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Research on the Design of Robot Biomimetic Frogs

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Abstract: ***This paper designs a biomimetic frog jumping robot that utilizes the jumping ability of frogs to achieve mechanical structure design. It employs pneumatic artificial muscles for driving, making the robot structure resemble a frog, thereby meeting military reconnaissance and other operational demands. Due to the complexity of biomimetic structures, the difficulty of dynamic and kinematic analysis is increased. Therefore, it is necessary to analyze the robot's dynamics at different jumping stages in order to design a biomimetic frog robot. Through validation of the robot, the correctness of the analysis is demonstrated.***

Keywords: Robot, Biomimetic frog, Frog-like design.

1. Introduction

Jumping robots exhibit good obstacle-surmounting capabilities, but their performance on flat surfaces is limited. Therefore, integrating with wheeled mobile robots enhances the adaptability of these robots. Both domestic and international researchers have conducted extensive studies on jumping robots. Japanese scholars have designed a small jumping robot using leaf springs and crank-slider mechanisms, capable of jumping 580mm high and 180mm in distance. However, this robot's movement is relatively singular and lacks flexibility. Chinese scholars have developed a four-wheeled jumping robot powered by chemical combustion, but it can only jump once. This paper explores biomimetic frog research to optimize the spring configuration of a transformable-wheeled jumping robot, enhancing energy storage through dynamic analysis of the transformable wheel mechanism design [1].

2. Dynamics of the Robot

2.1 Dynamics During Takeoff Phase

The robot's dynamic equations are established using the method of virtual work:

$$\frac{d}{dt}\left[\frac{\partial L}{\partial q_i}\right] - \frac{\partial L}{\partial q_i} = Q_i \tag{1}$$

Here, T and V denote the kinetic and potential energy of the system, respectively. Q_i represents generalized forces, and q_i denotes generalized coordinates.

In the process of deriving the dynamic equations, the reaction forces from the ground and the footprints are treated as constraint forces. Based on Newton's second law, the dynamic equations for the robot and the ground are formulated, and the reaction forces on the ground are solved.

2.2 Dynamics During Flight Phase

After the robot leaves the ground, only gravity acts upon it, and the center of mass remains neutral. Therefore, momentum and angular momentum conservation exist during the flight phase of the robot. The motion of the robot during flight can be represented as projectile motion:

$$\begin{cases} x(t) = v_x(t_0)t \\ y(t) = v_y(t_0)t - 0.5gt^2 \end{cases} \tag{2}$$

Here, $v_x(t_0)$, $y_x(t_0)$ denote the initial velocity components of the center of mass in the horizontal and vertical directions, respectively. During flight, the mass of the feet and other limbs is relatively small compared to the rest of the body and does not significantly affect the posture. Therefore, ankle joint rotation can be neglected, treating the shank and foot as connecting links. A fixed coordinate system is used with the center of the ground and toes as the origin. In the process of dynamic analysis, the base coordinate origin is the center of mass of the trunk at takeoff, and the axes are parallel to those of the fixed coordinate system.

2.3 Landing Process of the Robot

During the robot's landing phase, the initial position and posture of the center of mass are determined by its flight motion. Upon landing, the joints can assist in cushioning through backward movement, resulting in minimal joint motion during buffering. Assuming the total center of mass position of the robot remains unchanged upon landing, with other joint parameters held constant, the connection between the forefoot and the ground can be treated as a hinge. Upon landing, the robot's forelimbs make contact with the ground, altering the toe's velocity. When creating the robot's motion model at landing, the mass of the forelimbs can be neglected [2].

3. Hardware Structural Design Inspired by Frogs

3.1 Overall Architecture Inspired by Frogs

During the jumping process, a frog goes through four stages: preparation, takeoff, flight, and landing. The forelimbs of the frog serve to cushion the landing during jumps and can adjust angles and directions. Using the ADAMS environment, simulations were conducted to mimic the frog's jumping model, analyzing the relationship between limb joints and frog takeoff. Figure 1 shows the angular velocity curves of various joints. Each joint operates in a specific sequence during takeoff, allowing for directional adjustments.

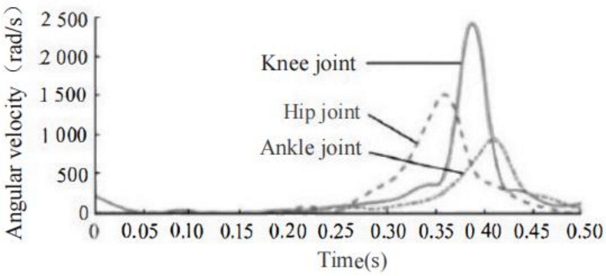

Figure 1: Angular velocity curves for each joint

Based on this, the paper proposes a novel wheeled jumping mechanism. The biomimetic frog robot designed consists of a shell, limbs, and power devices. The shell section includes an outer shell and cover plate to protect internal mechanical structures and electronic components. The limbs section comprises flaps, adjustable racks, springs, adjustable rack spacers, adjustable foot pads, and forelimbs, enabling the biomimetic frog's motion functionalities. The power devices include incomplete gears, reduction motors, shaft washers, and button batteries, providing power support and energy conversion [3]. Figure 2 illustrates the structure of the biomimetic frog.

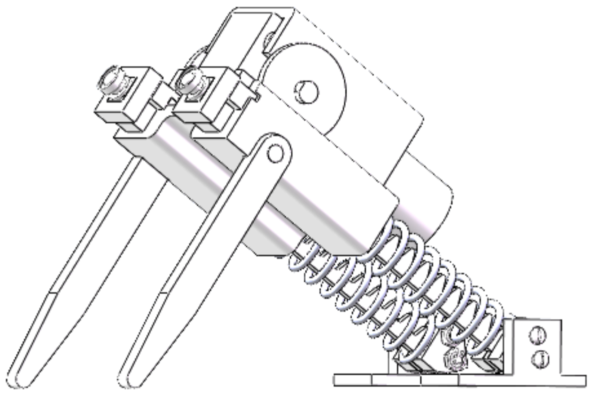

Figure 2: Structure of the Bionic Frog

3.2 Data Communication

Robot control primarily involves energy storage and posture adjustment, requiring the control system to regulate the angle and speed of DC motors. Sensors detect the position of incomplete gear teeth and measure the tilt of the foot pressure sensor and accelerometer. The control system of the biomimetic frog robot is composed of communication cables, embedded main controller, and motor drivers. The upper computer design is implemented through a PC to send control commands via serial communication. The embedded main controller translates commands for the robot and sends them to the drivers. The upper computer handles the transmission of sensor signals from the robot. Utilizing the TMS320LF2407 embedded controller, components include capture units, general timers, and orthogonal encoding pulse routing.

DSP can establish upper computer communication. To distinguish hardware system functions and avoid signal interference, separate it into drive modules, signal conversion, and control modules. Incorporate the DSP main circuit board into the control module, convert signals using the drive loop, and DSP output control loops, featuring DC motors and power to construct the drive module.

3.3 Limb Section

In the limb section's design process, energy storage and release occur through the hind limbs, converting elastic potential into kinetic energy to adjust the robot's body posture through the forelimbs, achieving the jump. Additionally, the front part of the hind limbs includes a pair of small cameras for environmental observation, facilitating reconnaissance. Components including forelimbs, adjustable racks, adjustable footpads, adjustable rack spacers, springs, and baffles are used. The hind limbs are tasked with storing energy, utilizing the spring's elastic properties to convert to kinetic energy, with the forelimbs for posture adjustment, ensuring stability and balance during the jump. Coordination of adjustable rack spacers, adjustable racks, and footpads regulates jumping intensity and height, providing efficient energy conversion and precise jumping movement, enhancing robot flexibility and adaptability [4].

3.4 Shell Design

The biomimetic frog robot's shell primarily protects and positions, preventing robot components from external damage and ensuring correct assembly and positioning of all parts for normal operation. Shell and cover plate designs typically prioritize aesthetics and structural stability, providing optimal protection and positioning effects.

3.5 Variant Structure Design

When the robot changes its jumping mode, it also adjusts the leg posture. During jumping, the legs are vertical to the ground, and in other postures, they are parallel to the ground. Utilizing two servos to drive parallel rotation axes for legs and body, changing between different modes. The rocker rotation mechanism is designed in three stages, with the middle stage constraining the frame's cylindrical axis and providing rotational freedom. The middle stage incorporates a double universal hinge structure to enable angular rotation in the variant structure, maintaining constant angular velocity between the master and slave axes.

4. Software Structure Inspired by Frogs

4.1 Upper Computer Software

In the biomimetic frog software system, components such as trajectory planning, PC interaction interface, sensor data collection, and embedded controllers constitute the system. It includes layers such as execution layer, command layer, strategy layer, and overall layer:

(1) Overall Layer: Plans motion trajectories by integrating control tasks with objectives such as obstacles and terrain.

(2) Strategy Layer: Implements tasks during specific jumping estimates using software algorithms, calculating posture based on trajectories.

(3) Execution Layer: Converts commands into pulse signals, controlling the operation of sensors and drivers.

(4) Command Layer: Refines postures and assigns sub-functions to modules, presenting them through commands.

The upper computer software is composed of algorithm programs and a human-machine interaction interface, designed using the Matlab software platform. It inputs and reads communication data, sets DC motor angles and speeds, and executes robot jumps through commands [5].

4.2 Communication Command Set

The SCI (Serial Communication Interface) enables communication between the host computer and the embedded controller, defining operation commands to exchange information between the PC and DSP (Digital Signal Processor). The high 8 bits of the data are used to set the command type, while the low 8 bits represent parameters such as servo angles, DC motor rotation angles, and positions. By configuring robot actions, commands can control and display robot command data, such as the unit angle of a DC motor, direction, etc. The detailed communication command set is shown in Table 1.

Table 1: Communication Command Set

	D15-D12	D11	D10-D8	D7-D0
A	Servo Control	Servo Selection 1-5		Angle Position
B	Left Leg Motor	Direction (CW/CCW)	Duty Cycle	rotation angle
C	Right Leg Motor	Direction (CW/CCW)	Duty Cycle	rotation angle
D	Linked Motor	Direction (CW/CCW)	Duty Cycle	rotation angle
E	Upstream Sensor	Hall Element State, ADC Data, Sensor Data		
F	Special Command	Indicator Light, Flags		

In the robot control process, the embedded controller is a key component, capable of coordinating multiple sensors and actuators. Due to the use of numerous external components in the design of the frog-inspired robot, the DSP software is designed modularly, employing different functions to implement Hall elements, motor rotation, etc., and executing them based on SCI command judgments. During the SCI data reception process described in this paper, variables are stored in the interrupt service routine, and all commands are executed after being output. At this time, the sensor status is queried in real-time, and if a change occurs, the command is executed. Figure 3 shows the program control flow of the frog-inspired robot. By debugging the program, the robot's jumping process is as follows: sending a forward command on the inner side changes the Hall signal, adjusting the robot's jumping posture. When the Hall signal reaches a certain position, the motor rotates to compress the spring, then releases the robot's legs, allowing it to jump. During the experiment, the robot's posture can be adjusted according to the set commands, enabling the robot to jump and verifying the performance of the robot control system [6].

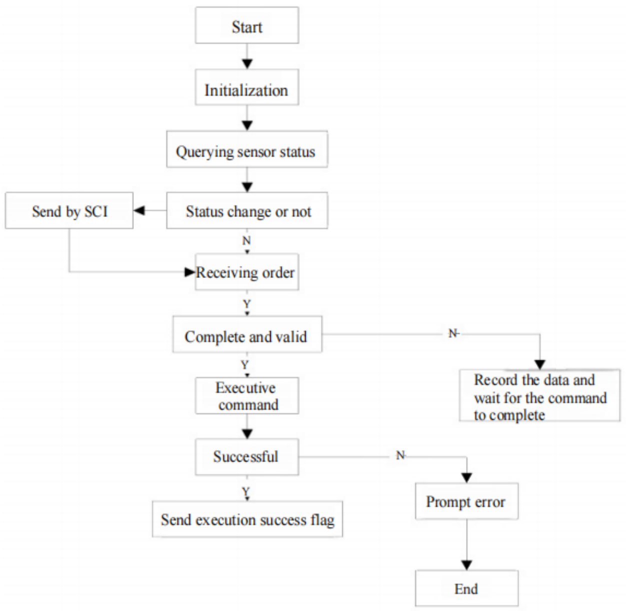

Figure 3: The program control flow of imitation frog robot

5. Conclusion

This paper presents a frog-inspired robot system based on a host PC and designs the system's DSP program and human-machine interface, enabling control of the frog-inspired robot's jumping process. By conducting jumping experiments with the robot, the feasibility of the designed control system can be verified. In future research, the system's functionality should be improved, and the robot control algorithm optimized. Studying the stability of the robot's jumps will further enhance the system's control performance. Additionally, the hardware and software design in this paper is versatile, making the system adaptable to other types of robots, thereby increasing its application value.

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