Design of a peristaltic crawling robot using 3-D link mechanisms

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Abstract: In disaster areas, rescue work conducted by humans is extremely difficult. Therefore, rescue work using rescue robots in place of humans is attracting attention. This study specifically examines peristaltic crawling, the movement mechanism of an earthworm, because it can enable movement through narrow spaces and because it can provide stable movement according to various difficult environments. We developed a robot using peristalsis characteristics and derived a robot motion pattern using Q-learning, a mode of reinforcement learning. Moreover, we designed each part of the robot based on required specifications and thereby developed a real robot. We present results of motion experiments assessing the robot’s level ground movement.

Keywords: biorobotics; peristaltic crawling robot; Q-learning; link mechanism.


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1 Introduction

In Japan, rescue operations performed by robots in dangerous areas and the hastened development of robots received attention after the Hanshin Awaji earthquake disaster. Rescue operations using robots are beneficial because they can mitigate damage from secondary disasters such as fires and aftershocks that might occur in disaster areas. Particularly, the development of a robot that can search deeply into small spaces was conducted (Harihara et al., 2010). Regarding movement, development of a robot for use in small spaces is necessary. Various movement mechanisms such as walking, rolling on wheels, and meandering have been developed for robots. Peristaltic crawling was chosen for our robot for three reasons. Peristaltic crawling can enable movement through narrow spaces, can enable stable postures, and can provide simple movement patterns (Ebuchi et al., 2002). We devoted attention to this mechanism from early stages, and
development, and developed robots of various kinds (Saga and Nakamura, 2002, 2004). For this study, we developed a motor-driven peristaltic crawling robot.

2 Robot design

2.1 Movement pattern of peristaltic crawling

An earthworm moves by letting segments expand and contract, and by creating regressive waves. We explain the movement mechanism using a simple model of an earthworm presented in Figure 1. First, the segment which becomes big comes into contact with the ground or wall and advances its position by forward segmental expansion. An expanding segment moves gradually, and the earthworm advances by movement to draw an adjacent segment to itself. It then advances further by pushing against it. The waves shown by the arrow opposing the direction of travel are called regressive waves. Earthworms become able to perform peristalsis by producing this wave motion repeatedly.

Figure 1 Movement mechanism of peristalsis

2.2 Outline of peristaltic crawling robot

We explain the overall structure of the peristaltic crawling robot to develop in this study. The peristaltic crawling robot developed in an earlier study in our laboratory used a mechanism to advance by expanding and contracting in a horizontal course in the ground, while retaining its position in relation to the wall. However for the robot, it was impossible to advance when right and left sides did not have a wall. The present study was conducted to develop a robot using three-dimensional movement to move on level ground under circumstances where there is no right or left wall.

The robot is comprised of an expanding and a contracting segment for peristalsis, and a joint connecting them. The earthworm can perform peristalsis if at least three segments expand and contract even when a segmental part does not function. Therefore, we decided to develop the three segmental robots in this study.

We design and choose parts to meet the requirement specifications with the proviso that a robot can do three-dimensional peristalsis. We defined as required specifications for the structure of the robot that the segments expand and contract in three directions and that they maintain their progress by two points of contact downward on the level ground.

The earthworm can always perform similar movements when which surface in the segmental circumference touches on the ground. Therefore, we designed the robot to be able to stable move even if turned over by at least two contact points. We chose 230 mm as the robot width for this study so that the size of a search robot is required less than the space of a human body because buildings that had been collapsed by the Hanshin Awaji great earthquake were unable to rescue people trapped under rubble. Moreover, the centres of segments are equipped with retentive portions that are parts keeping retention which are designed with passive joints. Both ends of the retentive portion are equipped with servo motors, by turning of the motor, retentive portion extends outside of a segment as shown in Figure 2.

Figure 2 Structure of peristaltic crawling robot (see online version for colours)

2.3 Choice of the motor

When the retentive portion retains its position with the ground or wall, retentivity is determined by the generative force of the motor. Therefore, it is necessary to choose a motor with sufficient torque. Retentivity is the power to fix segments when a robot comes into contact with an object. As a condition to provide sufficient retentivity, we require that the robot’s own weight be supported by retentivity.

Therefore, a motor must be chosen such that retentivity is greater than the robot’s own weight. We show the relational expression of the robot’s own weight and retentivity in formula (1) and present the definition of each variable in Table 1. We present the model of formula (1) in Figure 3.

\[ 3A \cdot \frac{N}{L} \cdot \mu \cdot \cos \theta > Mg \cdot S \]  

(1)

The left side of the formula is the maximum retentivity. The right side of the formula is the robot weight. Having chosen a motor that satisfies formula (1), we chose to use a servo motor (RS601CR; Futaba) of which the output torque is 2,256 N-mm (at 9.6 V) and the weight is 0.86 N. We present the required specifications of the motor in Table 2.
### Table 1 Definition of variables

<table>
<thead>
<tr>
<th>Variable</th>
<th>Definition</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A$</td>
<td>Number of motors to use for the segment on one side</td>
</tr>
<tr>
<td>$N \ (N \cdot mm)$</td>
<td>Torque of the motor</td>
</tr>
<tr>
<td>$L \ (mm)$</td>
<td>Length from an axis of the motor to the retentive portion</td>
</tr>
<tr>
<td>$\theta \ (deg)$</td>
<td>Rotary angle of the motor</td>
</tr>
<tr>
<td>$\mu$</td>
<td>Maximum static frictional force between retentive portion and wall</td>
</tr>
<tr>
<td>$M \ (kg)$</td>
<td>Weight of the robot</td>
</tr>
<tr>
<td>$g \ (m/s^2)$</td>
<td>Acceleration of gravity</td>
</tr>
<tr>
<td>$S$</td>
<td>Factor of safety</td>
</tr>
<tr>
<td>$F_E \ (N)$</td>
<td>Power to occur in $L \ (mm)$ point from axis of the motor</td>
</tr>
<tr>
<td>$F_c \ (N)$</td>
<td>Power to push the wall perpendicularly</td>
</tr>
</tbody>
</table>

### Table 2 Specifications of the motor

<table>
<thead>
<tr>
<th>Specification</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dimension $L \times W \times H$</td>
<td>$59 \times 26 \times 47 \ mm$</td>
</tr>
<tr>
<td>Weight</td>
<td>$0.86 \ N$</td>
</tr>
<tr>
<td>Output torque</td>
<td>$2,256 \ N \cdot mm \ (9.6 \ V)$</td>
</tr>
<tr>
<td>Consumption current</td>
<td>$45 \ mA$ (common temperature, no-load)</td>
</tr>
<tr>
<td>Range of motion</td>
<td>$240 \ deg$</td>
</tr>
<tr>
<td>Command method</td>
<td>RS485 communication</td>
</tr>
</tbody>
</table>

### Design of the motor cover

The motor cover is the part which connects the retentive portion to the motor. During the time when the robot retains contact with the wall, it is assumed that circumjacent parts are subjected to a big load. Therefore, when the motor cover is designed, we performed a strength calculation using FEM analysis and chose an external form. Moreover, because the robot has a mechanism that maintains retention in succession, we defined that a factor of safety must be 4. As might be appreciated from formula (1), the power to push the wall grows so big that the rotary angle of the motor is small. Therefore, the condition under which load depends on a part is the case of the robot retaining its position when the rotary angle of the motor is 0 deg and pushes the wall. The length from the axis of the motor to the retentive portion is 72.0 mm. The power to push the wall is 31.0 N from torque of the motor is 2,256 N mm. Furthermore, because motors are put at both ends of the retentive portion, the reaction force that the retentive portion receives from a wall becomes 62.0 N. We chose to use SolidWorks to design each part and the analysis condition in the FEM analysis is defined as follows.

- restraint condition: four places of the screw hole are fixed
- loading condition: power of 62.0 N occurs from a contact surface perpendicularly for a retentive portion.

We chose to develop the robot body materials using ABS resin. The material characteristics are just as shown in Table 3. We show the result that was finally provided under the conditions described above in Figure 4. Because the maximum stress is 6.6 MPa and because it can satisfy a safety factor of 4 for yield strength 28.0 MPa of the ABS resin, the required specifications are satisfied. Therefore, we understand that the parts do not yield during normal operation.

### Table 3 Material characteristics of ABS resin

<table>
<thead>
<tr>
<th>Quality of material</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Elastic modulus</td>
<td>$2,000 \ MPa$</td>
</tr>
<tr>
<td>Poisson ratio</td>
<td>$0.39$</td>
</tr>
<tr>
<td>Yield strength</td>
<td>$28.0 \ MPa$</td>
</tr>
<tr>
<td>Mass density</td>
<td>$1,040 \ kg/m^3$</td>
</tr>
</tbody>
</table>

We show an example with this part attached to a motor in Figure 5. The motor axis is fixed. Therefore, the retentive portion moves to the ground direction by the turn of the motor and becomes able to retain tension when the segment expands. The extending segments are fixed. Then the
contracting segments can move easily by a draw and push movement.

**Figure 5** State with attached a motor cover (see online version for colours)

Therefore, regarding the required specifications of the part which fixes a motor, we decided that the motor lower part does not come into contact with the ground as for the height of a motor fixing place. Moreover, we decided that the retentive portion is located below a ball caster when robot retains its position. We show in Figure 6 the external form of the part with a motor designed to satisfy the specifications described above. In addition, the motor is located on a segmental circumference at equal interval as shown in the figure, which shows three-fold symmetry seen from the front.

**Figure 6** Shape of the part that fixes a motor (see online version for colours)

2.5 **Design of the retentive portion**

We design the retentive portion to be able to retain its position for both the ground and the wall. It retains its position by the base of the retentive portion for the ground, and retains its position by an O-ring surrounding the circumference of the retentive portion as shown in Figure 5 for the wall. We assumed that these parts received a big load like a motor cover and calculated the strength and designed an external form. The analysis condition in FEM analysis defines it as follows.

- restraint condition: fixed the joint with the motor cover
- loading condition: power of 62.0N occurs from a contact surface perpendicularly for a retentive portion.

We present the results of the strength calculations in Figure 7. For these parts the safety factor was also defined as 4, as with the motor cover, which can provide yield strength of 28 MPa of ABS resin. By changing the rod thickness of the connection to the mover cover through trial and error, the result described above was provided for a 3.5 mm rod radius.

**Figure 7** Results of FEM analysis of the retentive portion (see online version for colours)

2.6 **Specifications of one segmental structure**

One segment comprises a motor cover, a motor frame, a retentive portion, a servo motor, and a ball caster. We show the state of combination of each part in Figure 8. One segmental length is 183.0 mm at the time of extension and is 116.0 mm at the time of contraction. Therefore, the greatest movement distance in the strokes is 67.0 mm. In addition, the width is 240.0 mm at the time of extension and is 132.0 mm at the time of contraction.

**Figure 8** Structure of a single segment (see online version for colours)
2.7 Design of the joint connecting segments

The joints have flexibility for changing the robot direction. The requirement specification of the joints is the capability of bending 90 deg from side to side and up and down. Anteroposterior segments must not come into contact when joints turn. We adopted a universal joint mechanism, which can bend side-to-side and which can also bend in top and bottom directions. To satisfy the condition in which anteroposterior segments do not come into mutual contact, the length from an axis of each joint to a segment must have length that is greater than a radius of the segmental width.

Therefore, we defined the length from a segment to an axis as 69.0 mm in this study. We show a joint that connects segments with Figure 9. The joints have a mechanism to function passively by forward segment motion.

2.8 Production of a real robot

We produced a three-segmental real robot using segments and joints that we designed. The body, which is made of ABS resin, is shown with the finished robot in Figure 10. Each motor is connected to a daisy chain and performs angle control from a PC input. We designed the wiring to run along the robot cavity and prevent obstruction of the robot movement. Moreover, the full length of the robot was 825.0 mm at the time of extension. It is 621.6 mm at the time of contraction.

3 Algorithm for robot movement

3.1 About Q-learning

The actions treated here are not numerous. Therefore, positive convergence and action selection are performed using Q-learning, which is generally useful.

The Q-learning algorithm is a typically used for strengthening studies (Yamashita et al., 2005; Yoshimoto et al., 2005). This learning algorithm enables repetition of a trial-and-error interaction with the path in the environment. It takes an action with the highest value (Q value) of an action valuation function among possible actions in each state, as outlined in Table 4.

Table 4 Algorithm flow of Q-learning

(Q1) The agent examines state $s_t$ in step $t$.
(Q2) The agent carries out action $a_t$ according to an action choice method.
(Q3) The agent receives reward $r_t$ from environment.
(Q4) The agent observes state $s_{t+1}$ after the state transition.
(Q5) The Q value is updated by expression for update:

$$Q(s_t, a_t) \leftarrow Q(s_t, a_t) + \alpha \left[ r_t + \gamma \max_a Q(s_{t+1}, a) \right]$$

$\alpha$: learning rate ($0 < \alpha \leq 1$); $\gamma$: discount factor ($0 \leq \gamma < 1$)
(Q6) Step $t$ is pushed forward to $t + 1$ and come back to (Q1)

3.2 Application of Q-learning

Assuming that all three segmental axes link, and that they are working, the angle can be segmental $\theta_t$ on the outside, with six ways of 0 deg, 20 deg, 40 deg, 60 deg, 80 deg, or 100 deg. Regarding the robot, the combination of segment shapes becomes $6^3$ ways for three segments. Furthermore, the number of actions that the robot can take next becomes $6^3$. Therefore, the Q-table size is $6^3 \times 6^3$. The distance moved from step $t$ to $t + 1$ becomes reward $r_t$. It updates expression (2) $Q(s_t, a_t)$ of the Q value of Table 4. The simulation is repeated for 1,000 trials. As a result of changing values through trial and error, we achieved learning rate $\alpha$ of 0.6 and discount rate $\gamma$ of 0.9.

3.3 Result of Q-learning

The migration length for the movement pattern of the acquired simulation results is presented in Figure 11 as a real robot’s pattern of operation. The real robot can move with the movement pattern gained in the simulation, which reflects that the robot’s simulation model setup was sufficient. In the simulation, using realisable actions, the robot moved in patterns by avoiding a penalty state in which the robot’s movement was unrealisable.
4 Experimental results for real robot

We experimented by applying the result obtained through Q-learning. The peristalsis movement mechanism is simple: expansion and contraction by the angle designation in a motor. We show an image depicting the divided state of the level ground run experiment of the robot at every second in Figure 12. Right and left walls were non-existent, but the robot became able to advance, which was impossible with the robot assessed in our earlier study.

In addition, the robot movement pattern is derived by Q-learning in this study. A robot can advance by creating a regressive wave resembling that of the peristalsis of an earthworm.

From application of a movement pattern derived by Q-learning to a robot, it became able to perform level ground motion. It might be said that it realised movement on level ground, which is a three-dimensional movement mode.

As a future problem, when running on a non-level surface, as in rubble or in a bent tube, the robot movement is expected to be difficult. Therefore, it is probably necessary to examine flexible patterns using the motor for swinging the head.

References


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