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Underactuated control of a bionic-ape robot based on the energy pumping method and big damping condition turn-back angle feedback

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HIGHLIGHTS

- A big damping turn-back feedback control method for a brachiation robot is proposed.
- The motion planning of the robot is inspired by the motion of gibbons and humans.
- Based on Lyapunov stability theory, a swing-up control law is designed.
- Position–orientation control is adopted to achieve fast and precise grasping motion.
- The simulations validate the universality and reliability of the proposed method.

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ABSTRACT

This paper studies a reliable control strategy for a bionic-ape brachiation robot with dual-arm hands, a four-link brachiate mechanism, which swings and grasps branches like a gibbon. Based on the analysis of the brachiation of gibbons and humans, the big damping nonholonomic constraints model is introduced. A control strategy which combines the energy pumping control with the big damping turn-back angle feedback control is proposed. The grasping motion was divided into several processes: the swing-up self-starting phase, the energy rising phase, the transition phase and the grasping phase. A self-starting controller is designed for swing-up motion from a downward stable position. In the energy rising phase, an energy pumping control law is deduced based on Lyapunov stability theory, and the singularity and convergence of the system are analyzed. The system energy is calculated periodically to determine if the robot gets enough energy for grasping, so that it could shift into the transition phase. A position–orientation control method is adopted to realize that the gripper grasps target bars in the desired position, orientation and speed. By means of ADAMS-MATLAB co-simulation, the bionic-ape robot achieves smooth swing-grasp motions under different heights and horizontal distances. The simulation results indicate that this method has advantages of universality and reliability in a grasping target bar. Therefore, the effectiveness of the proposed control strategy is validated.

1. Introduction

In bionic robotics research, primates' motion has attracted much attention of scholars. This paper introduces a bionic-ape robot with dual-arm hands (BARDAH) which can imitate the locomotion action of primates. It moves forward by alternating swinging arms and grasping branches.

Many scholars have studied bionic brachiation action and built bionic-ape robots. Most researchers [1,2] describe bionic brachiation as a pendulum-like motion. To simulate such motion, many brachiation robots [3–7] are designed as two-link underactuated mechanisms. Due to the underactuated and nonlinear properties of the robot, the major challenge is how to generate the desired trajectories for driving inputs feasibly and precisely. Saito et al. [3] first attempted to use heuristic methods on BMR (brachiation mobile robot); Hasegawa et al. [4] used a self-scaling reinforcement learning algorithm to generate fuzzy motion controller; Nakanishi et al. [5] proposed a strategy of 'target dynamics', which forces the robot to mimic a harmonic oscillator; Meghdari et al. [6] optimized the robot motion trajectory by making use of Pontryagin's minimum principle, and designed an adaptive robust controller to realize the actual control of the robot; Oliveira et al. [7] presented the application of the nonlinear model-based predictive control

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on the motion of a 3-link brachiation robot; To realize dexterous behaviors in brachiation, the Fukuda research team developed a 13-link brachiation robot and a 25-link brachiation robot named Brachiator III and Gorilla Robot III respectively; Hasegawa et al. [8] proposed a behavior-based hierarchical behavior controller for Brachiator III, which can efficiently handle nonlinear problems of multiple inputs and multiple outputs. However, it needs practice runs of tests and parameter adjustments accordingly. Fukuda et al. [9] introduced a stereo vision system to achieve reduced deviation of the grasping position; Kajima et al. [10] added energy control into the swing action controller to satisfy the desired energy requirements, as evaluated according to the distance between bars; Pchelkin et al. [11] presented numerical search algorithms to generate trajectories of Gorilla Robot III using energy optimization. All of the above forms of brachiation are continuous contact brachiation. Wan et al. [12] studied the non-horizontal ricochetal brachiation motion planning and control problems for a two-link bio-primate robot.

At the beginning of locomotion, the technical issue arises of how to swing up from the balance position for bionic-ape robot. It is noteworthy that the structure and dynamic properties of the bionic-ape robot are similar to that of Acrobot, a two-link gymnastics robot, thus the latter can serve as a point of reference. Spong [13] proposed a partial feedback linearization method and designed an energy pumping swing up control algorithm, which is the most widely used in Acrobot; Xinxin [14] designed an energy-based swing-up controller to realize the actual control of the robot. There are further swing-up methods such as the trajectory tracking strategy [15], sliding-mode tracking control [16], reinforcement learning method [17], the energy-optimal trajectory planning method [18], and so on. Varieties of control methods that were used on Acrobot have provided inspiration for the bionic-ape robot, but their direct application is infeasible, since the swing amplitude and configuration control of bio-ape robot needs further consideration.

These studies focused on the motion control of bionic brachiation robots under ideal conditions. Some of these theories were tested with physical robots. As a matter of fact, bionic brachiation is underactuated, strongly nonlinear and with poor anti-disturbance. It is hard to control the swing amplitude and the grasping time simultaneously during experiments with real brachiation robot's. Consequently, most of the previous bionic brachiation robots have shown poor capability:

- Many bionic brachiation robots share the problem of robustness. Some actual physical robots can only achieve brachiation under an horizontal irregular ladder. Most control strategies of previous studies have not always had success in being able to catch the bars in one swing.
- The size of the grippers are too large compared with the target bars. As a result, the robots are more likely to "hook" not "grasp" the target bar.
- In the literature [19], the energy pumping method was used to swing up the robot. This method has two drawbacks: One is that the active joint cannot track the time-variant reference trajectory, leaving a great tracking error; the other is that the robot is unable to swing-up from a downward static state. It needs a disturbance to activate the swing-up motion.

In our previous work [20], we proposed a big damping underactuated control strategy. The concept is to brake the robot during the grasping phase so that the brachiation robot has more time available for target bar grasping. We used parametric excitation in the swing-up control and turn-back angle feedback control in the big damping situation. The simulation showed that the robot could grasp the target bar successfully. But if the distance between the

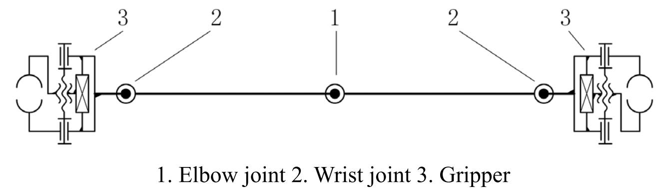

Fig. 1. Mechanism diagram of BARDAH.

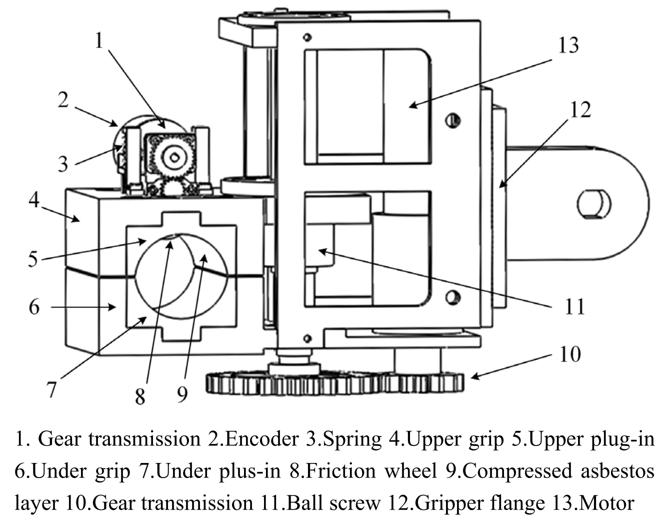

Fig. 2. Structure diagram of the gripper.

bars changes, the swing-up parameters need to be tuned manually again.

In this paper, the BARDAH is introduced in Section 2. In Section 3, the brachiations of humans and gibbons are observed and analyzed according to the bionic principle. Based on them, **the big damping underactuated control** is introduced [20]. In Section 4, the dynamic of the BARDAH is introduced briefly. In Section 5, based on the Lyapunov stability theory, we **improve the energy pumping method**. The new method reduces tracking error and realizes a robot self-starting from a static balance position. The singularity and convergence of the control law are discussed. During the grasping phase, a **position–orientation control method** is adopted to ensure the robot is able to grasp the target bars reliably. In Section 6, we carried out serial simulations of the bionic-ape robot. The result shows the proposed method has advantages of **universality and reliability** in grasping the target bars at different heights and distances.

2. The Bionic-ape robot with dual-arm hands

A mechanism sketch of BARDAH is shown in Fig. 1. The two arms of the robot are designed symmetrically and are connected by an elbow joint. Each arm includes a gripper and a wrist joint.

The gripper's structure is shown in Fig. 2. The structure of the paw is a linear-driving mechanism. To gain great clamping force and precise positioning, the ball-screw mechanism and the planetary gearhead is used on the driving of paw. The inner surface of the gripper is covered with damping material which can offer great friction.

The rotational displacement of the gripper relative to the bar is measured by a friction wheel mechanism within the gripper, as shown in Fig. 3. The mechanism is installed on a hole of the gripper. It is pressed tightly by springs. When the gripper rotates