Brachiation motion by a 2-DOF brachiating robot with hook-shaped end effectors

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Abstract
In this research I focus on mobile robots that move to target location, and I developed a new brachiating robot with a simple mechanism. The robot uses a hook-shaped end effector for sustaining the robot itself to avoid the falling. I proposed a motion principle and a control strategy to perform brachiation motion. In particular, I suggested a simple motion planning method based on the motion principle (pendulum motion) of a rigid body. Then, I realized the brachiation motion by using the developed brachiating robot and the proposed motion strategy in downward and upward slopes’ situations.

Keywords: Brachiation, High-speed actuator, Motion planning

1. Introduction

Recently, researches about mobile robots, such as biped robots, multi legged robots, drones and crawlers, have been actively studied. According to the mobile robots, the motion planning methods have been also proposed.

In this research, I focus on “brachiation motion” as a locomotive technique, and I develop a new simple brachiating robot. Also, I propose a simple method for the brachiating robot. The brachiation motion is what apes use to swing from tree to tree by using pendulum motion. There have been some researches of brachiating robots and brachiation motion. Fukuda et al. developed a brachiation robot (Brachiator) that mimics a gibbon and realized brachiation motion using their robot and proposed method (Fukuda et al.). Saito et al. achieved brachiation motion with heuristic control on a two-link brachiation robot (Saito et al., 1994), and Nakanishi et al. suggested a brachiating robot controller for this two-link brachiation robot (Nakanishi et al., 2000). Gomes et al. performed the analysis of a five-link 2D brachiating ape model with life-like zero-energy-cost motions (Gomes et al., 2005). Rosa et al. proposed a stable open-loop brachiation robot (gibbot) moving on a vertical wall (Rosa et al., 2012). Moreover, some studies have analyzed brachiation motion from the viewpoint of control engineering (Menezes de Oliveira and Lages, 2009) (Ebrahimi and Namver, 2016).

As discussed above, in order to realize brachiation motion using the high-speed motion and control capabilities of the robot, I developed a new simple 2-DOF (degree of freedom) brachiating robot and proposed a motion planning method using the developed robot (Yamakawa et al., 2016). In the previous researches, complex models of the robot for the brachiation motion were analyzed, and control laws based on model analysis for brachiation robots were also proposed. The feature of this research is that the brachiation motion with the high-speed motion can be achieved via only a basic principle (pendulum motion) and the desired posture of the robot using a simple mechanism. In addition, the brachiation motion in environment of upward slope can be realized using the proposed method, which is considered to be extremely difficult to achieve this by the conventional robots.

The advantages of the proposed method include;
(1) simple mechanism,
(2) ease motion and control strategies (geometric calculation for reference joint angle and PD control for joint angle), and...
(3) achievement of brachiation motion in upward slope situation.

The rest of this paper is organized as follows: The next section (Section 2) explains the brachiating robot system I developed in this research. Then I present a strategy for achieving brachiation motion and I show simulation results with various conditions (Section 3). After that I show experimental results of the brachiation motion using the developed robot system (Section 4). In particular, I show the experimental result of the brachiation motion in the situation of upward slope, as a difference from the previous works. Finally, I summarize the conclusion obtained in this research and outline my plans for the future work (Section 5).

2. Brachiating robot system

I explain a new simple brachiating robot with 2-DOF (Fig. 1). Next I describe the overall system, including the control system and the experimental environment. Moreover I present the features of the developed brachiating robot.

2.1. Development of a New Simple Brachiating Robot

I developed a brachiating robot with 2-DOF as shown in Fig. 1. Although brachiation motion can be performed with a 1-DOF robot by controlling the relative angle between the two links, I adopted the 2-DOF robot in order to perform high-speed motion by controlling each link and to control and keep a posture of the brachiating robot. Moreover, in order to execute high-speed motion, I used the small, high-power servo motors that were used in the high-speed robot hand (Namiki et al., 2003).

The developed brachiating robot consists of

- two small, high-power servo motors including harmonic drive ® and encoder (servo motor: RSF-5B produced by Harmonic Drive Systems Inc., reduction gear rate: 50, maximum angular velocity: 180 °/0.1 s and maximum torque: 0.9 Nm),
- two hook-shaped end effectors, and
- two links between motor and hook-shaped end effector.

The distance between the end effectors is 0.07 m, and the distance between the output axis of the motor and the end...

Fig. 1 Brachiating robot consisting of two high-speed motors, two hook-shaped end effectors and two links.

Fig. 2 Whole system; (a) shows experimental set-up including 2-DOF robot, experimental environment, controller and host PC for monitoring and operating controller, and (b) shows control flow from motion generation to joint angle control of robot.
2.2. Whole system

The whole system including the control system are illustrated in Fig. 2(a) and (b), respectively.

Input (joint angle)–Output (power signal) control, motion generation, and a control scheme (Proportional-Derivative (PD) control for reference joint angle) are carried out in the real time controller. The actuated torque of the servo motor is generated in accordance with these calculations. Each servo motor is actuated through a motor driver.

2.3. Features of brachiating robot system

The main feature of the developed brachiating robot is its high-speed motion capability (180°/0.1 s), and the robot also possesses high tracking performance to the given trajectory of the joint angles using the high-speed motion. Thus, I do not need to consider the dynamics of the robot, including the motors; instead, I consider only the posture and the reference joint angles of the robot, based on the angles of the motors. The brachiation motion can be considered to be a periodic motion. If the robot can be moved to the reference state faster than the period, it can be considered that only the geometric calculation of the reference state based on the robot structure and an environment is needed. This point is considered to be the originality of this research.

3. Strategy for brachiation motion

This section presents a strategy for achieving brachiation motion using the developed robot. First, I describe the motion principle (pendulum motion) of the brachiation motion. Second, I explain a basic motion from the viewpoint of the posture of the robot. Third, I propose a trajectory generation method for performing the brachiation motion based on the results of the pendulum motion and the posture during motion.

In this strategy, I assume that the friction between the hook and the bar is neglected, and the rolling motion in a frontal plane is also neglected by the flat shape of the hook in the width direction.

The research concept is the simple robot mechanism and the simple method. In particular, the simple motion method is the originality of this research, based on the simple and high-speed robot. If the robot moves to the reference joint angle faster than the period of the brachiation motion, I think that the problem of the brachiation motion strategy can be boiled down to the question of the geometric constraint condition of the reference state.

3.1. Motion principle

The motion principle of the brachiation motion is pendulum motion as shown in Fig. 3 and Fig. 4. In order to hook the end effector of the robot to the bar, I should determine an appropriate timing for such an action. Thus, I determine the timing based on the period, $T$, of the pendulum of the rigid body. Based on classical mechanics, the period, $T$, can be obtained by

$$T = 2\pi \sqrt{\frac{I}{Mgd}},$$

where $M (= 0.33 \text{ kg})$ is the mass of the brachiating robot, $d (= 0.135 \text{ m})$ is the distance from the rotation axis of the motor in the brachiating robot to the tip position, $g (= 9.8 \text{ m/s}^2)$ is gravitational acceleration, and $I (= \frac{4}{3}Md^2 \text{ kgm}^2)$ is the inertial moment of the brachiating robot. In the developed brachiating robot, the period $T$ is equal to about 0.6 s. However, the period varies depending on the posture of the robot. This reason is that the position of the center of gravity about the robot and the distance $d$ can change depending the posture of the robot. The variation of the period $T$ is considered to be about 10%.

Although the basis of the brachiation motion is, in essence, pendulum motion, it is considered that the previous papers do not fully utilize the characteristics of pendulum motion. The reason is that the motion angle of the arm was small. In my approach, on the other hand, the motion angle is as large as possible, and the proposed brachiation method is discussed based on this.

3.2. Basic motion

Here, I describe a basic motion of the robot for achieving continuous brachiation. In particular, I discuss the posture of the robot and the joint angles of each link.
I propose a motion strategy for the brachiating robot and a locomotive method using basic pendulum motion, as shown in Fig. 5. In the preparation state described in Section 3.2.3, both end effectors of the robot are hooked to the bars. Also I define the forward link and end effector as “arm_f”, and the backward link and end effector as “arm_b”, with respect to the motion direction.

The concrete procedure of the brachiation motion is divided into four phases as follows (Fig. 5):

1. The backward end effector in arm_b is unhooked.
   → The motor of the backward link is rotated so as to increase the angle between both links.

2. The link (arm_b) that is unhooked from the bar is actuated counter-clockwise, and the other link (arm_f) is not actuated.
   → The joint angle of the link (arm_b) is controlled so that the link position becomes the lowest when the center of gravity of the robot is located at almost the lowest position.

3. The link (arm_b) is swung up.
   → In order to avoid a collision between the robot and the bar and to overcome the height of the bar, the link (arm_b) is rotated and the rotation angle is determined by trial-and-error.

4. The end effector on the link (arm_b) is hooked on the bar (the descriptions of the links are changed: arm_b → arm_f, arm_f → arm_b).
   → The link (arm_b) is rotated so as to hook on the bar.

By repeating these motions, continuous brachiation motion can be realized with the developed robot system.

The reference joint angles of the brachiating robot at the start time and the end time for one brachiating robot are significantly important. The brachiation motion can be performed by translating these joint angles. The details are explained below.

3.2.1. Constraint condition for continuous brachiation motion

In order to perform continuous brachiation motion with the developed robot, it is desirable that the robot posture be controlled so as to keep the same posture in the steady state (namely, the end time of one brachiation motion). Thus, the following constraint condition can be obtained:

\[ \phi(0) = \phi(1) = \phi(2) = \cdots = \phi(i) = \cdots = \phi(N) = \phi_0, \]

where \( i \) in the bracket is an index of the brachiation action performed by the robot, and the angle \( \phi(i) \) is the angle between
the arm_f and the arm_b. This constraint condition means that the angles \( \phi(i) \) at the start time and the end time of the brachiation motion are kept the same at the value \( \phi_0 \) in the condition of the preparation state in Section 3.2.3. Namely, the same posture of the brachiating robot in the steady state can be achieved by this condition. The angle \( \phi_0 \) can be calculated by the distance between bars, as defined by \( L \), and the link length \( d \).

Next, I consider the detail of the brachiation motions based on the constraint condition, as shown in Fig. 7. By holding the condition during the brachiation motion, continuous brachiation motion can be performed.

### 3.2.2. Initial Condition
In the initial condition, the links are set at the horizontal direction (Fig. 6), and the initial joint angles of both motors are also defined by \( \theta_f(0) = 0 \) and \( \theta_b(0) = 0 \).

### 3.2.3. Preparation State
Let us consider a preparation state in Fig. 7(a). Preparation state is that the robot is hanged holding the condition during the brachiation motion, continuous brachiation motion can be performed.

The reference joint angles in the arm_f and the arm_b (\( \theta_f(0) \) and \( \theta_b(0) \)) are relative angles of the initial position are given by

\[
\theta_f(0) = \frac{\pi - \phi_0}{2}, \quad \theta_b(0) = \frac{-\pi + \phi_0}{2},
\]

where the number in the bracket is the index of the brachiation action performed by the robot.

### 3.2.4. First brachiation motion
Let us consider a transition phase from the state in Fig. 7(a) to the state in Fig. 7(b). The reference joint angles of the arm_f and the arm_b (\( \theta_f(1) \) and \( \theta_b(1) \)) in Fig. 7(b) are given by

\[
\theta_f(1) = \phi_0 - \theta_b + \theta_f(0), \quad \theta_b(1) = 2\pi - \phi_0 - \theta_f + \theta_b(0),
\]

where \( \theta_f \) is the angle of the posture change in the pendulum motion.

### 3.2.5. Second brachiation motion
Next, let us consider a transition phase from the state in Fig. 7(b) to the state in Fig. 7(a).

The reference joint angles of the arm_f and the arm_b (\( \theta_f(2) \) and \( \theta_b(2) \)) in Fig. 7(a) are also described by

\[
\theta_f(2) = \theta_f(1) + \theta_b(1), \quad \theta_b(2) = \theta_f(1) + \theta_b(1).
\]

From this result, assuming that two brachiation motions constitute one period, the reference joint angles of two joints in each arm are the same every second brachiation motion.

### 3.2.6. \( i \)-th brachiation motion
Next, let us consider a transition phase for \( i \)-th brachiation motion.

If the count of the brachiation motion is the odd number, the reference joint angles of the arm_f and the arm_b (\( \theta_f(i) \) and \( \theta_b(i) \)) in Fig. 7(b) are written by

\[
\theta_f(i) = \theta_f(i-1) + \theta_f(1), \quad \theta_b(i) = \theta_b(i-1) + \theta_b(1) \quad (i = 3, 5, \cdots).
\]

Moreover, if the count of the brachiation motion is the even number, the reference joint angles of the arm_f and the arm_b (\( \theta_f(i) \) and \( \theta_b(i) \)) in Fig. 7(a) are also given by

\[
\theta_f(i) = \theta_f(i-2) + \theta_f(2), \quad \theta_b(i) = \theta_b(i-2) + \theta_b(2) \quad (i = 4, 6, \cdots).
\]

Updating the reference joint angles according to the count of the brachiation motion, the joint angles can be obtained.

### 3.2.7. Translational motion
Using the reference joint angles described above, the transition motion (motor position and positions of both tips) can be calculated. The motor position (\( X_g \)) can be derived in the followings:

\[
X_g(i) = \left( \begin{array}{c} x_g(i) \\ y_g(i) \end{array} \right) = \begin{pmatrix} 2d \sin \frac{\phi_0}{2} \cos \psi \\ -2d \sin \frac{\phi_0}{2} \sin \psi \end{pmatrix} \times i \quad (i = 0, 1, 2, \cdots)
\]
where $\psi$ is the angle of the slope in the experimental set-up and $i$ is the index of the brachiation action performed by the robot. The positions ($X_f$ and $X_b$ for arm$_f$ and arm$_b$, respectively) of both tips in the $i$-th brachiation motion can be also given by

$$X_f(i) = \left( \begin{array}{c} x_f(i) \\ y_f(i) \end{array} \right) = X_g(i) + R \left( \begin{array}{c} d \cos(\theta_f(i)) \\ d \sin(\theta_f(i)) \end{array} \right), \quad X_b(i) = \left( \begin{array}{c} x_b(i) \\ y_b(i) \end{array} \right) = X_g(i) + R \left( \begin{array}{c} d \cos(\theta_b(i)) \\ d \sin(\theta_b(i)) \end{array} \right)$$

where the rotation matrix $R$ is expressed as

$$R = \left( \begin{array}{cc} \cos \psi & -\sin \psi \\ \sin \psi & \cos \psi \end{array} \right).$$

### 3.2.8. Simulation result

Here, I show the simulation results of the posture control and the transition motion proposed above. In this simulation, the angles ($\phi_0$) between the two links and the angles ($\theta_B$) used to change the posture via the pendulum motion are set as follows;

$$\phi_0 = 90, 120, \text{ and } 150 \text{ deg.}, \quad \theta_B = 70, 100, \text{ and } 130 \text{ deg.}.$$  \hfill (11)

Fig. 8 shows the simulation results calculated by using Eqns. (3)–(10). In this simulation, the angle of the downward slope of the bars is set at 18 degrees. In Fig. 8(a), (b) and (c), the angle ($\theta_B$) is fixed and the angle ($\phi_0$) is varied, and in Fig. 8(d), (e) and (f), the angle ($\theta_B$) is varied and the angle ($\phi_0$) is fixed. Moreover, in Fig. 8, the yellow, blue, green and pink zones depict 1st, 2nd, 3rd and 4th brachiation motion. From these results, I can obtain the same postures at the start time and the end time of the motion using the proposed method. Also, I can confirm that the distance of the one-step brachiation motion is the same. As a result, the effectiveness of the proposed method for the posture control can be confirmed through simulations.

In unknown environment or dynamic situation, if the angles ($\phi_0$ and $\theta_B$) can be measured by a high-speed vision with a high-speed image processing, the reference joint angles of the motors can be calculated by Eqns.(3)–(7). Thus the brachiating robot system and the proposed method can be applied to various situations by introducing the high-speed vision system. Experimental validation using the vision system is the future work.

### 3.3. Trajectory Generation

This section explains the detail of the phase 3) to swing over the bar, the trajectory of time series about the reference joint angle, and the joint angle control.
3.3.1. Motion scheme in phase 3) If $\theta_b(t)$ obtained by Eqns.(2)–(7) is used in phase 3), a distance between the tips cannot become less than the distance between the bars, and the tips cannot swing over the next bar and the arm $b$ will contact with the next bar. Therefore the reference joint angle in phase 3) should be corrected as follows:

1. A virtual length $l$ ($< L$ (the actual length between two bars)) is set.
2. The angle ($\phi_b$) between two links is calculated for the virtual length $l$.
3. A difference ($\Delta \theta = \phi_0 - \phi_b$) is obtained.
4. The difference ($\Delta \theta$) is added to $\theta_b(i)$.

The virtual length $l$ can be obtained based on the actual length $L$, the bar radius and the diameter of the hook.

3.3.2. Trajectory of reference joint angle and joint angle control The reference joint angles at the motion end time in each phase are obtained based on Eqns.(3)–(7) and the experimental environment such as the distance and the height difference between the two bars. The reference joint angle trajectories from the start time to the end time in each phase are given by a linear function of time.

The motion time for phase 3) can be given by the period $T$ (Eqn.(1)) of the pendulum motion of the brachiating robot, namely this motion time was set at $T/2$. Also, the motion for phase 2) is always performed during this motion time.

The motion times for phase 1) and phase 2) are obtained by trial-and-error. The joint angle control for arm $b$ is carried out only in phase 4), because this joint angle control does not affect the brachiation motion and the change of the joint angle is small.

Each joint angle of the robot is controlled by a simple PD (Proportional–Derivative) law as follows;

$$\tau(t) = k_p(q_{ref}(t) - q(t)) + k_d(q_{ref}(t) - \dot{q}(t))$$

where $\tau$ is the torque of the motor, $t$ is the time, $k_p$ is the proportional gain, $k_d$ is the differential gain, $q_{ref}$ is the reference joint angle ($\theta_f(i)$ or $\theta_b(i)$) given by Eqns.(3)–(7), and $q$ is the actual joint angle measured by the encoder of the motor. The control rate was set at 1 kHz.

Fig. 9 shows the trajectory of each joint of the brachiating robot, which is used in the experiment described in the next section. Originally, the joint angles ($\theta_f(0)$ and $\theta_b(0)$) in the preparation state are given by Eqn.(3), but in this figure the joint angles were corrected to 0 and indicated. Note that since one rotation axis is opposite to the other axis in the actual robot, the rotation direction in one axis is also opposite. Thus, the rotation angle of the axis takes a negative value in the simulation. Fig. 9(a) and (b) show the angles of joint-1 and joint-2, where joint-1 and joint-2 mean those of arm $f$ and arm $b$ at the preparation state, respectively. In this figure, the yellow, green, and blue zones describe the first brachiation motion, the stop state, and the second brachiation motion, respectively. Moreover, the brachiation motion is divided into four phases described in Section III. The timing of the phase transition of the four phases is shown in the gray dotted line in Fig. 9. Phase 2) and phase 3) are executed during the same motion state. In addition, the reference joint angles and the actual joint angles are plotted by the blue lines and the red lines, respectively. The actual joint angles are the result obtained in the experiments of the brachiation motion, described in the next section. A stop time between ($i - 1$)-th and $i$-th brachiation motions was set at 0.2 s.

4. Experiment

This section shows experimental results of the brachiation motion realized with the developed brachiating robot system and the proposed simple motion method in the experimental environment. Videos of the experimental results can be also seen on the web site (Yamakawa Laboratory).

4.1. Common experimental set-up

In the experimental set-up, the bars, which are hooked by the end effectors of the robot, had diameters of 0.03 m and lengths of 0.3 m, and the brachiating robot moved from one bar to another. The distance between the bars $L$ was set at 0.22 m based on the link length of the brachiating robot. The angle ($\phi_b$) between the two links and the angle ($\theta_b$) used to change the posture via the pendulum motion are set at 120 and 100 degrees, respectively. A stop time between ($i-1$)-th and $i$-th brachiation motions was set at 0.2 s.

4.2. Experimental result in situation of downward slope

Fig. 10 shows continuous photographs of the experimental result (Yamakawa et al., 2016). The angle of the downward slope of the bars was set at about 18 degrees in this experiment. It can be confirmed that brachiation motion using
4.4. Discussion

As shown in Fig. 10 and Fig. 12, although two kinds of brachiation motions (downward and upward slopes) could be achieved successfully, three or more times continuous and successive brachiation motions could not be executed in the experiments. The reason for this is that the motion timing of each phase was not appropriate for the actual motion. However, this problem can be solved by an implementation of a real-time visual feedback using a high-speed vision and high-speed image processing technique. An introduction of the real-time visual feedback control is the future work.

Another possible reason for the limited number of brachiation motions is that the cables for the encoders and supplying power were twisted around the robot, restricting the brachiation motion of the robot and making appropriate robot
control impossible.

It is considered for the realization of the brachiation motion that although there is no limitation of downward slope angle in the environment, there is a limitation of upward slope angle (about 5 degrees) due to the gravity effect. Also, the high-speed motion, for example $180^\circ / 0.1$ s, faster than the period of the brachiation motion is required as a hardware specification.

5. Conclusions

The purpose of this study was to develop a new simple 2-DOF brachiating robot, to propose a simple strategy for brachiation motion using the robot, and to realize the brachiation motion in the situations with downward and upward slopes.

Firstly I developed a new simple brachiating robot consisting of small, high-power servo motors, two hook-shaped end effectors for sustaining the robot itself, and two links between the motor and the end effector.

Secondly I proposed a motion principle with the pendulum motion of a rigid body, and I explained the detailed motion strategy in each phase of the brachiation motion. Reference joint angle based on the robot posture during the brachiation motion was also suggested, and the calculation of the translational motion was described. Then, the effectiveness of the posture control and the translational motion were confirmed by a kinematics simulations through various conditions.

Finally I successfully achieved the brachiation motion by using the developed robot and the proposed motion method in both situations of the downward and upward slopes. In particular, the realization of the brachiation motion in the situation of the upward slope is considered to be a new and excellent achievement in the brachiation motion.

As the future works, I will introduce real time trajectory correction using a high-speed visual feedback system to improve the success rate, to reduce needless motion, and to correspond various experimental situations. Moreover, I will re-design the brachiating robot mechanism, for example a suitable shape of the end effector. Consequently, I will realize continuous and smooth brachiation motion using the brachiating robot and the proposed method.

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