mechanism [8, 9]. Such locomotive mechanisms cannot move continuously due to working principal consisted of clamping and moving sequences. Therefore, the crawling based locomotive mechanism utilizing both directions of actuating forces of the linear actuator is developed. In order to investigate locomotion efficiency of the proposed locomotive mechanism, it is tested under various diameters and tilting angles of pipe.

Figure 1. Fabricated TULA (Tiny ultrasonic linear actuator)
2. An impact based piezo actuator

The developed piezo linear actuator is shown in figure 1, TULA is composed of piezoelectric ceramics, elastic material, a housing element to fix piezoelectric ceramics and a shaft to guide a moving element. The shaft guiding a moving element is fixed in a copper plate of the elastic material that bonded on ring-shaped piezoelectric ceramics. The unified copper plate and piezoelectric ceramics are also combined by the housing element.

Working principle of the proposed actuator is presented in figure 2. An attached moving element to the shaft is actuated with saw tooth shaped pulse as an input voltage to the piezo ceramic.

The ceramic actuator moves forward as much as amplitude of A during the pulse interval of a-b. On the other hand, the ceramic actuator moves backward as much as 2A when the input pulse changes from b to c and reaches to 0. At that time, only the shaft attached to the actuator moves backward and the mobile element keeps its position due to Newton’s First Law of Motion. In the pulse interval of c-d, the ceramic actuator moves forward with amplitude of 2A. At that time, a mobile element on the shaft follows the motion of an actuator due to enough friction between the mobile element and the shaft. In the range of d-e, again only the actuator comes back to base position and mobile element keeps same position. Based on repeated cycle in figure 2, the impact based actuator works. With reversed pulse wave, moving direction of the mobile element can be directed to the other direction. More precise specification of the invented actuator by S. Yoon et al. is described in reference [9]. The specifications of TULA are summarized in table 1.

There will be velocity difference between piezo actuator and locomotive mechanism assembled with piezo actuator due to friction and misalignment during assembling. Therefore, we investigate velocity of piezo actuator itself for evaluation of the developed locomotive mechanism. As shown in figure 3, velocity of the moving element is 23.1mm/s and time for pulse transformation requires 0.2 second for each direction. Then, average velocity of the TULA for one cycle is 13.9mm/s.

3. Design of locomotive mechanism

In order to prove advantage of the developed locomotive mechanism, we fabricate an earthworm-like mechanism and a crawling based mechanism to compare locomotion efficiency between both mechanisms. First of all, the working principle of earthworm-like mechanism using TULA is presented as shown in figure 4. (a).

(1) Initial stage.
(2) When the moving element moves backward, the rear legs connected with the moving element protrude from the robot’s body and push a pipe’s inner wall. The fore legs fixed on robot body are slipped over wall of pipe and the robot’s body moves forward.

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\text{Table 1. Specification of TULA}
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<table>
<thead>
<tr>
<th>Disk Diameter</th>
<th>5.5 mm</th>
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</thead>
<tbody>
<tr>
<td>Shaft Diameter</td>
<td>1.3 mm</td>
</tr>
<tr>
<td>Shaft Length</td>
<td>16.5 mm</td>
</tr>
<tr>
<td>Mobile Speed</td>
<td>23.1 mm/s</td>
</tr>
<tr>
<td>Thrust Force</td>
<td>40 g.f</td>
</tr>
<tr>
<td>Stroke</td>
<td>11 mm</td>
</tr>
<tr>
<td>Driving Voltage</td>
<td>25 V</td>
</tr>
<tr>
<td>Driving Frequency</td>
<td>65 kHz</td>
</tr>
<tr>
<td>Current</td>
<td>9 mA</td>
</tr>
</tbody>
</table>
(3) After the robot’s body moves as much as the stroke of moving element, it stops.

(4) When the moving element moves forward, the rear leg slides into the robot body by the lockup position of moving element. At that time, the fore leg supports on wall of pipe and the friction force between wall of pipe and fore leg is big enough not to retract the robot body.

(5) After the locomotive mechanism obtains stroke of A, it returns to initial stage.

As described above, the earthworm-like mechanism can move forward only when the moving element moves backward. However, the proposed crawling based locomotive mechanism (figure 4. (b)) is able to move forward regardless of the driving direction of the moving element since the working principle of the crawling based locomotive mechanism is as follows.

(1) Initial stage.

(2) Rear legs fixed on the moving element protrude from robot body and start pushing the wall of pipe. On the other hand, fore legs connected with the moving element slides in the robot body. Therefore, the driving force is obtained from contact between rear legs and wall of pipe and friction force between front legs and wall of pipe is almost eliminated.

(3) The robot moves as much as A of stroke until the moving element reaches to the bottom position of the actuator. At that time, friction force between fore legs and wall of pipe almost eliminated since fore legs slide in robot body and keep minor contact.

(4) Reversely, when the moving element moves to top position of the actuator, the rear legs slide into the robot body. In the meanwhile, the fore legs start pushing wall of pipe.

(5) After the moving element reaches to top position of the actuator, it obtains another A of stroke and return to the initial stage.

As moving element of linear actuator moves to the forward or backward, fixed fore leg and rear leg on the moving element pushes wall of pipe one after the other. Consequently, the crawling based locomotive mechanism always moves forward. In order to guarantee reliable locomotion, design of curvature radius of fore leg when it protrudes from robot body is a critical parameter. If it takes small curvature radius in small diameter of pipe, it overloads the piezo actuator. Consequently, it causes stopping of locomotive mechanism. Therefore, a guide cap to keep constant curvature radius is designed as shown in figure 5.

Main components of the proposed locomotive mechanism are the guide cap installed on robot body, an actuator and 3 pairs of forelegs and rear legs. The crawling based locomotive mechanism mimics crawling posture of a man who supports with arms and legs in pipe.

![Figure 4. Comparison of locomotive mechanism](image1)

![Figure 5. Conceptual design of the proposed locomotive mechanism](image2)

![Figure 6. Fabrication micro robot](image3)
4. Robot fabrication and experimental set-up

The earthworm-like mechanism and the crawling based mechanism using piezo actuator (TULA) are fabricated as shown figure 6. The material of the robot body is polycarbonate and external diameter of robot is 9mm. Legs of the robot are made of a thin plate (Asahigaugemfg®) used for feeler gauge. The length of earthworm-like mechanism and the crawling based mechanism is 32mm and 40mm, respectively. The weights of both robots are almost same as 1.1g. Specifications of each robot are presented in detail in table 2. Both sides of the shaft of TULA are fixed by shaft holder made of rubber within the robot body and the moving element installed with legs is disposed in the robot body.

Since a curvature radius is changed according to diameter of the pipe, friction force between the legs and the pipe can be changed due to unique design of the robot. Therefore, we carry out experiments under variation of diameter of the pipe and variation of tilting angle of the pipe to verify locomotion efficiency of the proposed locomotive mechanism. As shown in figure 7, a vibrometer (Polytec) and camcorder are used to measure displacement of the locomotive mechanism and DAQ board (NI) and LabVIEW are used to collect experiment date and to control locomotion of the robot locomotive mechanism.

5. Experimental results

Curvature angle of the leg is a main parameter to influence performance of locomotive mechanism. It is decided by flexibility of the leg. Therefore, we chose thickness of the leg thorough various experiments. For this experiment, thin plates with 2mm wide and thickness range of 0.01–0.1mm are employed. As a result, when the thickness is less than 0.04mm, the stiffness of legs is not big enough to support weight of the robot and they are bent. Consequently, the robot cannot move in the pipe properly. When it is thicker than 0.6mm, the legs do not slide in the robot body freely due to high stiffness of legs. Therefore, the proposed locomotive mechanism is tested with 2mm wide and 0.05mm thick legs.

5.1. Velocity under various diameters of pipe

Velocity of the robot is measured in the horizontal pipes with 14.0mm, 16.5mm and 18.5mm of diameter respectively since diameter of in-door pipe for water supply is around 15mm in Korea. As shown in figure 8, the robot shows the velocities of 6.7mm/s in the 14.0mm diameter pipe, 8.8mm/s in the 16.5mm diameter pipe and 9.2mm/s in the 18.5mm diameter pipe. As diameter of the pipe decreases, curvature angle of the legs decreases since space between robot body and pipe wall get smaller. It causes higher friction between the robot’s legs and holes that the legs come out. Consequently, it results in reduction of locomotion velocity. However, the crawling based locomotive mechanism can adapt to change of diameters and move stably although the velocity of it is little bit reduced.

5.2. Velocity under various tilting angle of pipe

In order to test adaptability of the robot according to change of tilting angle of pipe, velocity of the robot is measured with 18.5mm of diameter in conditions of 0, 30, 60, 90 degree. The experimental result of figure 9 shows that velocity of the robot is about 9.2mm/s regardless of the pipe’s tilting angle. It is because driving force of the robot is highly dominant over the weight of the robot and flexibility of the leg is stiff enough to support the robot stably in the centre of the pipe. Conclusively, the crawling based locomotive mechanism using TULA is very effective mechanism for inspection of pipe with various diameters as well as horizontal and vertical pipes such as in-door water pipes.

5.3. Locomotion efficiency

From working principle, theoretical stroke of locomotion of the proposed locomotive mechanism is two times bigger than that of earthworm-like mechanism. However, there is some efficiency reduction of locomotion due to fabrication process and change of test environment. Therefore, we investigate efficiency of actuator itself and locomotion efficiency of each mechanism out of the pipe and in the pipe. Displacement of the TULA is presented as shown in figure 10. It shows a velocity of 13.9 mm/s including switching time from forward movement to backward movement.
When the earthworm-like mechanism is assembled based on the TULA, the displacement is severely reduced since this mechanism can advance only when the moving element of piezo actuator moves forward. Consequently, velocity of earthworm-like mechanism is limited to 6.9 mm/s. However, 11.8 mm/s of velocity of the robot can be obtained with the proposed crawling based mechanism since this mechanism is designed to obtain the displacement no matter which direction the moving element moves to.

In pipe condition, however, velocity of the robot is significantly decreased due to deformation of the legs and friction force between hole and legs while the legs are sliding. If velocity of the proposed mechanism out of pipe compares to that of piezo actuator itself, it reaches to 84.9% of velocity of piezo actuator. The loss of locomotion efficiency comes from high load to the actuator due to curvature radius of legs and friction between legs and hole for sliding of the legs. In pipe, the curvature radius of legs gets much smaller than that in out of diameter state. Consequently, load to the actuator is significantly increased. Therefore, velocity of the proposed mechanism is reduced to 66.2% of velocity of the piezo actuator. In case of earthworm-like mechanism, velocity of this mechanism in pipe is exactly half of the piezo actuator because this mechanism utilizes only one way movement of the actuator and there is almost no load to the actuator due to simple design of mechanism. It does not have friction force between legs and sliding hole and bent legs that highly resist to the driving force. With the crawling based mechanism, however, we could realize continuous motion by using both direction movement, that is forward and backward, of the TULA and obtain 15% higher velocity although there is heavier load to the actuator due to friction between legs and sliding hole and bent legs with small curvature radius.

6. Conclusion

The crawling based locomotive mechanism that mimics a man who crawls in a pipe is constructed and evaluated under various environments. As an actuator of the locomotive mechanism, the invented piezo actuator, TULA, is employed and several legs made of high-elastic alloy thin bands are installed to obtain the driving force of the locomotive mechanism. Therefore, as the moving element synchronized with the legs moves forward and backward, fore and rear legs push the wall of pipe. Thus, it obtains driving force to move.

In order to evaluate efficiency of mechanism, locomotion efficiency of the proposed mechanism is compared to TULA itself and the earthworm-like mechanism. In addition, locomotion efficiency is investigated under in-pipe and out of pipe conditions. As the experimental results, efficiency of the crawling based mechanism was 33.3% higher than that of the earthworm-like mechanism since the proposed mechanism uses movement of moving element to both directions. As diameter of the pipe is increased, curvature radius of legs is
increased. Consequently, it causes less load to the actuator and velocity of the proposed mechanism is increased. In vertical pipe, there is no difference of locomotion efficiency owing to balance between the weight of the proposed mechanism and retaining force of legs to the wall.

In conclusion, the locomotive mechanism using the proposed crawling method shows excellent locomotion capacity in small sized pipe, it can be one of the alternatives of conventional locomotive mechanisms for small sized in-pipe inspection.

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8. References