Modeling and Simulation of a Jumping Four-legged Robot on Staircases

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Abstract–The new generation robots are the ones that have the ability to perform missions in the shortest possible time and with the best performance. In the new generation of quadruped robots, important scientific research topics include stability maintenance, mechanical structure, and control algorithms. The robot climbing the stairs or climbing the stairs is one of the up-to-date and unique topics that has been raised in the field of robotics in a rough way with its own complexity. Jumping the robot from the stairs can be one of the best possible solutions to reduce the time of walking and performing operations. The use of torsion springs as muscles and their location in the joints play an important role in the design of the robot. In this study, the springs at each robot's foot are designed so that the robot can jump using the springs. This has created a unique and unique robot jumping on the stairs, which in itself is one of the most important achievements of this paper.In this research, after designing the four-legged robot and analysing the dynamic equations governing it,the robot is simulated in Adams software.On the other hand, robot jumping has been proposed as the best solution for climbing stairs with specific dimensions and sizes to reach the upper terrace. The result of the simulation shows the acceptable performance of the robot in climbing the stairs.
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Keywords:Four-legged robot, Robot jump, Simulation, Stairs

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 specifically focused 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 , as well as four-legged robots like HyQ, Anymal [3], MIT Cheetah [4], Pegasus [5], Jueying [6], and Scalf [7]. Furthermore, robots such as THU-QUAD II [8], ALPHRED [9], and Qingzhui [10] have utilized six-legged configurations.

Li et al [11] 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 [12-13] is a crucial concern during stair climbing. Liu et al [14] 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 are able to ensure the stability of the robot. Robots are very capable of helping COVID-19 patients. NaghshNilchi et al. [15] presented a six-legged robot that was able to find a suitable method to help the medical staff

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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. [16] 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 [17], choosing the appropriate stepping mechanism [18-19], designing the stepping pattern [20-21], stability and balance of the robot [22-23], increasing the speed of stepping [24-25], passing or moving away from obstacles [26-27], planning the sequence of steps [28-29], and planning the movement path to the target point [30-31].Reddy et al. [32], they modeled and simulated the jumping of a frog robot. They modeled a spring model as the robot muscles (Four-bar spring/linkage mechanism) and simulated the presented model in Adams software.After the simulation, the presented model run correctly in the software. They received various graphs, including the graph of changes in the robot's joints, etc. from the software and performed analysis and review on those graphs.

In feline jumping, muscles play an effective role in the jump. In other words, animals in nature, store the energy necessary for the jump by straining their muscles and storing force in these muscles, and by releasing this force, the feline is thrown forward.

In this research, the simulation of four-legged robot in Adams software has been done first. Robot joints, springs and stairs are designed and simulated in the software.In other words, each leg of the robot has a rotating joint that acts as a muscle. By applying force to these springs, the energy required for jumping is stored in them, and by releasing the force (removing the force), the robot is launched forward.The timing of joint opening and closing is also very important in jumping. On the other hand, the timing of joint opening and closing helps the robot to overcome the obstacle in front of it and jump over it. One of the significant achievements in this research is obtaining dynamic equations that take into account the amount of joint opening and closing necessary for the robot to jump on the stairs.In the next step, the equations governing the four-legged robot are presented for the robot jump. In order to verify the validity of the governing equations, these equations are presented in the software and the results are presented in the form of graphs.

2. 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 1 presents the dimensions of the simulated robot, and Fig 1 illustrates the dimensions of the stairs.

Table 1. The dimensions of the four-legged robot

Parameter	Value
Four-legged robot body dimensions	(60cm×25.6cm×20cm)
Joint 1 (Length)	(34cm)
Joint 2 (Length)	(34cm)
Surface friction coefficient	0.4
The total mass of the robot	45 (kg)

It should be noted that, according to research and detailed investigations, the dimensions and specifications of the proposed robot have been stated first. Next, the simulation of the stairs in the software is discussed. The angle of the stairs is considered to be 35 degrees according to research and available cases. In figure 2, the dimensions and size of the stairs are shown.

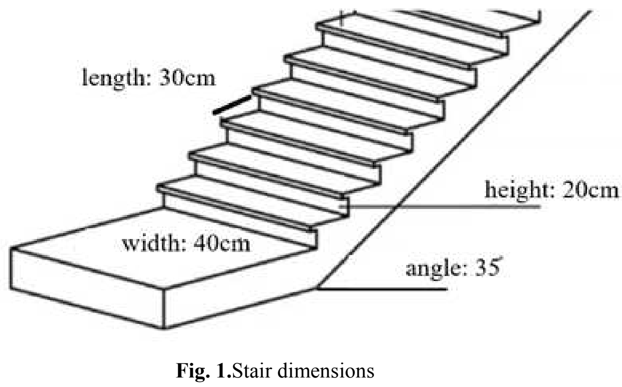

Fig. 1. Stair dimensions

As we know, legged robots have a high potential for application in challenging environments. Among these potentials, the four-legged robot's ability to jump can be mentioned. In four-legged robot jumping, assumptions are also considered. Some of these are mentioned below:

$$q \le q_{s\_k} \le \bar{q}$$
$$\dot{q} \le \dot{q}_{s\_k} \le \dot{\bar{q}}$$
$$\ddot{q} \le \ddot{q}_{s\_k} \le \ddot{\bar{q}} \quad (1)$$

$$\tau \le \tau_{s\_K} \le \bar{\tau} \quad (2)$$

$$q_{s\_i} = q_{s\_i,d}$$
$$\dot{q}_{s\_i} = \dot{q}_{s\_i,d}$$
$$\ddot{q}_{s\_i} = \ddot{q}_{s\_i,d} \quad i=0\ldots N \quad (3)$$

In the above relationships, q is the joint angle, $\dot{q}$ is the joint speed, and τ is the joint torque.$\tau$and$\bar{\tau}$are the upper and lower boundaries of the torques. $q_{s\_i,d}$, $\dot{q}_{s\_i,d}$ and $\ddot{q}_{s\_i,d}$ are given joint variable, velocity, and acceleration vectors at time step 0 and N (the launch moment), respectively.

Figure 2 shows the coordinates and inputs of the four-legged robot for jumping.

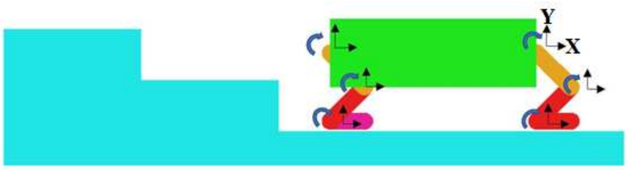

Fig. 2. Four-legged robot coordinates and inputs for jumping

In the jumping of animals in nature, muscles play an essential role in jumping. In other words, when the force is applied to the muscles in the animals, the necessary force for jumping is stored in the muscles and when this force is released, the animals jump forward. In the simulation of four-legged robot jumping, springs are used as muscles for the robot. In fact, by entering the force in the springs, the energy necessary for the robot to jump is stored in the springs, and then by releasing this force, the four-legged robot jumps forward. In Figure 3, the placement of the springs in the robot as well as the surface relationships between the robot and the ladder are shown.

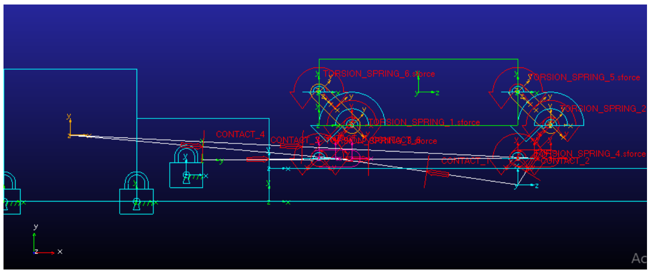

Fig. 3. Placement of springs in the robot

Also, all the relationships between the legs and the ground and the stairs have been done in the software. According to Figure 3, three torsion springs are placed in each leg of the robot. The specifications of these springs are given in Table 2.

Table 2. Specification of springs in robot legs

Spring number	Spring stiffness factor	Damper coefficient
1	500	1.43
2	500	1.43
3	100	1.06
4	100	1.53
5	100	0.108
6	100	0.108

In Table 2, springs 1, 3, and 6 belong to the front legs and springs 2, 4, and 5 belong to the rear legs of the robot.

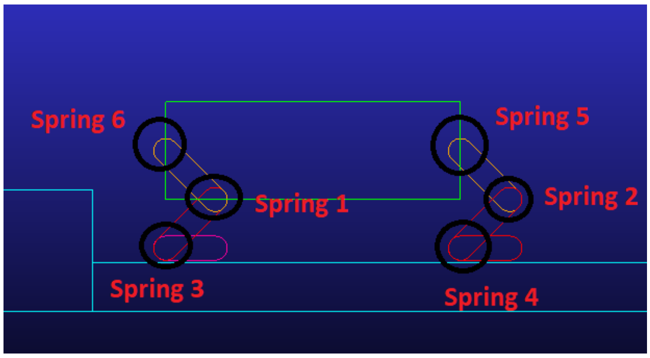

Fig. 4. Torsion springs in each leg of the robot

It should be noted that the values presented in Table 1 are based on the trial and error method as well as the physical conditions of the robot.

3. Dynamic Equations

Equations After designing and simulating the four-legged robot, the dynamic equations for jumping the four-legged robot have been investigated. The dynamic equations of the four-legged robot jump should be written in such a way that there is no interference between the robot's legs and the stairs when the robot jumps. On the other hand, these equations should be such that the balance of the robot is maintained during the jump or when the robot lands on the stairs and the robot can continue on its path. Based on this, the dynamic equations of four-legged robot jump are obtained as follows:

$$\begin{aligned}&\text{step}\left(\text{time},.5,20\text{d},0.51,0\text{d}\right)+\\&\text{step}\left(\text{time},1.5,0,1.6,29\text{d}\right)+\\&\text{step}\left(\text{time},1.6,0\text{d},1.61\text{d},-29\text{d}\right)\end{aligned}\tag{4}$$

$$\begin{aligned}&\text{step}\left(\text{time},.5,20\text{d},0.51,0\text{d}\right)+\\&\text{step}\left(\text{time},1.5,0,1.6,29\text{d}\right)+\\&\text{step}\left(\text{time},1.6,0\text{d},1.61\text{d},-29\text{d}\right)\end{aligned}\tag{5}$$

Equation (4) is related to the front leg of the robot and equation (5) is related to the rear leg of the quadruped robot. The above equations are also obtained by trial and error method and by repeated repetition and getting the results. These equations are put in the software and finally the results can be checked and analyzed by the software.

4. Conclusion and Conclusion

After designing and simulating in Adams software and presenting dynamic equations to the software, the problem has been executed by the software. In figure 5, the robot jump is shown.

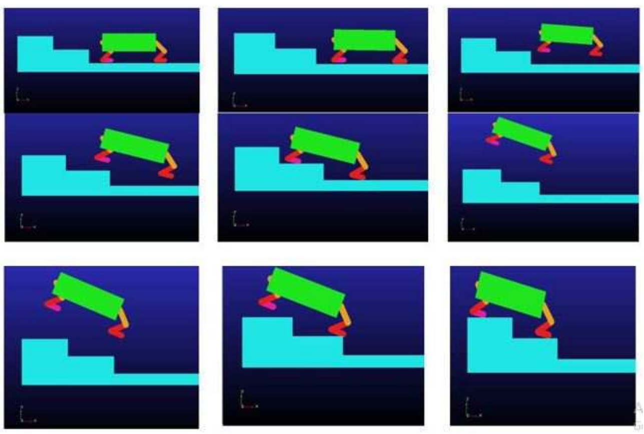

Fig. 5. Robot jumping in Adams software

As seen in Figure 5, by means of the springs in the joints of the robot and the reaction force, the robot jumps forward and lands on the stairs. By repeating this method, the robot finally reaches the top step.

For a more detailed analysis, the graphs taken from the software are examined. For this purpose, at first, the displacement diagram of the center of mass of the robot along the x and y axes has been examined. Figures 6 and 7 respectively show the displacement of the center of mass of the robot along the x and y axis.

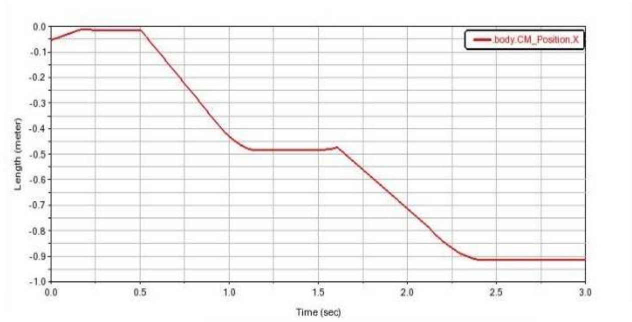

Fig. 6. Moving the center of mass of the robot along the X axis

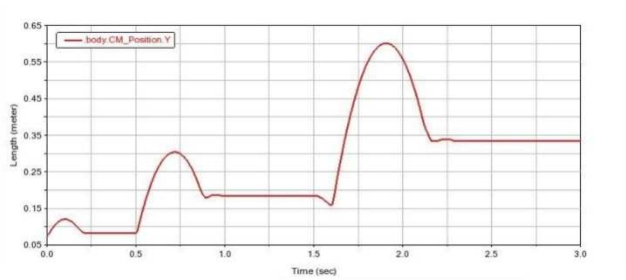

Fig. 7. Moving the center of mass of the robot along the Y axis

According to Figure 6, the robot approaches the left side of the X diagram (toward the stairs) with the passage of time. On the other hand, in Figure 7, the robot made a jump on the stairs with the passage of time and continued to jump after pausing for a few seconds.

Another diagram that is effective in the analysis of robot jumping is the diagram of kinetic energy and potential energy of the robot. Figure 8 shows the kinetic and potential energy diagram of the robot.

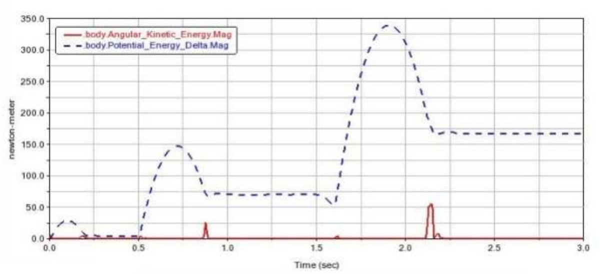

Fig. 8. Diagram of kinetic energy and jumping potential of the robot

As seen in Figure 8, the kinetic energy has increased when the robot has jumped. In fact, creating speed during jumping has increased the kinetic energy of the robot. Also, with the increase in the height of the robot during the jump times, the potential energy of the robot has increased.

In the last step, the deformation of the springs in each leg of the spring have been investigated. Figures 9 and 10 show the amount of torsion spring deformation in the front and back legs, respectively.

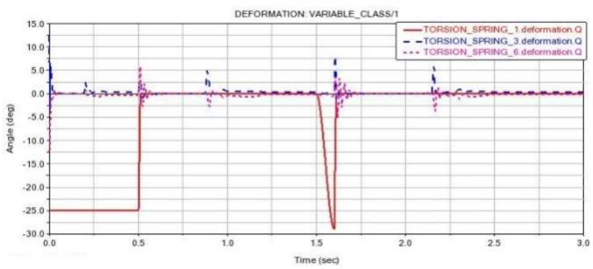

Fig. 9. The deformation of the torsional spring (front leg)

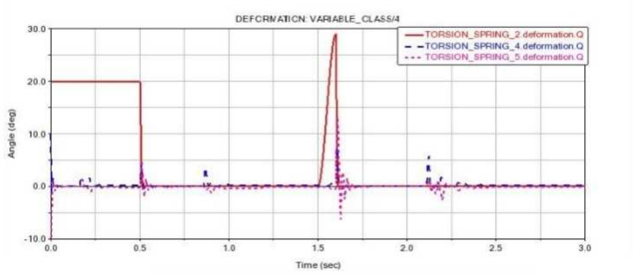

Fig. 10. The deformation of the torsional spring (back leg)

As seen in Figures 9 and 10, the deformation rates of the corresponding springs in each leg are equal to each other. In other words, the amount of changes of springs 1 and 2, springs 3 and 4, as well as 5 and 6 are equal to each other. In fact, in the robot jump, the robot joint in the front leg has shown the same behavior as the robot joint in the rear leg of the robot.

Many animals utilize jumping as a means of traversing uneven terrain in nature. In fact, 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.

In general, jumping robots have been one of the best solutions for the problems of robot movement in unstructured environments. The flawless jumping of the robot in the stair structures can make difficult missions easier to a great extent. In this article, a robot with the ability to jump on the stairs was designed and simulated by referring to the dynamic equations for robot jumping as well as the unique structure. To verify the accuracy of the robot's jump in the software, various graphs were examined and analyzed, which confirmed the robot's jump on the stairs and moving forward.

Among the design options for the four-legged robot capable of jumping on stairs, shock location or the design of a quadrilateral robot with sliding joints can be considered. In other words, the robot's jumping motion utilizes a linear spring mechanism. Additionally, the design and simulation of a quadruped robot with the ability to jump on uneven surfaces with a damaged foot is a key focus of this research. The research showcases a quadruped robot capable of stair-jumping, featuring a unique model considering springs in each leg, setting it apart in the field of robotics. This uniqueness is underscored by simulating the model in Adams software, enabling a close approximation of real-world performance.

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