A ROBOT WITH A SUSPENDED LOAD

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Xingye Da is a senior majoring in mechanical engineering. As a junior in Dr. Justin Seipel's lab, Da applied Fast Fourier Transform and used the marker tracking method to study the dynamics and energetic cost of legged locomotion with a suspended load. Following this research experience, Da continued to design and manufacture a new generation legged robot by rapid prototyping. After graduating from Purdue University, Da is going to the University of Michigan as a PhD student in the controls area.

Abstract

In this research, the objective is to reduce energy (or power) consumption for a legged robot and demonstrate a correlation between energy (or power) consumption and center of mass (CoM) motion. The approach used is to experimentally measure and analyze the power consumption and center of mass motion of a legged robot carrying an elastically suspended load. A high-speed motion-tracking camera system was used to capture the robot body and load trajectories, and an analog-to-digital converter was used to record the robot's average power. By analyzing the frequency content of the trajectories, we found that the center of mass dynamics exhibited multiple frequency components. Each frequency had a unique phase and amplitude that contributed to the average power. A multivariable fitting method was used to quantitatively define the contribution weight of each frequency on the overall center of mass dynamics. We found that the center of mass dynamics may be loosely correlated with the power consumption of locomotion and that multiple modes of motion complicate this relationship.

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Keywords

center of mass, energy cost, locomotion, robotics, suspended load

Mentors

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A ROBOT WITH A SUSPENDED LOAD:

The Statistical Relationship Between Energy Cost and Mass Center Motion

Xingye Da, Mechanical Engineering

INTRODUCTION

Consider two methods of carrying a heavy load. One uses a backpack, and the other uses a shopping cart. The former method costs a significant amount of energy to balance the body and generates significant pressure on the legs, while the latter consumes much less energy and can easily accommodate a heavier load without consuming much additional energy. This energy consumption difference comes from a difference in the motion mechanism of legged motion and wheeled motion. Figure 2 shows how legged motion generates a periodic vertical center of mass (CoM) motion, while wheeled motion minimizes vertical CoM motion. When a leg is raised, the CoM also rises, and when the leg comes down, the CoM also comes down. Since both humans and robots have limited energy storage capacity in the leg, the vertical CoM motion may tend to cost additional energy during locomotion.

On the other hand, legged motion is favorable for mobility and flexibility. People can easily step over an obstacle and make a sharp turn at high speed. Recent research in robotics locomotion is trying to take advantage of legged motion, but at the same time decrease the energy consumption from CoM vertical motion. ASIMO (Sakagami et al., 2002), BigDog (Raibert, Blankespoor, Nelson, & Playter, 2008), and RHex (Saranli, Buehler, & Koditschek, 2001) represent prominent progress of legged robot research (Figure 3). Though BigDog and RHex have the ability to traverse rough terrain, they have not yet approached the energy efficiency found among legged animals.

Figure 1 (Above). Honda's ASIMO is an example of robotic legged locomotion. Courtesy of AZAdam.

Our previous study of a legged robot with a load shows that the energy consumption drops significantly when the rigidly attached load is replaced by a spring-suspended load. Ideally, we want to achieve a maximum reduction in energy consumption. Doing so requires understanding how the energy consumption varies with robot speed, load mass, and the suspension spring stiffness. The relative energy consumption could shift from negative 13% to positive 7%; that is, the spring-suspended load could either save energy or cost more energy.

In this research, we try to target the minimum energy consumption for the legged robot and demonstrate a correlation between energy consumption and CoM motion. We will also address a tradeoff between minimizing the energy consumption and load displacement. The CoM motion turns out to be more complicated than expected, and we use multivariable

Figure 2. Center of mass (CoM) motion in human walking. It bounces up and down periodically like a sinusoidal function. Courtesy of the *Journal of Experimental Biology*.

(a)

(b)

(c)

Figure 3. (A) ASIMO can walk, run, take water, and open a bottle, though it costs five times as much energy as for human beings. Thus, it has to carry a battery as a backpack. (B) BigDog is designed for military march. It can carry a 340-pound load while walking 4 mile/h, with a capacity of 40 miles total. (C) RHex is a hexapod robot with C-shaped legs. It is stable and easy to control, so it is widely used in the legged locomotion research field. Courtesy of Kod*lab.

regression to develop a new conceptual model of robot locomotion with a suspended load.

EXPERIMENTAL PROTOTYPE

We aim to measure the power consumption and CoM motion on a RHex-like hexapod robot (Figure 4). The only variable is the spring stiffness. To represent a general case, we use natural frequency to replace stiffness, which combines the spring stiffness and load mass of the suspension, and is given by the equation $\omega_n = \sqrt{k/m}$. Natural frequency is a fundamental characteristic of periodic motion.

Our hexapod robot has a load suspended by a spring on the top of the robot. The load is attached on a crank that rotates a shaft on the center top of the body. With our robot, the only variable of the experiment is the spring stiffness; that is, we try soft springs and hard springs to test the effect on the robot's mobility and power consumption. Three markers are attached on the robot's body center, the front, and the load, and we track the 3-D motion of the markers by high-speed cameras (Figure 5). CoM motion is calculated by the body and load marker and their mass.

$$y_{CoM} = \frac{y_{body}m_{body} + y_{load}m_{load}}{m_{body} + m_{load}}$$

We also used the voltmeter and ammeter to record the robot's power (Figure 6). From this we calculate the CoM motion and power consumption.

Figure 7 and Figure 8 show the body and load markers' trajectories for different natural frequencies. In Figure 8, the load trajectory is significantly smoother than that in Figure 7. The power consumption drops significantly when the rigidly attached load is replaced by a spring-suspended load. Thus, the CoM amplitude is also smaller in Figure 8 according to the CoM motion formula. Referring to Figure 9, the power consumption is 12% lower than the rigidly attached load when the natural frequency is 2 Hz.

Figure 9 shows the robot average power versus the natural frequency. The minimum power cost is -13% and the maximum is 7%. The overall profile is like an "S" shape with an extra peak around 4 Hz.

DISCUSSION

Minimum Power Consumption

One of the goals of this research is to find the minimum power consumption point over a series of natural frequency setups (i.e., spring stiffness). In contrast to our expectation, we noticed that some natural frequencies of

the load suspension require more power than the rigidly attached load. This behavior can be explained by the following reasons. In the experiment, the robot speed was 30.79 m/s, which bounced the robot body up and down in a domain frequency of 7 Hz and a sub-domain of 3.5 Hz. We call these frequencies the excited frequencies. When the natural frequency is close to the sub-domain frequency, 3.5 Hz, or above the domain excited frequency, 7 Hz, the power consumption would be worse than the rigidly attached load. In Figure 9, when the natural frequency was 4.01 Hz, close to the 3.5 Hz excited

Figure 4. Diagram of the legged robot with an elastically suspended load. The hollow dots are the infrared Vicon tracking markers used to measure the position of the load mass, the body mass, and the front of the robot in 3-D space.

Figure 5. The center of mass moves up and down along with the robot motion. The red line tracks the body marker motion, which is also captured by high-speed camera. The amplitude of the vertical motion is about 3 mm.

Figure 6. The robot is powered by a single DC motor on approximately 3V. The current and voltage are measured, and their product is the power.

frequency, the power consumption “shoots upward,” and we observe a 3% increase in power consumption compared to the rigidly attached load. When the natural frequency was 7.16 Hz or higher, which was over the domain excited frequency 7 Hz, the power consumption was also higher than the rigidly attached load. This phenomenon is known as a resonance effect.

In between the frequency of 7 Hz and 3.5 Hz, the elastically suspended load power consumption was lower than the rigidly attached load, with minimum power consumption at 5.12 Hz. If the frequency is lower than 3.5 Hz, say 2.17 Hz, the power consumption can be

Figure 7. The body and load trajectories with a rigid load (could be regarded as very stiff spring).

Figure 8. The body and load trajectories with a suspension natural frequency of 2 Hz (soft spring).

Figure 9. The average power consumption over 5 trials for each suspension stiffness configuration compared with that of a rigidly attached load at the same speed.

minimized to 12% less than the power consumption of a rigidly attached load.

There exists a tradeoff in choosing either the middle natural frequency (5.12 Hz) or the lowest frequency (2.17 Hz). At the minimum, we want to avoid the frequencies where the power consumption is greater than that of power consumption of rigidly attached loads. As noted in our prior discussions, those bad frequencies arise relative to the domain frequency, 7 Hz, and sub-domain frequency, 3.5 Hz. The values of the domain frequencies, in turn, are determined by the walking speed of the robot, and once the speed increases, say from original 30.79 m/s to 40 m/s, the domain frequency may change to 10 Hz and the sub-domain frequency will change to 5 Hz (the sub-domain frequency is always a half of the domain frequency). In this case, our optimal frequency of 5.12 Hz will hover around the sub-domain frequency of 5 Hz, and the power consumption will increase dramatically. The lower frequency of 2.17 Hz, however, will still exhibit low power consumption. Thus, one may observe that selecting a spring that leads to relatively low natural suspension frequency will be optimal.

On the other hand, keeping a low natural frequency has its disadvantages. Assume the load mass is constant; the lower natural frequency means lower stiffness and larger amplitude of the load when suffering a disturbance. The large amplitude will make the control and stabilization process harder to realize and may exceed the amplitude

$$\omega_n \downarrow \xrightarrow{k = \omega_n^2 m} k \downarrow \xrightarrow{A = F/k} A \uparrow$$

limit of a suspended mechanism. Moreover, lower natural frequency requires longer pre-load distance to keep the load in an equilibrium position, and mechanism design becomes more difficult.

Relationship Between CoM and Power Consumption

From Figure 7 and Figure 8, we might derive a direct relationship between the CoM motion and power consumption: the smaller the amplitude of the CoM motion, the less the power consumption. Notice, it is often the variables such as CoM speed, acceleration, and force that relate to the power and energetic cost of locomotion. Based on the introduction section, the CoM vertical motion is the characteristic motion of legged locomotion, which requires legged locomotion to use more energy

than wheeled motion. Thus, previous research supported the hypothesis of such a direct relationship between CoM motion and energy (or power) consumption (Rome, Flynn, & Yoo, 2006). We could write the following formula that says that the power consumption is a function of the amplitude of the CoM motion:

$$P = f(A)$$

However, the relationship is not obvious in Figure 10, so we took both the amplitude and frequency of motion into

Figure 10. The relationship between CoM and power consumption is unclear in the figure. The CoM amplitude is almost the same at the natural frequency of 3.27 Hz and 4.01 Hz, though the power is significantly higher at 4.01 Hz.

Figure 11. The frequency spectrum of the legged motion at 4.01 Hz natural frequency. The motion includes multiple frequency components and each frequency component corresponds to a different amplitude.

consideration. To simplify the model, we only model the domain and sub-domain frequency, which reaches the largest amplitude in the frequency spectrum (Figure 11).

$$P = f(A, \omega)$$

In addition to Figure 10, we show the CoM amplitude separately with different frequency components in the frequency spectrum (Figure 12). We used multivariable regression to compute the relationship among power, amplitude, and frequency. The multivariable regression provides a complicated formula among frequency components, amplitude, and power. Though the correlative coefficient is as low as 0.48 (close to 1 is a perfect fit), the trend itself matches the experimental

Figure 12. Two main frequency modes in the Fourier expansion are posted in order to find a relationship between CoM and power consumption. Each frequency mode has its dominant area (e.g., a 3.5 Hz mode is significant when the natural frequency is lower or equal to 4.55 Hz).

Figure 13. The regression data qualitatively matches the experimental data.

data (Figure 13). Still, the regression formula is too complicated and may lose this generalization when we apply it to another elastically suspended load mechanism or to the robot with different speed.

$$P = \sum_{i=1}^2 (0.1344\omega_i + 0.1122) A_i^{1/4}$$

CONCLUSIONS

In this paper we investigated the power consumption (which is related to energy consumption) and the CoM motion of legged robot locomotion with an elastically suspended load. We discovered that the minimum power consumption could happen over two ranges of the suspension natural frequency. One is the lowest frequency range, 2 to 3 Hz. The other is between the pitching frequency 3.5 Hz and the walking frequency 7 Hz. There exists a tradeoff in choosing between these possible ranges of the suspension natural frequency. Overall, a multivariable regression can qualitatively fit the observed patterns of power consumption. However, further investigation is needed to determine the relationship between the CoM motion and power (or energy) consumption.

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