SICE Annual Conference 2010
August 18-21, 2010, The Grand Hotel, Taipei, Taiwan

A squeezing control for snake-like robots to climb up trees

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***Abstract*—The purpose of this study is to realize a control method of snake-like robots in order to climb up trees. The control method is able to divide into locomotion controls on a tree trunk and staying controls to avoid falling off. This paper shows the force for squeezing a tree trunk to avoid falling off is calculated by the relationship between the actuator torque and the friction force at each link which can be derived according to Projection Method. The effectiveness of the proposed method is verified by a numerical simulation.**

***Keywords*—*Snake-like Robot; Projection Method; Constraint Condition;*.**

I. INTRODUCTION

A snake has a simple figure like one string. Utilizing the figure adeptly, a snake can move on various environments such as flat plane, rubble ground, sand and underwater. It can also climb up walls and trees. If adaptive and intelligent locomotive methodologies for snake-like robots are realized, that robots can be useful in wide fields such as disaster relief, buildings and plants maintenance, medical services and so on.

Snake-like robots attracts much attention from the viewpoint of control theory, because the robots are hyper redundant and non-holonomic systems. Hence, they are chosen actively as research targets[1][2][3]. There are a lot of researches on locomotion of snake-like robots on the two dimensional plane. Recently, researchers pay much attention to locomotion in the three dimensional space. The research team at Carnegie Mellon University developed snake-like robots climbing up trees. However its motion seems different from natural snake's behavior, and it's kind of a pure mechanical one. It is not necessary for robots to mimic behavior of real creature, but learning from real creature might be a better way for realizing a sort of adaptivity, optimality and intelligence by robots[4].

This study aims to develop a control algorithm for snake-like robots to achieve a climbing up a tree much naturally. The algorithm might be useful for wide application of snake-like robots. The control method can consist of two parts: (1) a control to keep a robot staying on a tree without falling off, and (2) locomotion control on a tree trunk. This paper focuses on the first part, and shows a method to calculate force and torque for squeezing a tree trunk in order to avoid falling off. The key idea is to derive a relationship between actuator torques and friction forces at each link is derived according to Projection Method (PJ method)[5]. The effectiveness of the proposed method is verified by a numerical simulation.

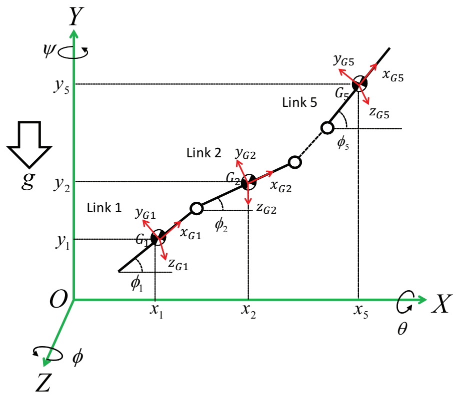

Fig. 1. 3D snake-like robot

TABLE I
PARAMETER($i = 1, 2, 3, 4, 5$)

J_{xi}	Inertia moment of x_{Gi} axis turned [kg$\cdots m^2$]
J_{yi}	Inertia moment of y_{Gi} axis turned [kg$\cdots m^2$]
J_{zi}	Inertia moment of z_{Gi} axis turned [kg$\cdots m^2$]
m_i	Mass [kg]
L_i	Length [m]
l_i	Length from center to end of gravity[m]
d_i	Length from extremity to center of gravity [m]
g	Acceleraition of gravity [Nm$\cdots$s/rad]

II. MODELING OF SNAKE-LIKE ROBOT

We assume about the model of the snake-like robot in the state that coils around the tree. It was assumed the system of 5 links as an example this time. Even if the number of links increases, it is possible to considering similarly. Each joint of this system is 2 degree of freedom because it has the pitch and yeoh. Originally, it is necessary to assume about the condition that the snake-like robot doesn't slip sideways to use and to promote power in the direction of the normal. Slipping sideways is not thought this time. Because to assume

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a simple model in the state that coils around the cylinder. Fig.1 shows the model of 5link snake-like robot. Table 2 shows each parameter. To consider a squeezing control, a motion equation of a 5-link snake-like robots is derived by PJ method. It is possible to assume about the tree as well as the cylinder. The motion equation of three dimension model is complex but It can be easily derived by using the geometric transformation. The motion equation of 5link snake-like robot in the state that doesn't coil around the cylinder is derived in the beginning. The motion equation in the state that coil around the cylinder is derived by the geometric transformation and the restraint condition. The orthogonalization coordinate system fixed to the space is a fixed system of coordinates. The moving coordinate system is made a movement coordinate system. A fixed system of coordinates is assumed to be $O - XYZ$. A movement coordinate system is assumed to be $G_i - x_{Gi}y_{Gi}z_{Gi}$. Let $(\phi_i, \theta_i, \psi_i)$ is Euler angle seen in a fixed system of coordinates, (x_i, y_i, z_i) is position of mass of each link seen in fixed coordinate system, $(\omega_{xi}, \omega_{yi}, \omega_{zi})$ is an element axially of angular velocity vector of movement coordinate system and (v_{xi}, v_{yi}, v_{zi}) is an element axially of velocity vector of movement coordinate system.

A. Motion equation of each link in the movement coordinate system

The motion equation of each link in the movement coordinate system is derived. Define a generalized velocity v as

$$\begin{aligned} v = \; & [\omega_{x1}\ \omega_{y1}\ \omega_{z1}\ \omega_{x2}\ \omega_{y2}\ \omega_{z2}\ \cdots\ \omega_{x5}\ \omega_{y5}\ \omega_{z5} \\ & v_{x1}\ v_{y1}\ v_{z1}\ v_{x2}\ v_{y2}\ v_{z2}\ \cdots\ v_{x5}\ v_{y5}\ v_{z5}]^T . \end{aligned} \quad (1)$$

The motion equation of the rotation can be derived from Euler's equation of the motion.

$$\begin{aligned} J_{xi}\dot{\omega_{xi}} &= -(J_{zi} - J_{yi})\omega_{yi}\omega_{zi} \\ J_{yi}\dot{\omega_{yi}} &= -(J_{xi} - J_{zi})\omega_{xi}\omega_{zi} \\ J_{zi}\dot{\omega_{zi}} &= -(J_{yi} - J_{xi})\omega_{xi}\omega_{yi} \end{aligned}$$

The motion equation of the transition can be derived from Newton's equation of the motion.

$$\begin{aligned} m_1\dot{v_{x1}} &= m_1(-v_{z1}\omega_{y1} + v_{y1}\omega_{z1}) \\ m_1\dot{v_{y1}} &= m_1(v_{z1}\omega_{x1} - v_{x1}\omega_{z1}) \\ m_1\dot{v_{z1}} &= m_1(-v_{y1}\omega_{x1} + v_{x1}\omega_{y1}) \end{aligned}$$

When the motion equation of translation and rotation is made a procession form, it becomes as

$$M\dot{v} = h(v), \quad (2)$$

where,

$$\begin{aligned} M = \mathrm{diag}\,(& J_{x1}, J_{y1}, J_{z1}, J_{x2}, J_{y2}, J_{z2}, \cdots, J_{x5}, J_{y5}, J_{z5}, \\ & m_1, m_1, m_1, m_2, m_2, m_2, \cdots, m_5, m_5, m_5), \end{aligned}$$

and $h(v)$ is made the right side of each motion equation.

B. Motion equation of each link in the fixed system of coordinates

The motion equation in this coordinate system derives the motion equation in the movement coordinate system by using the geometric transformation. The motion equation of each link in the movement coordinate system is derived. Define a generalized velocity q_G as

$$\begin{aligned} q_G = \; & [\phi_1\ \theta_1\ \psi_1\ \phi_2\ \theta_2\ \psi_2\ \cdots\ \phi_5\ \theta_5\ \psi_5 \\ & x_1\ y_1\ z_1\ x_2\ y_2\ z_2\ \cdots\ x_5\ y_5\ z_5]^T . \end{aligned} \quad (3)$$

The anguler velocity for the fixed coordinate system is converted into the anguler velocity for the movement coordinate system. The angular velocity vector of the movement coordinate system is defined as follows.

$$\omega_i = [\omega_{xi}\ \omega_{yi}\ \omega_{zi}] \quad (4)$$

When unit vector is assumed to be e_{xi},e_{yi} and e_{zi}, it becomes as

$$\omega_i = \omega_{xi}e_{xi} + \omega_{yi}e_{yi} + \omega_{zi}e_{zi}. \quad (5)$$

Moreover using $\dot{\phi}_i$, $\dot{\theta}_i$ and $\dot{\psi}_i$, ω_i can be

$$\begin{aligned} \omega_i = & \left(-\dot{\phi}_i \cos\theta_i \sin\psi_i + \dot{\theta}_i \cos\psi_i\right) e_{xi} \\ & + \left(\dot{\phi}_i \sin\theta_i + \dot{\psi}_i\right) e_{yi} \\ & + \left(\dot{\phi}_i \cos\theta_i \cos\psi_i - \dot{\theta}_i \sin\psi_i\right) e_{zi}. \end{aligned} \quad (6)$$

Angular velocity transformation matrix A_{ri} becomes expression (7) from expression (6).

$$A_{ri} = \begin{bmatrix} -\cos\theta_i \sin\psi_i & \cos\psi_i & 0 \\ \sin\theta_i & 0 & 1 \\ \cos\theta_i \cos\psi_i & -\sin\psi_i & 0 \end{bmatrix} \quad (7)$$

The velocity $[\dot{x}_i\ \dot{y}_i\ \dot{z}_i]^T$ of a fixed coordinate system is converted into the velocity $[v_{xi}\ v_{yi}\ v_{zi}]^T$ of the movement coordinate system. It has to rotate the velocity of a fixed coordinate system in order of Z axis X axis Y axis. Velocity transformation matrix A_{di} becomes expression (8).

$$A_{di} = R_{yi}R_{xi}R_{zi} \quad (8)$$

$$R_{zi} = \begin{bmatrix} \cos\phi_i & \sin\phi_i & 0 \\ -\sin\phi_i & \cos\phi_i & 0 \\ 0 & 0 & 1 \end{bmatrix},$$

$$R_{xi} = \begin{bmatrix} 1 & 0 & 0 \\ 0 & \cos\theta_i & \sin\theta_i \\ 0 & -\sin\theta_i & \cos\theta_i \end{bmatrix},$$

$$R_{yi} = \begin{bmatrix} \cos\psi_i & 0 & -\sin\psi_i \\ 0 & 1 & 0 \\ \sin\psi_i & 0 & \cos\psi_i \end{bmatrix}.$$

Transformation matrix A that becoms $v = A\dot{q}_G$ becomes as

$$A = \begin{bmatrix} A_r & 0 \\ 0 & A_d \end{bmatrix}, \quad (9)$$

where,

$$
\begin{aligned}
A_r &= \mathrm{diag}(A_{r1}, A_{r2}, A_{r3}, A_{r4}, A_{r5}), \\
A_d &= \mathrm{diag}(A_{d1}, A_{d2}, A_{d3}, A_{d4}, A_{d5}).
\end{aligned}
$$

Moreover, $h(v)$ of expression (2) is a function of v the movement coordinate system at the generalized velocity.It is necessary to convert $h(v)$ at generalized velocity $\dot{q}_G$ of a fixed coordinate system.

$$
\begin{aligned}
\omega_{xi} &= -\dot{\phi}_i \cos\theta_i \sin\psi_i + \dot{\theta}_i \cos\psi_i \\
\omega_{yi} &= \dot{\phi}_i \sin\theta_i + \dot{\psi}_i \\
\omega_{zi} &= \dot{\phi}_i \cos\theta_i \cos\psi_i - \dot{\theta}_i \sin\psi_i \\
v_{xi} &= \dot{x}_i \left(\cos\phi_i \cos\psi_i - \sin\theta_i \sin\phi_i \sin\psi_i\right) \\
&\quad + \dot{y}_i \left(\cos\psi_i \sin\phi_i + \cos\phi_i \sin\theta_i \sin\psi_i\right) \\
&\quad - \dot{z}_i \cos\theta_i \sin\psi_i \\
v_{yi} &= -\dot{x}_i \cos\theta_i \sin\phi_i + \dot{y}_i \cos\theta_i \cos\phi_i + \dot{z}_i \sin\theta_i \\
v_{zi} &= \dot{x}_i \left(\cos\phi_i \sin\theta_i \sin\phi_i + \cos\phi_i \sin\psi_i\right) \\
&\quad + \dot{y}_i \left(-\cos\phi_i \cos\psi_i \sin\theta_i + \sin\phi_i \sin\psi_i\right) \\
&\quad + \dot{z}_i \cos\theta_i \cos\psi_i
\end{aligned}
\tag{10}
$$

Generalized force h_{G1} of a fixed coordinate system can be derived by substitution expressioin (10) for h(v).

$$
\begin{aligned}
h_{G2} = [&-\tau_{\theta_2}, -\tau_{\psi_2}, -\tau_{\phi_2}, \\
&\tau_{\theta_2} - \tau_{\theta_3}, \tau_{\psi_2} - \tau_{\psi_3}, \tau_{\phi_2} - \tau_{\phi_3}, \\
&\tau_{\theta_3} - \tau_{\theta_4}, \tau_{\psi_3} - \tau_{\psi_4}, \tau_{\phi_3} - \tau_{\phi_4}, \\
&\tau_{\theta_4} - \tau_{\theta_5}, \tau_{\psi_4} - \tau_{\psi_5}, \tau_{\phi_4} - \tau_{\phi_5}, \\
&\tau_{\theta_5}, \tau_{\psi_5}, \tau_{\phi_5}, \\
&0, -m_1 g, 0, \\
&0, -m_2 g, 0, \\
&0, -m_3 g, 0, \\
&0, -m_4 g, 0, \\
&0, -m_5 g, 0]^T
\end{aligned}
\tag{11}
$$

Therefore, the motion equation of each link in a fixed coordinate system becomesas

$$
M_G \ddot{q}_G = h_G, \tag{12}
$$

where,

$$
\begin{aligned}
M_G &= A^T M A, \\
h_G &= A^T (h_{G1} + h_{G2} - M \dot{A} \dot{q}_G).
\end{aligned}
$$

C. Motion equation of each link in the cylindrical coordinate system

The motion equation of the snake-like robot in the state that coils around the cylinder is derived. The motion equation of a fixed coordinate system is converted into the movement coordinate system. Figure.2 shows the cylindrical coordinate system. Define a generalized velocity q_c as

$$
\begin{aligned}
q_c = \;& [\phi_1 \; \theta_1 \; \psi_1 \; \phi_2 \; \theta_2 \; \psi_2 \; \cdots \; \phi_5 \; \theta_5 \; \psi_5 \\
& r_1 \; \xi_1 \; y_1 \; r_2 \; \xi_2 \; y_2 \; \cdots \; r_5 \; \xi_5 \; y_5]^T .
\end{aligned}
\tag{13}
$$

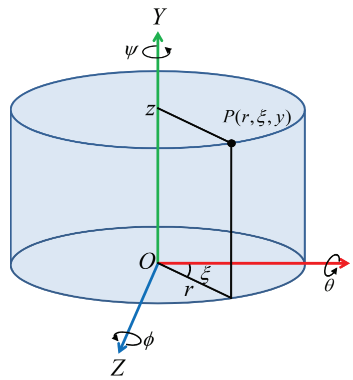

Fig. 2. cylindrical coordinate system

The transformation matrix that converts $[r_i \; \xi_i \; z_i]^T$ of cylindrical coordinate system into $[x_i \; y_i \; z_i]^T$ of a fixed coordinate system is requested.

$$
\begin{bmatrix} x_i \\ y_i \\ z_i \end{bmatrix} = \begin{bmatrix} r_i \cos\xi_i \\ y_i \\ r_i \sin\xi_i \end{bmatrix} \tag{14}
$$

When expression (14) is differentiated at time, it is

$$
\begin{bmatrix} \dot{x}_i \\ \dot{y}_i \\ \dot{z}_i \end{bmatrix} = \begin{bmatrix} \dot{r}_i \cos\xi_i - r_i \dot{\xi}_i \sin\xi_i \\ \dot{y}_i \\ \dot{r}_i \sin\xi_i + r_i \dot{\xi}_i \cos\xi_i \end{bmatrix}. \tag{15}
$$

$$
A_c = \mathrm{diag}(I^{15\times15}, A_{c1}, A_{c2}, A_{c3}, A_{c4}, A_{c5}), \tag{16}
$$

where,

$$
Ac_i = \begin{bmatrix} \cos\xi_i & -r_i \sin\xi_i & 0 \\ 0 & 0 & 1 \\ \sin\xi_i & r_i \cos\xi_i & 0 \end{bmatrix}
$$

. The motion equation of the cyrindrical coordinate system, it becomes as

$$
M_c \ddot{q}_c = h_c, \tag{17}
$$

where,

$$
\begin{aligned}
M_c &= A_c^T M_G A_c, \\
h_c &= A_c^T (h_G - M_G \dot{A}_c \dot{q}_c).
\end{aligned}
$$

D. Deriving of the restraint procession to coil around cylinder

To derive the motion equation in the state that coils around the cylinder, the restraint condition to coil around the cylinder is requested. The restraint condition of this system is that the link is connected, the barycentric position of each link exists on the surface of the cylinder, and the first link touches the cylinder. The condition of connecting each link is derived by using the Euler angle. Where, The barcentric position of the link of ith is

$$
p_i = \begin{bmatrix} x_i \\ y_i \\ z_i \end{bmatrix}. \tag{18}
$$

The barycentric position of the link of $i+1$th becomes expression (19).

$$\begin{aligned}\Phi_{pi} = R_{yi}^T R_{xi}^T R_{zi}^T [d_i, 0, 0]^T \\ + R_{y(i-1)}^T R_{x(i-1)}^T R_{z(i-1)}^T [l_{i-1}, 0, 0]^T \\ + p_{i-1} - p_i = 0\end{aligned} \quad (19)$$

Therefore, the restraint of the position of each link is brought together, it becomes

$$\Phi_{h1} = \begin{bmatrix} \Phi_{p2} \\ \Phi_{p3} \\ \Phi_{p4} \\ \Phi_{p5} \end{bmatrix} = 0. \quad (20)$$

Horonomic constraint matrix C_{h1} becomes

$$C_{h1} = \frac{\partial \Phi_{h1}}{\partial q_G} A_c \quad (21)$$

from expression (20). The condition that the center of gravity of each link exists on the surface of the cylinder becomes

$$\Phi_{h2} = \begin{bmatrix} r_1 - R \\ r_2 - R \\ r_3 - R \\ r_4 - R \\ r_5 - R \end{bmatrix} = 0. \quad (22)$$

Horonomic constraint matrix C_{h2} becomes

$$C_{h2} = \frac{\partial \Phi_{h2}}{\partial q_c} \quad (23)$$

from expression (22). The condition for the first link to touch the cylinder becomes

$$\Phi_{h3} = \psi_1 + \xi_1 = 0. \quad (24)$$

Horonomic constraint matrix C_{h3} becomes

$$C_{h3} = \frac{\partial \Phi_{h3}}{\partial q_c} \quad (25)$$

from expression (24). Therefore, constraint matrix C of the system becomes

$$C = [C_{h1}\ C_{h2}\ C_{h3}]\,. \quad (26)$$

E. Deriving of the orthogonal matrix

It divides into $C = [C_1\ C_2]$ so that constraint matrix C may become it in velocity that can move freely and other order. The orthogonal matrix D that fills CD=0 and $\dot{q_G} = D\dot{q}$, and differentiation $\dot{D}$ is

$$D = \begin{bmatrix} I^{15\times15} \\ -C_2^{-1}C_1 \end{bmatrix}, \quad \dot{D} = \begin{bmatrix} I^{15\times15} \\ -C_2^{-1}\dot{C}D \end{bmatrix}. \quad (27)$$

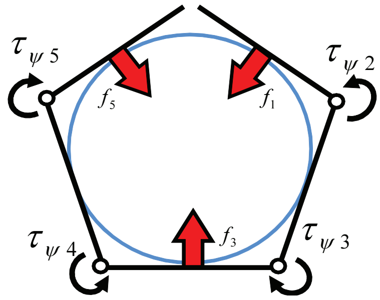

Fig. 3. Force when cylinder is tightened

F. Definition of velocity that can move freely

The degree of freedom of the system in the state that each link is not connected is 30 degree of freedom because 6 degree of freedom a link, and 5 links. As for this system, each link is connected by the horonomic constraint of 18. Therefore, 12 degree of freedom after it is restrained. The velocity that can move freely even after it is restrained is

$$\dot{q} = \left[\dot{\phi}_1\ \dot{\theta}_1\ \dot{\phi}_2\ \dot{\theta}_2\ \dot{\phi}_3\ \dot{\theta}_3\ \dot{\phi}_4\ \dot{\theta}_4\ \dot{\phi}_5\ \dot{\theta}_5\ \dot{\xi}_1\ \dot{y}_1\right]^T. \quad (28)$$

To become the can move freely and other, the generalized velocity $\dot{q}_c$ is permuted. A_c, M_c, and h_c are similarly permuted.

G. Deriving of motion equation after it is restrained

The motion equation after it is restrained can be shown by expression (14) by using Ca.

$$M_c\ddot{q}_c = h_c + C^T\lambda \quad (29)$$

Where, λ is Lagrange multiplier. When $q_c = D\dot{q}$ is substituted for expression (30), the motion equation only of the degree of freedom after it is restrained is obtained.

$$D^T M_c D\ddot{q} + D^T M_c \dot{D}\dot{q} = D^T h_c \quad (30)$$

III. Input Torque Design

The input torque for the robot to squeeze a cylinder is designed based on the derived model. The key point is the model representing the relationship between the actuator torque and the normal force against the cylinder surface was easily derived by Projection Method. Therefore the input torque can be calculated straightforwardly by the model. In this case, the gravity force comes up to $-5mg$ [N] along the Y-axis at each link, and then the necessary friction force should be generated by applying the sufficient normal force to the surface. However, we should pay attention to the fact that, for a set of two links next to each other, applying an input torque to the actuator between the links causes the consequence in that a link is pushed to the surface, but the other is pulled from the surface. Therefore, in case of a 5-link snake-like robot, only the 1st, 3rd and 5th link can generate normal force for necessary friction force. Normal component of reaction f_i needed though a frictional force necessary to deny gravity is caused is

$$f_i < \frac{-5\mu mg}{3} \ (j = 1, 3, 5).$$

TABLE II

EACH PARAMETER LIST IN SIMULATION $(i = 1, 2, \cdots, 5)$

Symbol	Value
J_{zi}	0.02[kg·m^2]
J_{xi}	0.02[kg·m^2]
J_{yi}	0.02[kg·m^2]
m_i	1.0[kg]
l_i	0.5[m]
d_i	0.5[m]
c_i	0.01[Nm·s/rad]
g	9.81[m/s^2]
μ	1.0

Therefore, input torque τ_ψ around Y axis needed to tighten the cylinder is

$$\tau_{\psi_2} = l_1 \frac{m_1 g}{\mu},\ \tau_{\psi_3} = -\tau_{\psi_2},\ \tau_{\psi_4} = l_3 \frac{m_3 g}{\mu},\ \tau_{\psi_5} = -\tau_{\psi_4}. \tag{31}$$

IV. SIMULATION

The designed control system was verified by numerical simulations. The initial posture was given as shown in Fig.4. It showed the robot squeezd a cylinder with 0.5[m] in radius. The simulations were performed by MaTX (Visual C++ 2005 Ver. 5.3.37) [6], and the used solver for ordinary differential equations was the Runge-Kutta method with the sampling interval, 0.01 [s]. The simulation results are shown in Fig.9. The figure shows the normal forces at the 1st, 3rd and 5th link were generated according to the proposed method. As the consequence, the robot kept itself squeezing the cylinder without falling off.

The input torque was generated 1 second the start of the simulation later as shown in Fig.5. Even if force is added because neither distance r_i nor attitude angle ψ_i from the center of the circle of each link have changed from Fig.6 and Fig.7, the state that always coils around the cylinder can be kept. When gravity balances the frictional force from Fig.8, it is possible to stay in the height at that time. Moreover, Fig.9 shows that the normal component of reaction of the 1st, 3rd, and 5th link was generated by the proposed method. Therefore, it was possible to stay without being able to obtain an enough frictional force, and slipping down in the cylinder.

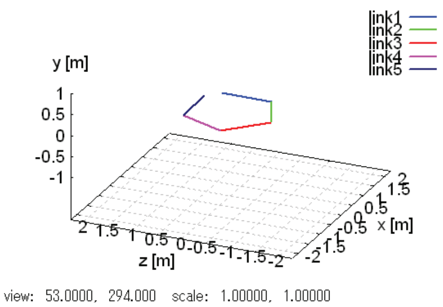

Fig. 4. Initial posture

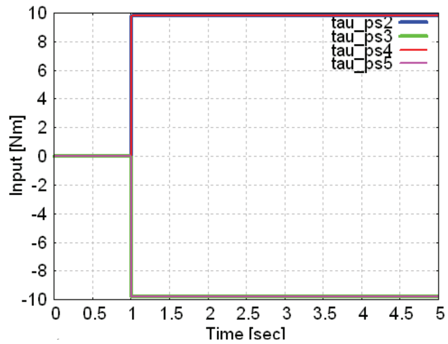

Fig. 5. Input torque

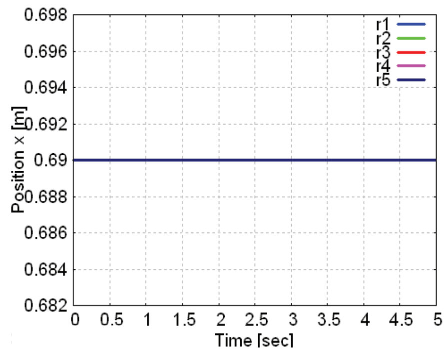

Fig. 6. Barycentric position of each link

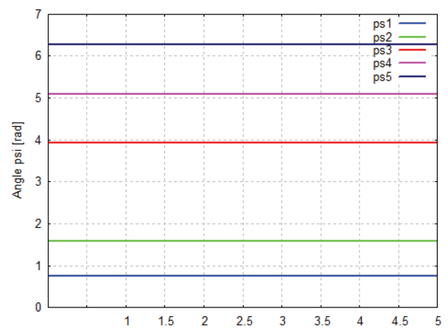

Fig. 7. Attitude angle of each link

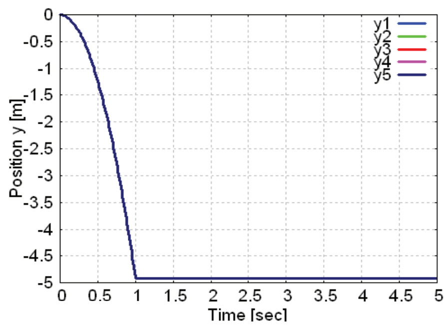

Fig. 8. Height of center of gravity of each link

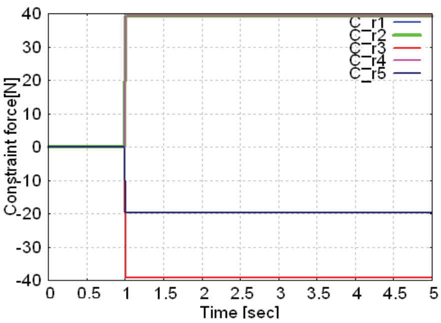

Fig. 9. Constraint force in the vertical direction against the cylinder

The input torque was generated 1 second the start of the simulation later as shown in Fig.5. Even if force is added because neither distance r_i nor attitude angle ψ_i from the center of the circle of each link have changed from Fig.6 and Fig.7, the state that always coils around the cylinder can be kept. When gravity balances the frictional force from Fig.8, it is possible to stay in the height at that time. Moreover, Fig.9 shows that the normal component of reaction of the 1st, 3rd, and 5th link was generated by the proposed method. Therefore, it was possible to stay without being able to obtain an enough frictional force, and slipping down in the cylinder.

V. Conclusion

The equations of motion of the 5-link snake-like robot were derived by Projection Method. In the process, the relationship between the actuators of the robot squeezing a cylinder and the normal force against the cylinder surface was modeled. These models allowed us to calculate the input torque to generate necessary friction force corresponding to the normal force for keeping the robot squeezing the tree. The effectiveness of the calculated input torque was verified by numerical simulations. As a next work, we will try to realize driving force as the robot was squeezing the cylinder.

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