Design of a Two-Mass Multi-Modal Walking and Jumping Robot

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***Abstract*— If a robot is designed so that its dynamic behavior is generated by its mechanical system, this issue will play a significant role in simplifying the robot control system. In underactuated robots, the dynamic characteristics of the robot affect its behavior, and as the speed of the actuators increases, this effect becomes more significant. This fact can be used to design robots that spontaneously change performance with increasing speed. In this study, a two-mass robot was designed that is consisting of a rigid body and a rotating arm. If the arm rotates slowly, the robot walks without detaching from the ground. As the arm rotation speed increases, due to the dynamic effects of the arm rotation, the robot gait pattern gradually changes from walking to jumping, such that the robot jumps forward with each rotation of the arm. This process is similar to the role of arm motion in human jumping. With a further increase in speed, a double jump occurs, and a high jump is performed with every two rotations of the arm. This robot was simulated in MATLAB SimMechanics software, and its design parameters were selected such that the dual movement pattern is well generated. It was also observed that this robot works well on the uphill ground if there is sufficient friction. Maybe this robot is suitable for moving on rough and rocky surfaces because it does not need flat ground in either of its two motion modes. Also, it can be used as multi-modal rowing and jumping boat.**

Keywords—multi-modal walking and jumping, Passive dynamic robot, Gait transition, Two-mass robot

I. Introduction

The behavior of a mechatronic system is generated through the interaction between its mechanical system, control system, and the environment. So in designing each of the mechanical and control systems, two other factors must be considered [1, 2]. If the mechanical system of a robot is designed without attention to the expected function, and function generating left entirely to the control system, it may be not easy to control the system, and too much control gains may be required. So it is better to design the dynamic characteristics of the robot body so that it can naturally generate some of its function [3]. For this purpose, underactuated robots are designed that generate a specific function based on their dynamic nature [4]. Passive dynamic walkers are the most obvious example of these robots, which have been the subject of much research in recent decades. A group of these robots are completely passive and have to be downhill to walk [5, 6], and the other group have a motor that provides energy for their movement [7-9]. There has been much research on underactuated robots that are actuated only by one actuator [10-12]. Also, there are passive or quasi-passive robots that can run [13, 14].

Some researchers have designed robots that can perform two different functions, such as walking and running. Some of them change their performance mode by changing one of their design parameters. For example, D. Owaki et al. have designed a robot that changes between walking and running by changing the body elasticity [1]. Also, T. Kobayashi et al. designed a bipedal robot that switches between walking and running by changing the damping ratio [15]. Also, some other robots have been designed that have several performance modes like crawling, jumping, gliding, etc. [16-18]. However, what is less worked on is that the change in performance is a function of motor speed, e.g., as the motor speed increases, the performance changes from walking to running. D. Owaki and A. Ishiguro designed a quadruped robot that spontaneously changes its steps between energy-efficient patterns by changing only its speed parameters. It changes its gait from walking to trotting to galloping [19]. Indeed this robot is a model for four-legged animals' locomotive pattern changing. Also, T. Fukui et al. designed a quadruped robot like the previous one, which changes mode with increasing speed and can jump over unperceived obstacles [20]. D. Owaki et al. also designed a bipedal robot with a spring that walks on low slopes and runs on steep slopes [21].

In this paper, a two-mass robot is introduced consisting of a rigid body and an arm that walks by the arm rotation. This robot has two gait modes: walking and jumping; at low speeds, it walks, and by increasing the speed, the movement of the robot slowly turns into jumping, due to the effect of arm inertia.

II. Conceptual Design

An overview of the designed robot is shown in Fig. 1. It consists of a body and an arm. There is a revolute joint between the arm and the body, and a motor rotates the arm.

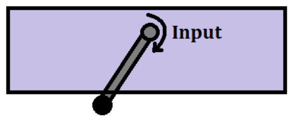

Fig. 1 An overview of the designed robot

At low speeds, the robot movement is quasi-static, and the inertia of the arm does not affect it. The arm acts as a lever, and by hitting the ground, one side of the body detaches from the ground. The friction force between the arm and the ground is greater than the friction force between the body and the ground, so the body slides on the ground and the arm doesn't slide, therefore the robot moves forward.

At high speeds, the body is lifted off the ground due to the significant mass of the arm, and the robot jumps forward. For conceptual analysis of the robot behavior, the arm rotation is divided into four stages, according to Fig. 2. When the arm rotates, its head acceleration vector is in the opposite direction of the arm. If the body is motionless, and r and ω are the length and angular velocity of the arm respectively, the magnitude of the acceleration is $r\omega^2$. So the force exerted from the body on the arm is in the opposite direction of the arm, and the exerted force from the arm on the body is in the arm direction. So, the arm always tends to pull the body towards itself. Of course, this magnitude and direction for the force exerted on the body are approximate because of the body movement and the presence of gravity.

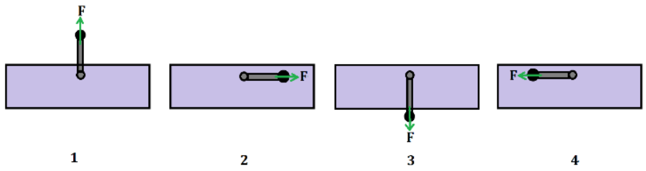

Fig. 2 Stages of the arm rotation

In stage 1, when the body is on the ground, the force exerted on the body is upwards, which, if the magnitude of this force is enough, lifts the body from the ground. In stage 2, due to the fact that no external force is exerted on the robot in the horizontal direction and the relative acceleration of the arm to the body is in the left direction, the acceleration of the body is in the right direction, and the body moves to the right. In stage 3, the arm rotation causes the body to lower, although it may have reached the ground before that due to gravity. In stage 4, if the friction between the body and the ground is sufficient, the exerted force on the body will not move it. Thus, in each rotation of the arm, the robot jumps and moves one step forward.

The effect of arm motion in jumping of this robot is similar to the human arm motion while jumping. When jumping, the person throws his arm forward and up, to have a longer and higher jump [22, 23].

The length and speed of the arm rotation must be selected appropriately so that the robot can make a good jump. Also, the geometric and dynamic characteristics of the body and the arm play an essential role in determining the behavior of the robot at different speeds.

III. Simulation Results

The two-mass robot was simulated in MATLAB SimMechanics, and the solver ode23s was used. The design parameters were selected so that both walking and jumping patterns are generated regularly.

A. Assumptions and Selection of Parameters

In the simulations, the collision of the robot with the ground was assumed viscoelastic, and the Kelvin-Voigt model (parallel spring and damper) was used. The Coulomb model was used for friction between the robot and the ground and approximated by a function according to Fig. 3. In this figure, v is the relative speed, f is the friction force, μ_k is the kinematic friction coefficient, N is the normal force, and v_0 has a very small value.

At the initial moment, the body considered on the ground, the arm considered upwards, and the body velocity was considered zero. Also, the arm rotation velocity (relative to the body) considered being a constant value.

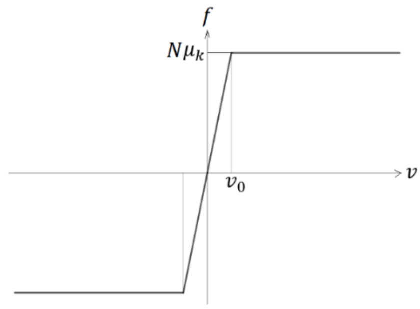

Fig. 3 Model of the friction force

The selected design parameters of the robot are shown in table 1.

TABLE I. Design Parameters (The coordinate system is located on the bottom left corner of the body.)

Length of the body	$0.4\ (m)$
Coordinates of body C.G.	$(0.17\ , 0.02\ )\ (m)$
Coordinates of the revolute joint	$(0.2\ , 0.05\ )\ (m)$
Length of the arm	$0.15\ (m)$
Distance between arm C.G. and revolute joint	$0.13\ (m)$
Mass of the body	$2\ (kg)$
Body moment of inertia	$0.01\ (kg\ m^2)$
Mass of the arm	$2\ (kg)$
Arm moment of inertia	$0.001\ (kg\ m^2)$
The friction coefficient between body and ground	0.5
The friction coefficient between arm and ground	0.8
Collision elasticity	$10000\ (N/m)$
Collision damping	$1000\ (Ns/m)$

B. Results

For input speeds of less than about 12 rad/s, the robot body is detached from the ground only when the arm strikes the ground and is pushed forward by the arm hitting the ground. The stages of this process are shown in Fig. 4. The same thing happens at higher speeds up to about 17 rad/s, except that the body detaches slightly from the ground before the arm hits the ground. Figs. 5 and 6 show the trajectory of the center of the robot (revolute joint location) for different speeds in a range of 4 meters. Fig. 5 shows that up to the speed of 12 rad/s, the graphs are almost the same, i.e., with increasing input speed, the robot follows the same path, and only its speed is increased. However, as the speed increases, the length of the steps decreases slightly, because when the arm moves forward, the body slides back a little. Fig. 6 shows that as the velocity increases, the shape of the trajectory curve changes slightly, indicating that the dynamic characteristics of the robot have affected its motion.

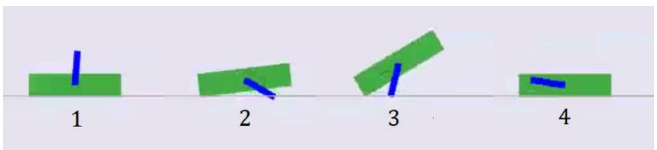

Fig. 4 Stages of the robot walking

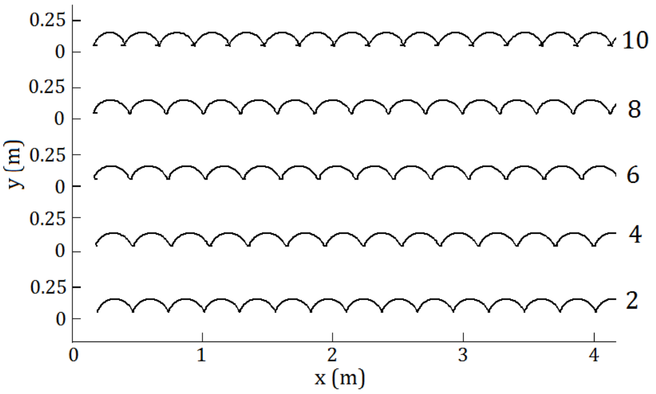

Fig. 5 The Trajectory of the robot center for speeds less than 12rad/s. The numbers on the right are velocities in rad/s.

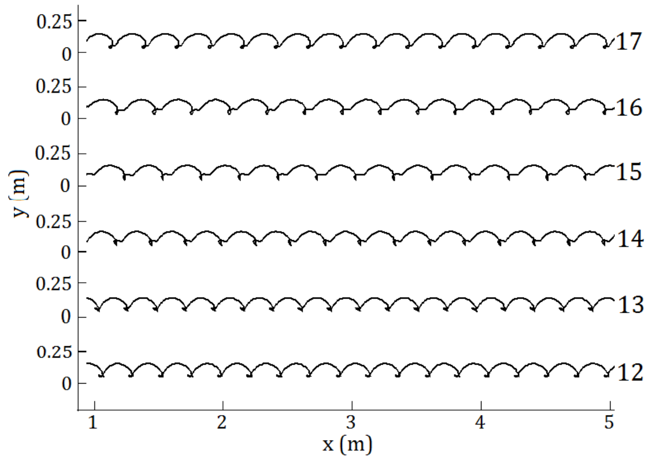

Fig. 6 The Trajectory of the robot center for speeds 12-17 rad/s. The numbers on the right are velocities in rad/s.

At speeds of 18 and above, the body is completely lifted off the ground, and after a short time (less than two seconds), the arm will no longer hit the ground, and the robot jumps and moves forward only due to the inertia of the arm (Fig. 7). Fig.8 shows the trajectory of the robot center for speeds 18 rad/s to 22 rad/s in a range of 4 meters. (which the robot has reached a steady-state.) It can be seen that in this range of speed, the robot has an almost regular and periodic movement pattern. Of course, at speed 22 rad/s, this period is equal to two cycles of the motor.

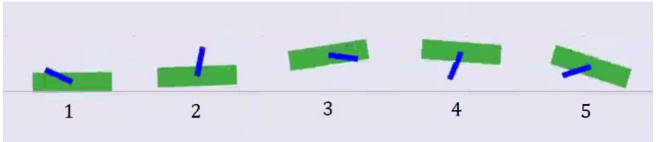

Fig. 7 Stages of the robot jumping

At speeds higher than 22 rad/s to 26 rad/s, it is observed that the robot no longer has periodic movement, and the length and height of its jumps are different, and also sometimes the arm hits the ground (Fig.9).

At speeds higher than about 26 rad/s to about 30 rad/s, it is observed that for every two rotations of the input, the robot has a high jump (Fig. 10). Fig. 11 shows the trajectory of the robot center for speeds of 27 rad/s to 30 rad/s. This figure shows that after a few seconds (between 1 and 5 seconds), the robot reaches a periodic state.

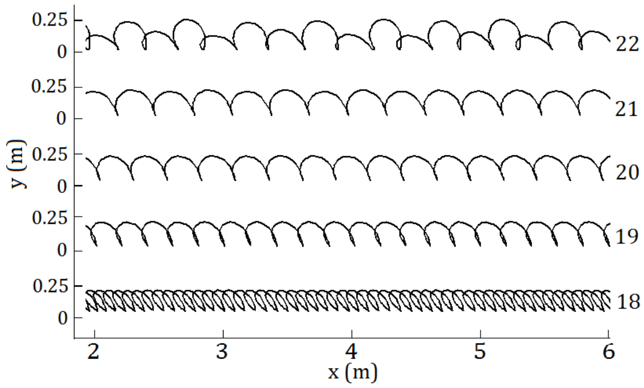

Fig. 8 The Trajectory of the robot center for speeds 18-22 rad/s. The numbers on the right are velocities in rad/s.

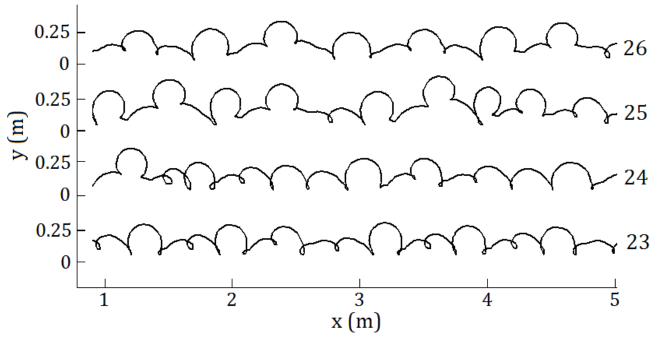

Fig. 9 The Trajectory of the robot center for speeds 23-26 rad/s. The numbers on the right are velocities in rad/s.

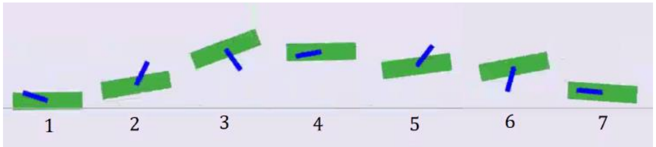

Fig. 10 Stages of the robot double jumping

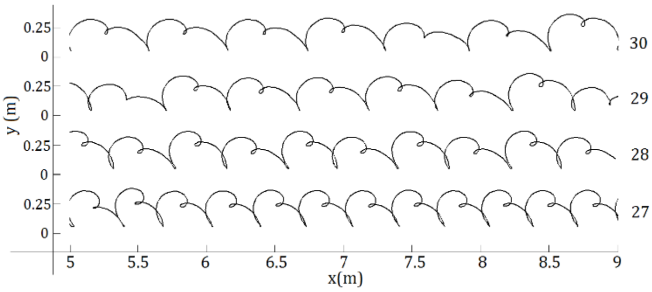

Fig. 11 The trajectory of the robot center for speeds 27-30 rad/s. The numbers on the right are velocities in rad/s.

For input speeds greater than about 30 rad/s, the robot moves irregularly, and sometimes the robot turns upside down.

The simulation results show that for speeds less than about 22 rad/s and also 27 rad/s to 30 rad/s, the robot moves periodically, and this periodic motion will continue for a long time. For example, for speed 20 rad/s, the simulation was performed for 60 minutes, and it was observed that the motion was completely regular and periodic. Also, at speeds where the robot motion does not reach a periodic state, it will not reach after a long time too.

C. Robot Speed

To study the robot travel speed and its relationship with the input speed, the simulation was performed for speeds 0.25 rad/s to 30 rad/s with 0.25 rad/s steps, and the travel speed was measured. The results are shown in Fig. 12. In order to reach the steady-state speed, the simulations were performed for 15 seconds, and the average travel speed was calculated from the second 5 to 15.

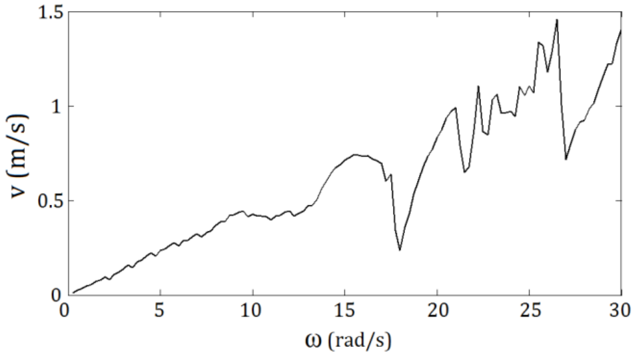

Fig. 12 Robot speed as a function of arm speed

It is observed that by increasing the input speed, the robot travel speed also increases on average. However, the ratio of the robot travel speed to the input speed is not exactly constant and is slightly decreasing on average. Of course, for some input speeds, such as 25-26.5 rad/s, this ratio is even higher than the walking mode.

D. Power Consumption

In this section, the power consumption of the robot is calculated. The work done by the motor on the robot is obtained from the following equation.

$$W = \int M \, d\theta = \omega \int M \, dt \tag{1}$$

Where M, θ are the moment and the angle of the motor. Fig. 13 shows the robot energy consumption as a function of time, for input speed 20 rad/s. It is observed that the rate of energy consumption is variable, and in some moments, when the robot rises from the ground, it is high, and in other moments it is low. The average power consumption rate is approximately 50 watts, which is a reasonable amount.

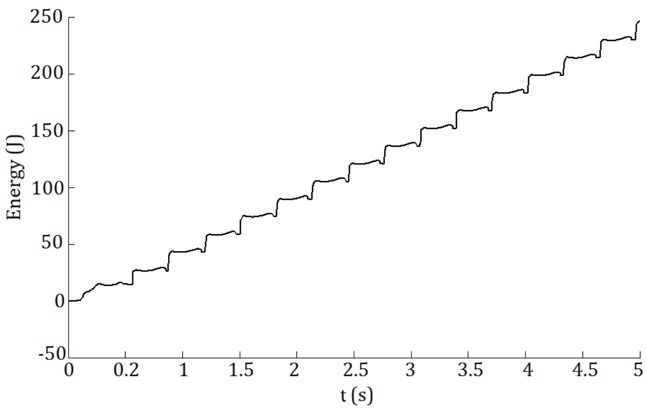

Fig. 13 Robot energy consumption as a function of time for the input speed of 20 rad/s

E. Moving Uphill

By placing the robot on an uphill, it was observed that the robot slips with the previous coefficients of friction, and its progress is meager, and if the slope is high, it even goes backward. Therefore, the coefficients of friction were increased, and the friction coefficients of the body and arm with the ground were set equal to 2. By installing rakes in the corners of the robot body, this amount of friction coefficient can be obtained and even more. The robot was placed on an uphill slope of 15 degrees, and the input speed was given 20 rad/s. The trajectory of the robot center is shown in Fig. 14. It can be seen that the jumps are perpendicular to the ground, and periodic jumping occurs as before. The jump height has not changed compared to the level ground, but the length of each jump has been reduced from 26 cm to 21.5 cm.

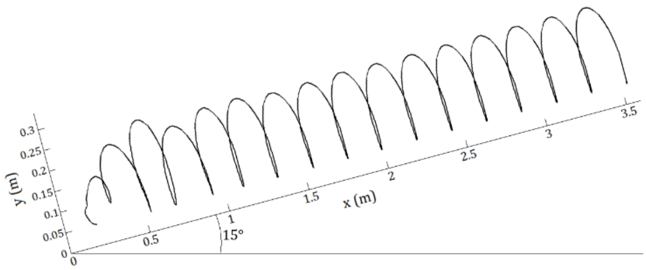

Fig. 14 The trajectory of the robot center on the uphill ground. (The horizontal and vertical axis scales are not the same.)

IV. Discussions

The results show that at speeds up to about 17 rad/s, the robot moves such that the arm hits the ground. This is because the force exerted from the arm on the body is not enough to lift it from the ground. From this speed on, the robot lifts entirely from the ground and jumps because of the reason described in Section 2. For a speed of 18 rad/s, it is observed that the robot progress is very low. This is because if the rotation speed is low, the jump height will be low, and the robot body will reach the ground in stage 2 instead of stage 3 (Fig. 2), and the robot does not move enough to the right because the robot progress must occur in stage 2.

Also, if the arm rotation speed is too high, the arm reaches the left side (stage 4) before the robot reaches the ground, causing the jump stages not to be performed correctly. For this reason, jumps at speeds of 23 rad/s to 26 rad/s are not performed regularly. But at speeds of 27 rad/s to 30 rad/s, the robot motion becomes regular again because the robot reaches the ground at the stage it should reach, but this time after two rounds of arm rotation.

The reason for the slow progress of the robot at high input speeds (27 rad/s and above) is that for every two times that the arm comes to the left, one of them is when the robot has no contact with the ground, causing it to bounce back (Stage 4 in Fig. 2). Of course, at high input speeds, the jump height is higher.

V. Conclusions and Future Works

In this study, a simple two-mass robot consisting of a body and a rotating arm was designed, and its behavior was studied. It was observed that for input speeds less than about 12 rad/s, the robot moves without any jump, and it is always in contact with the ground, which is called walking here. From this speed up to about 17 rad/s, the robot gait pattern is “walking” with a slight jump. From a speed of about 18 rad/s to about 22 rad/s, the motion pattern is jumping, and with each rotation of the robot arm, the robot jumps and takes a step forward, and the arm has no collision with the ground. At speeds of 23 rad/s to 26 rad/s, the robot jumps, but its motion is not regular and periodic, and sometimes the arm hits the ground. At speeds of 27 rad/s to 30 rad/s, the regular forward jump is seen again, but this time for every two rotations of the arm, one jump occurs. In conclusion, it can be said that this robot walks at low input speeds and jumps at high input speeds.

By calculating the energy consumption of the robot, it was observed that its power consumption is not very high, and it has a reasonable amount. Also, by placing the robot on an uphill with a slope of 15 degrees, it was observed that if the coefficient of friction is sufficient, the robot will work well, and only its progress speed will be slightly reduced.

Maybe this robot is suitable for moving on rough roads such as rocky lands because neither at low speeds nor at high speeds does not need flat ground. For example, if the roughness is not too great, it can move in the walking mode, and if the amount of roughness is so tremendous that it needs to lift from the ground, it can move in the jumping mode only by increasing the speed of the arm rotation. Also, if it is being used as a boat, it will act like a rowboat at low speeds, and at high speeds, it can jump on the water surface and move forward. In this case, the boat should be designed with a low drag coefficient in forward-moving and high drag coefficient in backward-moving so that it does not turn back when it is on the water surface due to the arm rotation.

The advantage of this robot is its simplicity because it can perform two different gait patterns by having only two links and a motor, and there is no need to change the robot configuration for changing the gait pattern.

The next step of the research could be to put a DC motor for the input instead of a constant speed so that the robot behavior can be more realistically investigated. The robot can also be simulated on rocky and mountainous surfaces.

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