

Design and Simulation of a Jumping Quadruped Robot with Torsional Spring Joints

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Abstract: Many animals utilize jumping as a means of traversing uneven terrain in nature. Animal jumping enables them to overcome obstacles that exceed their body size. Today, there is a clear need for mobile robots that can perform human missions in complex environments instead of humans. Performing these tasks by humans is either risky or costly. Legged robots are more capable of performing missions than wheeled robots. The mechanism of these robots allows them to traverse inaccessible surfaces. In this paper, a two-dimensional, four-legged robot model is introduced. In the next step, the four-legged robot and the walking path are simulated using Adam's software. All the physical properties of the four-legged robot, as well as parameters related to jumping, are inputted into the software. Following that, the simulated model is implemented in Adam's software, and the four-legged robot jumps on the stairs. The Adams software is used to review jumping path diagrams, robot joint changes, and contact forces. The deformation diagram of the robot's torsion springs for the rear and front legs of the robot showed the same behavior, which showed the accuracy of the simulation. Also, for better analysis, the contact force diagram of the robot's legs was also examined, which showed the simultaneous impact of the rear legs on the step and the front legs on the steps in the diagram.

Keywords: Quadruped Robot, Robot Energy Consumption, Robot Jump, Stairs

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Research paper

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1 INTRODUCTION

Robots have always been a preferred solution for addressing movement challenges in unstructured environments. Legged robots offer several advantages over wheeled and tracked robots, although they also come with increased complexity. This complexity arises not only from the mechanism used but also from electronic systems, sensory capabilities, and control algorithms. Numerous studies have been conducted in the field of four-legged robots, which exhibit significant flexibility in their movement. In general, legged robots surpass other mobile robots in their ability to navigate complex environments [1].

Researchers have focused explicitly on designing robots capable of crossing obstacles like stairs. Through various designs and control systems, several robots have demonstrated successful stair-climbing capabilities. Examples include two-legged robots like Cassie [2] and ASIMO [3], as well as four-legged robots like HyQ [4], AnyMal [5], MIT Cheetah [6], Pegasus [7], Jueying [8], and Scalf [9]. Furthermore, robots such as THU-QUAD II [10], ALPHRED [11], and Qingzhui [12] have utilized six-legged configurations.

Li et al [13] devised dimension-based designs to enhance the stair-climbing ability of a six-legged robot, investigating various scenarios while also addressing foot-step mechanism interference. To achieve this, they initially derived the analytical model of the single-leg mechanism based on step size.

The belt base mechanism is frequently employed in six-legged robots. Additionally, stability [14-15] is a crucial concern during stair climbing. Liu et al [16] explored the behavior of a defective leg on a ramp in a six-legged robot. In the meantime, four-legged robots have lower computational and economic costs than six-legged or eight-legged types and can ensure the stability of the robot. Robots are very capable of helping COVID-19 patients. Naghsh Nilchi et al. [17] presented a six-legged robot that was able to find a suitable method to help the medical staff and COVID-19 patients. They simulated a robot that can easily walk and cross the unevenness in front of it, and provide services to COVID-19 patients. Coelho et al. [18] examined the six-legged robot in CoppeliaSim software. By using the control system defined for the robot, they managed to make the robot pass through several types of uneven surfaces. On the other hand, legged robots face many challenges in order to be widely used in various cases. Some of these challenges are the design of stepping mechanisms [19], choosing the appropriate stepping mechanism [20-21], designing the stepping pattern [22-23], stability and balance of the robot [24-25], increasing the speed of stepping [26-27], passing or moving away from obstacles [28-29], planning the sequence of steps [30-

31], and planning the movement path to the target point [32-33].

In nature, all creatures utilize their muscle-equipped movement organs to execute jumps. By contracting their muscles, they propel themselves into the air, storing and subsequently releasing energy. In this paper, the Dinavit-Hartenberg matrix and Jacobian matrix associated with the four-legged robot were determined based on available parameters. Subsequently, a simulation of the four-legged robot's stair jump was performed. For this simulation, all springs and joints were designed to enable successful jumps from the stairs. By compressing and releasing the stored force within the springs, the robot was propelled and landed on the stairs. After the simulation, all relevant diagrams were obtained from the Adams software for analysis and evaluation. Finally, an optimization process was undertaken, resulting in the best outcomes for this research project.

2 FOUR-LEGGED ROBOT MODELING

To mimic the jumping ability observed in animals, it is necessary to define joints for the robot. In nature, animals possess multiple muscles within their joints that facilitate jumping. Figure 1 illustrates the two-dimensional model of the four-legged robot. In this study, torsion springs are utilized in each joint of the four-legged robot to emulate the function of muscles.

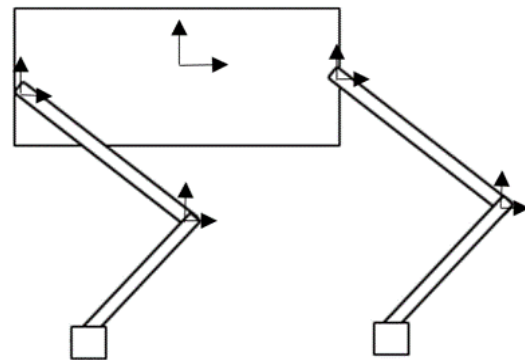


Fig. 1 Two-dimensional model of four-legged robot.

As we know, configuration variables are [16]:

$$Q=[x;z;q_{pitch};q] \quad (1)$$

In "Eq. (1)", x and z represent the COM (center of mass) position of the robot, q_{pitch} is the body pitch angle in the world frame, and q is the joint angle vector that includes the hip and knee joint angles of the front and back legs

[16]. By using space vector algebra [17], the dynamic equations of the robot can be derived [16]:

$$H(Q)\ddot{Q} + C(Q, \dot{Q})\dot{Q} + g(Q) = B\tau + B_{fric} + \tau_{fric}(\dot{Q}) + \sum_i J_i^T(Q)F_i \quad (2)$$

In “Eq. (2)”, H denotes the mass matrix, and the matrix C contains the Coriolis and centrifugal terms. Additionally, g represents the gravity vector, J_i is the spatial Jacobian of the body containing the i^{th} foot expressed at the foot and in the world coordinate system, F_i is the spatial force at the i^{th} foot, and matrices B and B_{fric} define how the actuator torques τ and the joint friction torques τ_{fric} are incorporated into the model [29]. To obtain the kinematics of the robot, it is necessary to define the movement of the body in space and the corresponding generalized coordinates. For this purpose, the Denavit-Hartenberg (DH) matrix is employed. The reference variables for the legs of the four-legged robot are shown in Figure 2.

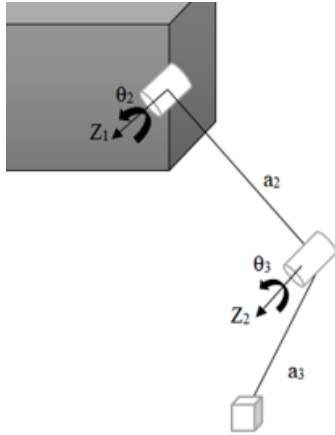


Fig. 2 Reference variables for four-legged robot legs.

The parameters of the DH matrix are listed in “Table 1”. It is important to note that each leg of the four-legged robot in this paper has three degrees of freedom. On the other hand, the DH matrix for the i^{th} joint is ($s_i = \sin(\theta_i)$ and $c_i = \cos(\theta_i)$):

$$A_i^{i-1} = \begin{bmatrix} c\theta_i & -s\theta_i c\alpha_i & s\theta_i s\alpha_i & a_i c\theta_i \\ s\theta_i & c\theta_i c\alpha_i & -c\theta_i s\alpha_i & a_i s\theta_i \\ 0 & s\alpha_i & -c\theta_i s\alpha_i & d_i \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (3)$$

Table 1 DH parameters for legs

Lin k	a_i	d_i	α_i	θ_i
1	a_1	0	0	θ_1
2	a_2	0	0	θ_2

So the DH matrix of each joints is:

$$A_1^0 = \begin{bmatrix} c_1 & -s_1 & 0 & a_1 c_1 \\ s_1 & c_1 & 0 & a_1 s_1 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (4)$$

$$A_2^1 = \begin{bmatrix} c_2 & -s_2 & 0 & a_2 c_2 \\ s_2 & c_2 & 0 & a_2 s_2 \\ 0 & 0 & 1 & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \quad (5)$$

Also, the Jacobian matrix of the leg is [32]:

$$J(q) = \begin{bmatrix} Z_0 \times (p - p_0) & Z_1 \times (p - p_1) \\ z_0 & z_1 \end{bmatrix} \quad (6)$$

In “Eq. (5)”, z_0 , z_1 , and z_2 represent the joint axes, while p_0 , p_1 , and p_2 are joint position vectors, and p is the foot position vector. The submatrices of the Jacobian matrix can be found in Equations (6) and (7):

$$J(\theta_1) = \begin{bmatrix} -a_1 s_1 - a_2 s_{12} \\ a_1 c_1 + a_2 c_{12} \\ 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} \quad (7)$$

$$J(\theta_2) = \begin{bmatrix} -a_2 s_{12} \\ a_2 c_{12} \\ 0 \\ 0 \\ 0 \\ 1 \end{bmatrix} \quad (8)$$

3 FOUR-LEGGED ROBOT JUMPING SIMULATION

To simulate the jumping of a four-legged robot on the stairs, the dimensions of the robot, including the dimensions of the legs and the body, need to be determined. Similarly, the dimensions of the stairs also need to be determined. “Table 2” presents the dimensions of the simulated robot, and “Fig. 3” illustrates the dimensions of the stairs.

Table 2 The dimensions of the four-legged robot

Parameter	Value
Four-legged robot body dimensions	(20cm×20cm×50cm)
Hip of the four-legged robot	(12.5cm×4cm)
Knee of the four-legged robot	(12.5cm×4cm)
Ankle of the four-legged robot	(7cm×6.5cm×4cm)
The total mass of the robot	32.6 (kg)

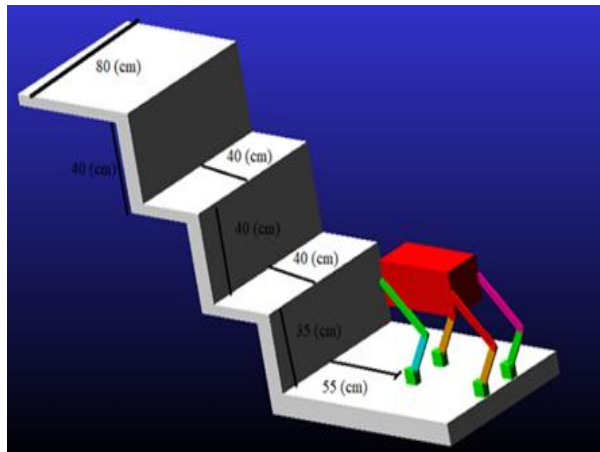


Fig. 3 Stair dimensions.

As mentioned, springs are used to mimic the muscles of the robot during the jumping process. The compression of these springs allows energy to be stored and released, propelling the robot forward. In this research, torsional springs were utilized in the joints, as shown in “Fig. 4”.

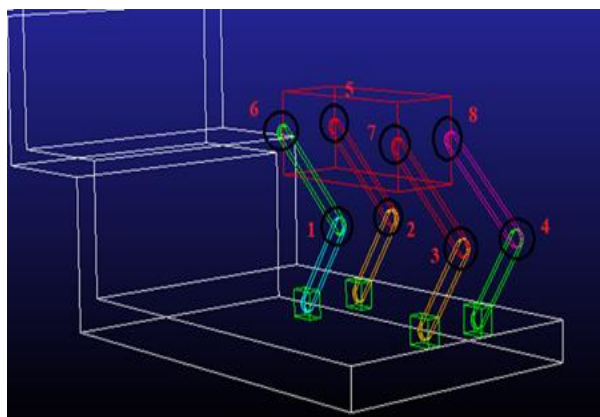


Fig. 4 Torsion springs in each leg of the robot.

The stiffness values of these torsional springs are provided in “Table 3”. Additionally, it should be noted that the damper coefficient for all joints is set to 10000 (Newton-mm-sec/deg).

Table 3 Stiffness value torsional spring

Spring	Stiffness value (Newton-mm/deg)
1	7000
2	7000
3	7000
4	7000
5	2000
6	2000
7	2000
8	2000

Once all the contact conditions between the legs of the four-legged robot and the stairs are applied, the software initiates the simulation. As seen in “Fig. 5”, the four-legged robot begins to jump after running the simulation using Adam’s software.

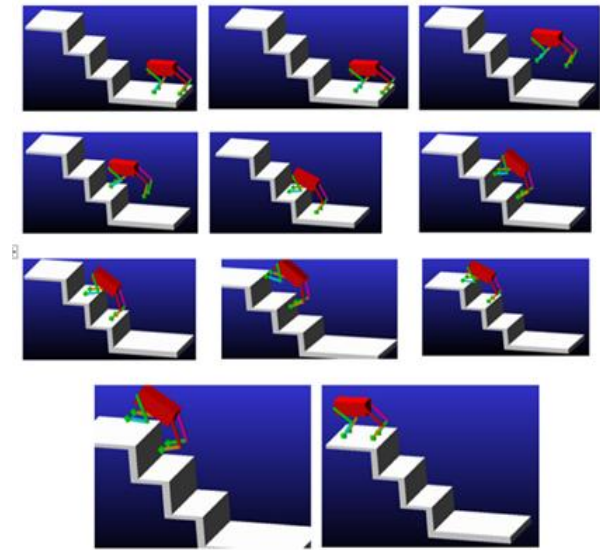


Fig. 5 Four-legged robot jumping on the stairs.

By exerting force on its legs, the four-legged robot generates the necessary energy to jump and land on the first step. Subsequently, it prepares itself to jump onto the second step by turning a small angle. This process continues until the four-legged robot successfully reaches the upper terrace through a series of jumps.

4 CONCLUSIONS

After simulating Adam’s software, the results of the four-legged robot’s jumping on the mineral stairs are analyzed and evaluated using relevant diagrams. Figure

6 displays the position of the robot's center of mass along the y-axis. This helps understand the robot's movement during jumping.

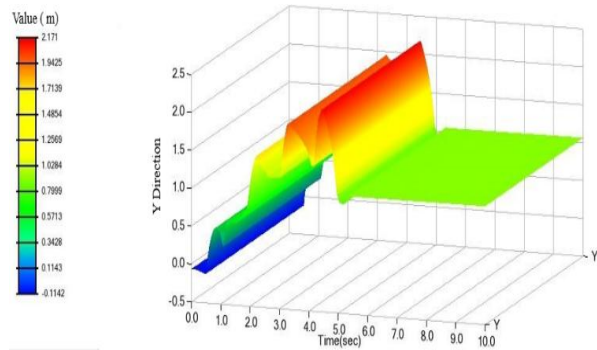


Fig. 6 Four-legged robot jumps along the Y axis.

The deformation of the torsional springs in the knee joints is an important aspect to analyse the jumping behaviour of the robot on the stairs. Figure 7 illustrates the deformation of the knee joint torsional springs. Additionally, there are four torsion springs in the hip part of the robot, and “Fig. 8” shows the deformation of these hip joint torsional springs.

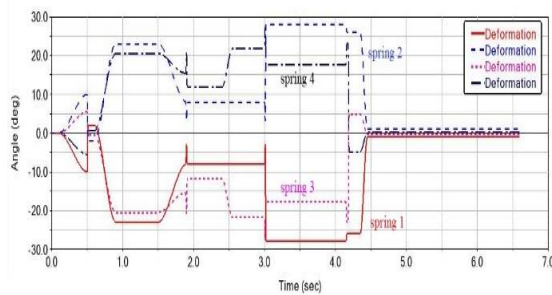


Fig. 7 The deformation of the torsional spring in the knee joint.

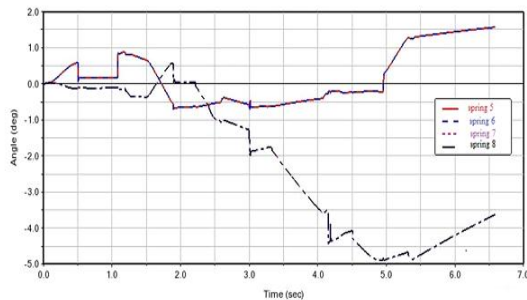


Fig. 8 The deformation of the torsional spring in the hip joint.

Based on “Fig. 7”, springs 3 and 4 (back legs of the quadruped robot) exhibit similar behavior, while springs 1 and 2 (front legs of the robot) demonstrate a similar

pattern at different times. This highlights the significance of the front legs in the jumping and landing process when the robot jumps on the stairs.

According to “Fig. 8”, springs 5 and 6 (front legs of the quadruped robot) and springs 7 and 8 (rear legs of the robot) display similar behavior at different times. Furthermore, the rear legs of the four-legged robot undergo greater changes in angle compared to the front legs. In general, during the jumping of the four-legged robot on the stairs, the rear legs experience more significant angle changes.

The impact of the robot's feet on the surface of the stairs is another crucial aspect of the jumping process. The contact between the robot's legs and the stair surface is carefully analyzed. This is depicted in “Fig. 9”, where the surfaces between the robot's legs are defined as step surfaces in the modeling process using Adam's software. “CONTACT” constraints are utilized to define these surfaces.

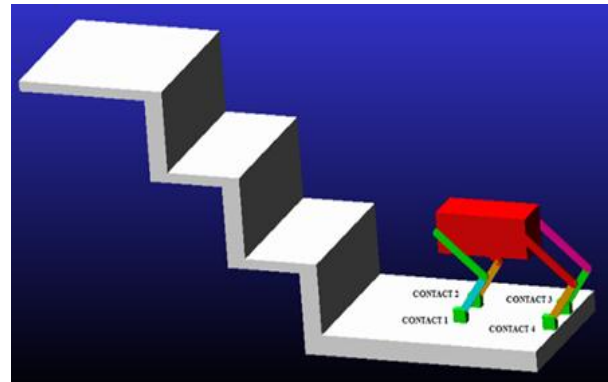


Fig. 9 “CONTACT” constraints for each leg of the four-legged robot.

To gain a better understanding of the contact forces between the four-legged robot's legs and the stairs, a contact force diagram is provided in “Fig. 10”.

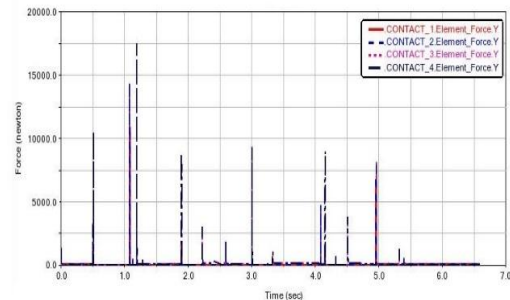


Fig. 10 Contact force diagram of the robot's legs.

All the contact lines in the diagram coincide with each other. This indicates that when the four-legged robot jumps and lands on the stairs, all legs of the robot are

simultaneously separated from the ground and land on the stairs together.

The four-legged robot modeled in this paper can be considered as the best model for jumping on the stairs. Additionally, this robot has the ability to jump up to a certain height over other obstacles. Based on the relationships obtained and the simulation of the four-legged robot in this article, future research can focus on the robot's ability to perform jumps on the path of the mineral stairs while carrying weight. Moreover, a potential area of investigation for future research could involve the four-legged robot jumping with a defective leg, utilizing the model presented in this paper.

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