Transactions on Engineering and Technology Research
ISSN: 2960-1797, eISSN: 2960-2246 | Volume 1
AMMEE 2023

Research on Bionic Climbing Robot Based on Gait Analysis

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Abstract: In order to replace humans performing hazardous tasks in complex high-altitude environments, we have designed a two-armed modular bionic robot with clawing, climbing and mobility capabilities for high-altitude tasks in agriculture, forestry and construction. In this paper, a five-degree-of-freedom climbing modular robot with the ability to maneuver between poles in space is presented and analyzed. Three types of climbing gaits is designed and compared in the ADAMS simulation environment based on the torques required by the main joints and the energy consumed by the robot to climb the poles in different directions. The simulation results are the basis for planning the gait of the robot during climbing.

Keywords: gait analysis; bionic; climbing; robotics.

1. Introduction

Field robots are widely used in agriculture, forestry, and construction to assist with tasks like picking fruit from trees, cutting branches and leaves, painting, and repairing steel frames of bridges etc. Tasks in these fields have the following in common: 1) the work area is high above the ground; 2) the work environment is complex, harsh and risky; and 3) the workload is heavy, time-consuming and monotonous. Due to these characteristics, it is particularly important to develop robots capable of climbing to replace humans in performing dangerous tasks at high altitudes. Current research on climbing robots includes, but are not limited to: Recently, this has been recognized both domestically and internationally, and research on climbing robots has begun and several prototypes have been developed. In Japan, a tree-climbing robot was developed at Waseda University, and its prototype, WOODY-1, was exhibited at the 2005 Aichi International Exhibition. In Spain, a CPR tree-climbing robot was developed based on a parallel robot consisting of two identical wheels, both of which move up and down the trunk of a tree, with one wheel gripping the trunk tightly and the other controlled by a linkage, so that the whole system can move continuously and alternately and can be used for a variety of purposes. This prototype robot has six legs and can crawl along a tree trunk like a cockroach. The Massachusetts Institute of Technology (MIT) has developed the Shady3D robot, which can ride on a windowsill and move around. Harbin Institute of Technology (HIT) has developed a robot that can crawl along decks to inspect and maintain infrastructure such as bridges, stadiums and towers.

Overall, the current prototype has in principle achieved a certain degree of climbing ability, but there are still some shortcomings: (1) It has a single climbing target, and can only climb columns, trusses or trees, making it difficult to climb other targets. (2) Due to the limitation of its unique design, it lacks the ability to climb transitions between poles, making it difficult to adapt to complex environments; (3) It lacks a control function, requiring the installation of additional controllers or robotic arms during operation. In this paper, inspired by the principles of tree climbing by geometric monkeys, apes and sloths, a 5-DOF modular climbing robot is proposed. The robot consists of three pivot joints, two rotary joints and two end effectors ;. The robot is characterized by (1) a powerful climbing function that allows it to climb various objects such as poles, trusses, and trees, and to move between two poles in space; (2) sufficient degrees of freedom for climbing with different types of gaits; and (3) the robot itself is a functioning actuator arm without the need to install any other actuators. Using modular design methods, the robot can have low R&D costs and high structural and functional scalability.Guan et al. have studied modular robots and developed a variety of modular robots, such as articulated modules, pivoted articulated modules, a set of independent and complete robotic joints, and single-degree-of-freedom main functional modules, such as a gripper module.A variety of modules were designed and fabricated, and various robotic systems have been assembled using these modules to assemble various robot systems. These modules are used to configure different robot systems.

In this paper, the above bionic climbing robots are studied in depth, their configurations and kinematics are described, three possible climbing steps are designed, analyzed and compared, and the maximum joint moments and energy consumption of different steps are calculated and compared through simulation. They are compared to provide criteria for climbing design.

2. Robot Configuration and Climbing Motion Analysis

2.1. Robot configuration

Five joint modules with one degree of freedom are connected in series to form the main body of the robot.

There are three pendulum joints (T-type) in the middle, whose axes are parallel; two pivot joints (I-type) at each end, whose axes are perpendicular to the axes of the pendulum joints; and two grasping modules are connected at each end of the body to complete a symmetrical two-armed climbing robot with its head and tail connected to each other. the CAD model and the mechanism are as shown in Fig. 1 (the letters T, I, and G in Fig. 1 stand for pendulum, pivot, and grasping respectively, hereafter). the three pendulum joints have a rotational range of 0.5 to 0.5 degrees, with a range of 0.5 to 0.5 degrees. The three pendulum joints have a rotation range of -110°-110°, an outer diameter of 100 mm, a length of 238 mm, and an outer diameter of 1.5 mm.

The two pivots have a full rotation range of -180° to 180°, an external diameter of 100 mm, a length of 165 mm, a weight of 2.5 kg and a maximum output torque of 150 N-m. The gripping module (hereinafter referred to as the G-module) grips a cylindrical rod in the range of -10° to 110° and has a weight of 2.5 kg. The gripping module (hereinafter referred to as G-module) holds cylindrical rods from ø 50 to 120 mm with a maximum gripping force of 300 N and a weight of 2.2 kg.

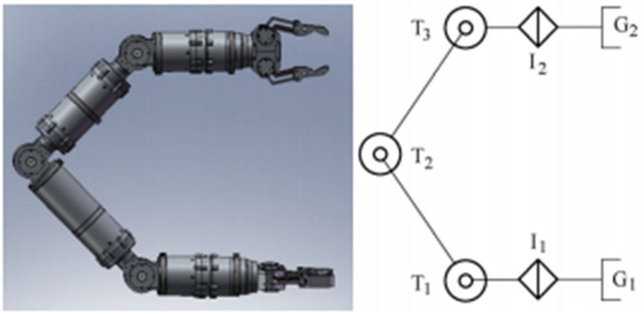

Fig. 1 CAD model and mechanism sketch of modular bionic climbing robot

2.2. Motion analysis of climbing transition between rods in space

When the robot lifts upwards, one gripper holds the rod and supports the whole system while the second gripper moves to the target position and fixes the target rod, then releases the previous gripper and the two grippers alternately hold and change roles. The position and orientation phase of the target gripper with respect to the reference coordinate system can be represented by the following matrix:

$$T = \begin{Bmatrix} n & o & a \\ 0 & 0 & 1 \end{Bmatrix}$$

The initial position and coordinate system of the robot are determined as shown in Fig. 2. According to the D-H description of robot kinematics, the transformation matrix of each position can be expressed as:

$$A_n = \left\{\begin{array}{llll} c_n & -s_n c a_n & s_n c a_n & a_n c_n \\ s_n & c_n c a_n & -s_n a_n & a_n s_n \\ 0 & s_{a_n} & c a_c & d_n \\ & 0 \quad 00 & 1 & \end{array}\right\}$$

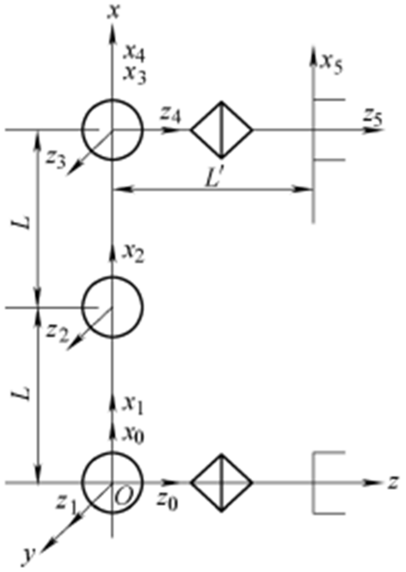

Fig. 2 Robot kinematics reference coordinate system

Thus the position of the gripper at the gripping target end can be expressed as:

$$T = A_1 A_2 A_3 A_4 A_5$$

3. Three climbing gaits

Depending on the configuration, the robot can use three different walking modes while climbing,looping, twisting and flipping.

3.1. Looping Mode

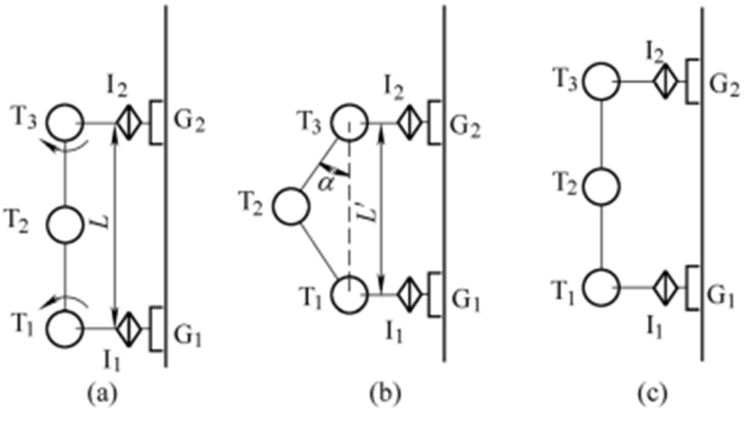

Fig. 3 Inchworm climbing gait

As shown in Fig.3, the steps of climbing are as follows:

(1) The robot is in the initial position, and the tentacles G1 and G2 are in the clamping mode; G1 is slowly unfolded, and G2 remains in the clamping state to support the robot independently (Fig. 3a).

(2) The rocker joints T1, T2, and T3 begin coordinated rotation and the robot body contracts. It is required that T1 and T3 rotate at an α angle while T2 rotates at a 2α angle (Figs. 3a, 3b).

(3) When the robot climbs at a walking speed of one inch, the walking distance per motion cycle is shown below.

$$\Delta L = L - L' = Lcos\alpha = L(1 - cos\alpha)$$

There are no major climbing steps with this type of walking. The order of the front and rear wheels remains the same throughout the climb.

3.2. Twisting Mode

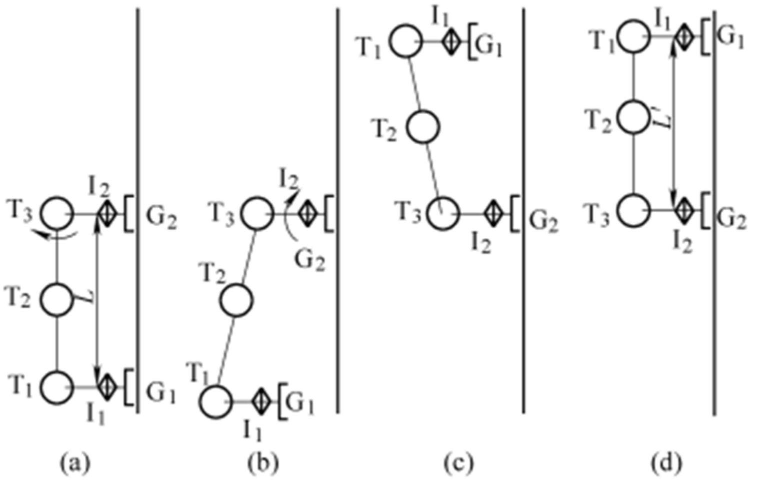

Fig. 4 Twisting climbing gait

As shown in Fig.4, The torsion process is as follows:

(1) The robot is in the initial position, and the tentacles G1 and G2 are both compressed, with G1 slowly unfolding and G2 remaining compressed and supporting the robot itself (Fig. 4a).

(2) The T3 joint opens slowly, allowing G1 to move outward and completely away from the rod, preventing the tentacles from interfering with the rod as the robot rotates (Fig. 4b).

(3) Joint I2 is rotated by 180°, and the robot is rotated by half a turn so that it is flush with the pole (Fig. 4b, 4c).

3.3. Flipping Mode

? Fig & Description

4. Climbing Simulation and Analysis

As shown in Section 2, different joints play important roles in different climbing gaits. Therefore, the torque of the end joints and the energy consumed by the robot are different in different climbing gaits.The ADAMS software was used to simulate and analysis the robot climbing with different gaits on a pole with different orientations. The following assumptions were made during the simulation: i) the robot gripper is always able to generate a sufficiently large gripping force; and ii) the robot's own friction is neglected.

During the geometric walking climb shown in Fig. 6, a sharp and sudden change in the joint torque was observed at 6.45 seconds. This is due to simultaneous gripping of the crossbar by both the grippers, resulting in overloading of the robot, which leads to abnormal values of joint torque. In the actual system, this does not happen due to the elasticity and flexibility of the robot.

If the angle of inclination of the crossbar to be climbed is different, the joint torque required and the energy consumed by the robot to climb it can vary greatly. For robustness purpose, a series of climbs were performed on poles with different tilt angles for each of the three runs to ensure that the robot was always climbing safely with the lowest possible energy consumption.In order to compare the three runs and to ensure that the robot was always climbing safely with the lowest possible energy consumption,. The poles were spaced at 15° intervals from vertical to horizontal, with a climbing distance of 0.78 meters and a climbing time of 30 seconds. The walks were divided into three different walking patterns.

The data in the table shows that the maximum torque for all three climbing gaits is less than 93 N-m when the lever is tilted more than 60°, indicating that the twisting gait consumes the least amount of energy and is the most appropriate choice. Therefore, when the mast inclination is between 30° and 60°, only the loop and torsion gait can fulfill the torque requirement, and the torsion gait is the best choice for climbing this kind of mast. The torsion walk is suitable for climbing this type of mast. For masts with an inclination of less than 30° and which are nearly horizontal, only ring walking can fulfill the torque requirements. Therefore, depending on the inclination angle of the mast, mast climbing can be divided into three main types.1) Vertical masts, i.e. masts with an inclination angle of more than 60°, can be climbed in the three steps described above, with helical climbing being the most labor-intensive. Masts with an inclination angle between 30° and 60° can be climbed by both twisting and spiral walking, with twisting climbing being the more energy efficient; iii) twisting climbing is more energy efficient than geodesic climbing because twisting consumes less energy; and (iii) horizontal masts, i.e., masts with an angle of inclination of less than 30°, can only be climbed whilst performing spiral walking. The other two walking styles increase the climbing time and energy consumption because the robot's body cannot be straightened and can only climb in small steps.

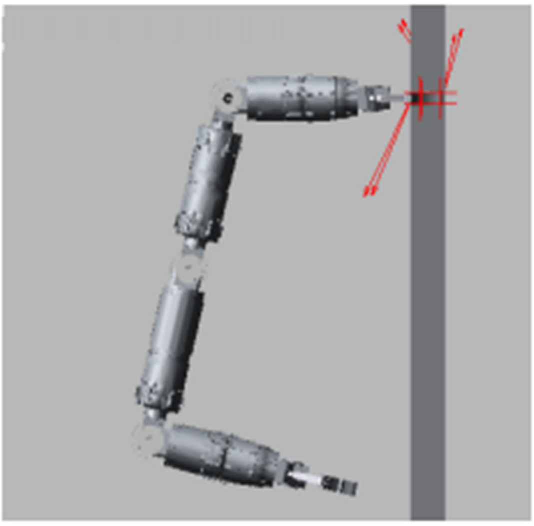

Fig. 5 Simulation of robot climbing in ADAMS environment

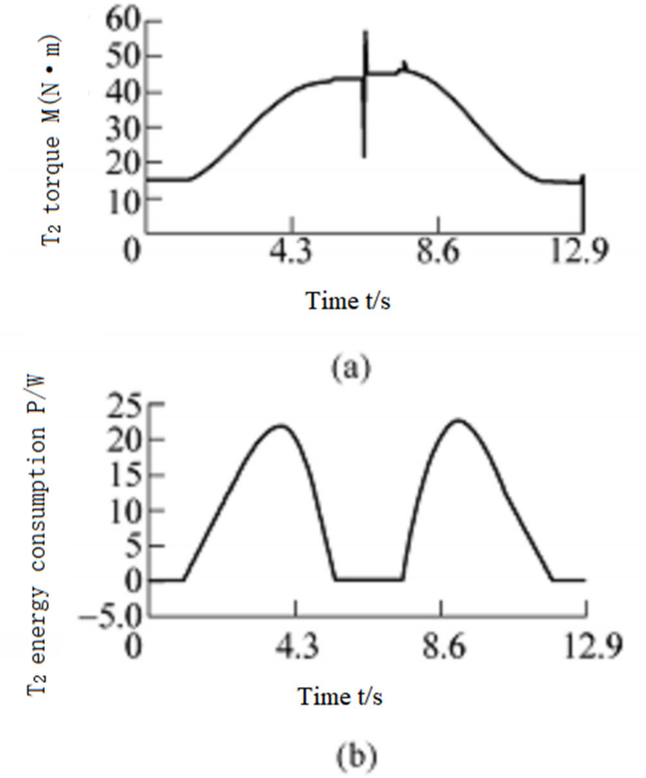

Fig. 6 Torque and power variation of major joint T2 in looper gait

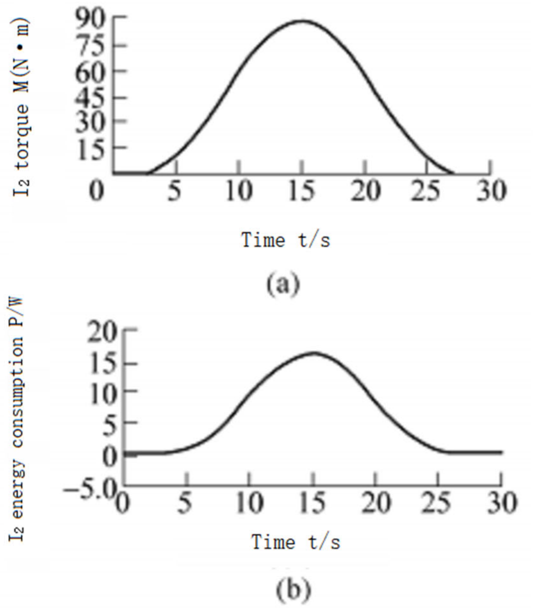

Fig. 7 Variation of torque and power of major joint I2 in torsional gait

5. Conclusion

Robots with climbing capabilities have been developed for high altitude tasks in agriculture, forestry and construction. In this paper, we presented a bionic climbing robot inspired by animal climbing with multiple degrees of freedom and systematically analyzed the possible ways of walking. The robot consists of three pivot joints and two rotary joints in tandem, with tentacles attached at both ends to form a symmetrical climbing robot capable of climbing utility poles and moving between cylindrical poles. The climbing robot can climb the poles by inching, spiraling or walking upside down. Each gait is characterized by different maximum torque and energy consumption of each joint while climbing the same column. The simulation results presented in this paper show that different climbers should adopt different gaits depending on the position of the column. This is an important guideline for climbing design and instruction and will be used in ongoing climbing trials.

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