Comparison of Leg Dynamic Models for Quadrupedal Robots with Compliant Backbone

Edgar Andres Parra Ricaurte

Universidad Politecnica de Madrid - CSIC

Jesus Pareja

Universidad Politecnica de Madrid - CSIC

Sergio Dominguez

Universidad Politecnica de Madrid - CSIC

CLAUDIO ROSSI (✉ claudio.rossi@upm.es)

Universidad Politecnica de Madrid - CSIC

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Abstract

Many quadrupeds are capable of power efficient gaits, especially trot and gallop, thanks to their flexible trunk. The oscillations of the system that includes the backbone, the tendons and musculature, store and release elastic energy, helping a smooth deceleration and a fast acceleration of the hindquarters and forequarters, which improves the dynamics of running and its energy efficiency. Forelegs and hindlegs play a key role in generating the bending moment in the trunk. In this paper we present our studies aimed at modeling and reproducing such phenomena for efficient quadrupedal robot locomotion. We propose a model, called mass-mass-spring model, that overcomes the limitation of existing models, and demonstrate that it allows studying how the masses of the legs generate a flexing force that helps the natural bending of the trunk during gallop. We apply our model to two representative animals, the cheetah and the horse, that adopt different galloping patterns, and compare their energy efficiency.

Introduction

Bio-inspiration and bio-mimetics are growing research fields. In the last years, the animal kingdom has served as an example in the development of several bio-inspired structures and mechanisms, especially in robotics. An example of this is legged locomotion, that allows agile movements, great stability on different terrains, high speed and energy efficient running [1].

Some of the first walking machines were ODEX one [2], PVII Quadruped Vehicle [3] and SILO4 [4], that achieved optimal gait patterns through a statically stable walking. These prototypes had important movement restrictions, since at least three of their legs had to be in stance with the ground.

In the field of running legged robots representative examples are KOLT [5], Scout II [6], BigDog [7], Star1ETH [8] and the MIT Cheetah 2 [9]. However these prototypes do not take advantage of the flexibility of the trunk in order to achieve fast galloping speed and power efficiently as their natural counterparts do, like, e.g., cheetahs, horses and greyhounds [10].

In our current work, we focus on such key feature, and aim at designing legged robots with high energy efficiency and speed using a compliant backbone. In the literature, research devoted to understanding and developing the mechanics of bending of the trunk can be found. Three types of flexible trunks have been proposed: actuated, semi-actuated and passive.

In the class of robots with actuated trunk, the work presented in [11] showed how the performance of a quadrupedal can be improved actuated joints that allow flexion and extension of the trunk, compared to a rigid bodied robot. The quadruped robot presented in [12] was equipped with a tensegrity-based spine that helped maintaining movement and balance during gaits. Lastly, robot Stoch2 [13] showed the advantages of actuated spine.

As far as legged robots with semi-actuated trunk is concerned, a comparison between three types of flexible spines in the Lynx-robot was performed in [14]. The first of such spines was actuated for both

flexion and extension movements, while the other two, made of a glass fiber rod with different stiffness, were actuated only for the flexion movement and the extension movement was passive.

Concerning legged robots with passive trunk, in [15] the effect of trunk flexibility on the dynamics of a quadruped robot running with a bounding gait was studied. This model was composed of two rigid bodies representing the hindquarters and forequarters, connected through a torsion spring. It was demonstrated that at a constant energy level, the trunk oscillation range and the average forward speed are inversely related. In [16] a robot with a flexible backbone whose stiffness could be changed varying the pressure of pneumatic actuators was used to study the stability of gait pattern for different the trunk stiffnesses. Finally, in [17] the difference between rigid and passive articulated trunk was investigated. The authors showed that the articulated trunk allowed longer strides and significantly affects the dynamics of the robot as well as its power efficiency^[1].

In our current work we are investigating flexible backbones for legged robots, and how this can be exploited for fast and energy efficient running for quadruped robots. We have shown how a flexible spine can greatly help to achieve low power consumption storing and releasing energy during gait. Additionally, a dramatic energy saving can be obtained when the oscillations of the trunk reach a quasi-resonant regime.

It is important to highlight that in most rigid-bodied running quadrupedal robots the legs mass is considered negligible for the purpose of studying robots body dynamics. Such assumption allows a simpler dynamic modeling, and light legs allow faster movements, and therefore faster running. However, when it comes to flexible trunk, this plays a key role, since the motion of the masses of the legs (plus tail and head) and their contact with the ground generates the trunk bending [1, 20].

In a running gait, the center of mass of the leg reaches its lowest point at the middle of step. The kinetic energy and gravitational potential energy reaction force are stored as elastic energy during the *stance phase*, when the leg touches the ground, and recovered during the *flight phase*, when the leg leaves the ground (see Fig. 1, steps h, a, b).

The most studied model for robotic legs for running gaits is the SLIP (Spring Loaded Inverted Pendulum) model (see Figure 2, top). In the flight phase the spring has no effect and thus is not considered, so the dynamics of the leg is represented taking into account only the point mass.

One of the first works on the SLIP model is due to Marc Raibert [28], who showed that SLIP can describe the characteristics of running, trotting or hopping in one leg for bipeds and quadrupeds. Aspects such as stability, dynamics and energy efficiency can be taken into account in this model. Also, Fumiya Iida et al. [29] showed that walking can be described using the bipedal version of this model. Using the SLIP models, various types of quadruped robots have been developed, such as KOLT [5], Scout II [6], BigDog [7], Start1ETH [8] and the MIT cheetah [30], which are capable of walking, trotting and galloping at high speeds in different terrains.

However, the SLIP model characterizes the dynamic formulation in a simple way, since it represents the robot's leg as a point mass and a massless spring that extends towards to the ground. This neglects the inertia of the leg [31]. Hence, this model falls short when it comes to the flight phase of the legs of a galloping robot, i.e. when the leg is not in stance with the ground, since it does not allow generating a force for bending the trunk. In most animals the mass of the leg is very important when performing the galloping movement, especially in quadrupeds with flexible trunks [1]. As mentioned earlier, the mass of the legs helps bending the trunk, allowing it to store and release elastic energy, which allows smoother movements and a more energy efficient gallop [18–20].

Therefore, in order to study the effect of the legs' masses in the dynamics, new models need to be developed. In this paper, we propose a Mass-Mass-Spring (MMS) leg model, as an alternative for quadruped robots with flexible trunk, and demonstrate that considering the mass of the leg in its dynamic modeling, it is possible to control the rotational force at the hip, and therefore induce a bending moment at the end of the trunk in the flight phase.

In the following we compare the proposed Mass-Mass-Spring (MMS) leg model with the Spring Loaded Inverted Pendulum (SLIP) model. As can be seen in Figure 2 (top), the SLIP model is composed of a point mass, M , which represents the hip, and a linear spring, k , that transmits the reaction forces between the ground and the hip, acting as energy storage during the stance phase. For more details about this model we refer the reader to [32–33]. The MMS model takes into account the mass of the leg, located at the knee joint, in addition to the mass of the hip, and a spring that establishes the contact between the mass of the leg and the ground, as shown in Fig. 2, (bottom). Thanks to the additional mass m , it is possible to model the forces that allow the trunk to bend in the flight phase.

[1] Such effect has been observed also in [21,22] and [23] for hopping robots with compliant legs, and on flexible backbones for fish-like robots [24]. Also, a similar effect is also present in insects and birds, whose thoraxes contain compliant structures that accumulate and release energy during the flapping cycle at the benefit of consumption, and also flight stability, see, e.g. [25,26].

The Mass-mass-spring Model

The Mass-Mass-Spring model considers an extra mass, m , that represents the mass of the leg itself, and it's located in the knee joint (Fig. 2, bottom). The mass of the hip, M , and the mass leg, m , are joined by a rigid bar with fixed length L_{hk} (the femur, whose mass is considered negligible).

The MMS model, like the SLIP model, has two main phases. The stance phase, which represents the system dynamics while it is in contact with the ground and where the spring, which joins the mass m of the leg with the ground, acts passively. Then, the flight phase represents the system dynamic during the flight, with the spring resting as the mass m . As can be seen in Figure 3, these two phases alternate in time, achieving a continuous movement pattern that cause the system to move along the x and y coordinates.

Methods

In order to assess the impact that the mass of the leg has on the spine of a quadruped legged robot, we considered the galloping movements of the cheetah and the horse for being fast animals that employ two different types of gallop, the so-called “rotary” gallop for the cheetah and the “transverse” gallop for the horse [10]. In both modes it can be observed how the mass of the leg affects the bending of the trunk.

For the purpose of comparison, the same physical dimensions have been adopted for the two motion patterns (see Table 1). The physical properties of the hind leg of a cheetah *Acinonyx Jubatus* were taken into account, obtained from [35].

Figure 1 shows the differences between the two gallops. The cheetah starts the rotatory gallop with a footfall of one of the forelimbs, to later support with the contralateral forelimb. After that, the cheetah has a flight phase, where the legs are completely below itself, and then continue a footfall with the ipsilateral hindlimb and support with the contralateral hindlimb, and then carry out another flight phase where the legs are extended. In contrast, the horse starts the gallop with one footfall of the hindlimbs and later to support with the contralateral hindlimb, following by the contralateral support of the ipsilateral forelimb and later a footfall of the contralateral forelimb, and then carry out flight phase, where the legs are completely below itself [34].

For the comparison between the MMS and the SLIP model, the following Key Performance Indicators (KPIs) were used: stride length and hopping height, which are used to evaluate the performance of quadruped robots [30,31], and normal effort, tangential stress, minimum bending moment, maximum bending moment (see Fig. 4, left) and bending moment difference, which are used to know the stresses in the materials [36, 37].

Figure 4, (bottom-left), shows the diagram of the simulation setup for measuring the energy that can be stored in the trunk thanks to the mass of the leg, located in the knee joint. The leg is attached at one end of a beam, while the other end of the beam was fixed. The aim of this setup is to measure the forces that are exerted at the ends of the beam representing the trunk of the robot.

In order to assess the effectiveness of the two models, we carried out simulations of a galloping cheetah and horse, using the kinematics and dynamics equations of the models. To acquire the movements described by the hip and the knee we analyzed footage of the running sequence of the two animals^{[2],[3]} using the Tracker^[4] software for the stance and flight phases. To perform the simulation was used Simulink[®] and to have a visualization of the movements was used Robotics toolbox system of MathWorks.

[2] “Maverick Galopp”, 2012, <https://youtu.be/iWGKOHSpE0>

[3] “The Science of a Cheetah’s Speed” – National Geographic and the Cincinnati Zoo, 2013, <https://youtu.be/icFMTB0Pi0g>

[4] Tracker is a video analysis and modeling tool built on the Open Source Physics (OSP), <https://physlets.org/tracker/>

Results

To demonstrate the performance advantage of the MMS model over the SLIP model when used in quadruple robots with a flexible spine, the KPIs obtained using the two models.

Figures 5 and 6 show the trajectories of the hip and the knee resulting from the simulation of the two dynamic models (SLIP and MMS) for the cheetah and for the horse.

Table 1
Physical parameters of the models used

Parameter	Expression	Value
Femur length	L_{hk}	280 mm
Tibia length	L_{kf}	280 mm
Spring length	L	280 mm
Total length	L_{total}	560 mm
Hip mass in MMS model	M	15 kg
Knee mass in MMS model	m	3 kg
Total mass in SLIP model	M_{total}	18 kg
Backbone length	L_{col}	700 mm

Table 2 reports the results of the cheetah simulations. Although the stride length is slightly bigger in the SLIP model, it is important to note the difference in the minimum and maximum bending moments of the two models. As it can be seen in Figure 7, the MMS model is capable of generating a more accurate bending of the trunk. This is because it is the *minimum bending moment* that causes a bending of the trunk, similar to one of the cheetah galloping. The SLIP model only allows to obtain a buckling in the spine.

Table 2
Key Performance Indicators cheetah trajectory.

<i>Parameter</i>	<i>MMS</i>	<i>SLIP</i>
Stride length	0.89977 m	0.93272 m
Hopping height	0.40868 m	0.1954 m
Normal effort	-1.3545 N	0 N
Tangential stress	-178.094 N	-176.58 N
Minimum bending moment	30.5814 Nm	0 Nm
Maximum bending moment	-95.2065 Nm	-123.61 Nm
Bending moment difference	125.7879 Nm	123.61 Nm

Table 3
Key Performance Indicators horse trajectory.

<i>Parameter</i>	<i>MMS</i>	<i>SLIP</i>
Stride length	0.9149 m	0.70173 m
Hopping height	0.2100 m	0.1569 m
Normal effort	2.473 N	0 N
Tangential stress	-179.1306 N	-176.58 N
Minimum bending moment	10.9151 Nm	0 Nm
Maximum bending moment	-114.5645 Nm	-123.606 Nm
Bending moment difference	125.4796 Nm	-123.606 Nm

Similar results are obtained in the horse galloping mode (Table 3). As for the cheetah, in the trajectory of the horse it can be noticed an increase in the minimum bending moment and a decrease in the maximum bending moment for the MMS model, compared to the SLIP model. Again, this is due to the mass of the leg, which induces a rotational force in the hip, which in turn, causes a bending moment to be generated in the spine.

Discussion

The purpose of our current work is to understand and model the mechanics of bending of the trunk in quadrupeds with flexible trunk, with the aim of reproducing the mechanism of storing/releasing energy during galloping. This is a key feature for improving the performance of quadruped robots. Additionally, a flexible trunk helps a smooth deceleration and a fast acceleration of the different parts of the body involved during running, as well as it reduces shocks in the mechanical structure at the benefit of lighter structures and smoother movements.

We have demonstrated how using the modeling the gallop of a quadruped robot with flexible trunk by using the proposed MMS leg model produces better results with respect to the commonly used SLIP leg model. This model, by considering the mass of the leg and positioning it at the point of the knee joint, allows a rotational force to be generated at the center of mass of the hip when performing the galloping movement. Thanks to this, at the end of the quadruped robot's spine, a bending moment is generated in the trunk.

Comparing the cheetah and horse trajectories' KPIs, it can be seen that the horse achieves a longer stride and the cheetah achieves a higher hop. But the most interesting result is the difference in the bending moments. The cheetah presents a bigger minimum bending moment while the horse presents a bigger maximum bending moment. The difference is due to galloping mode. As mentioned earlier, the horse performs the transverse gallop whilst the cheetah performs the rotating gallop. The horse begins to gallop positioning the hind legs on the ground and the front legs in the flight phase, generating a rotational force that allows generating a maximum bending moment higher than the minimum bending moment on its hind limb. On the contrary, the cheetah begins to gallop positioning its front legs on the ground and its hind legs in the flight phase, generating a high rotational force in its rear part and consequently a bigger value of the minimum bending moment, allowing a bigger flexion in the trunk and therefore a higher energy storage, which allows more powerful gait when "launching" its forequarters in the beginning of the aerial phase. This may explain its high velocity and faster galloping compared to the horse.

Declarations

Data availability

The datasets generated and analyzed during the current study are available in the Simulation_Data repository (https://github.com/eaparra01/Simulation_Data). The code of the two models is available at <https://github.com/chechugador/MMR>.

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Figures

Figure 1

Illustrations of the *stance* and *flight* stages of the rotary gallop of the cheetah (top) and the transverse gallop of the horse (bottom). Adapted from [34].

Figure 2

Diagram of the SLIP leg model (top) and Mass-Mass-Spring (MMS) leg model (bottom).

Figure 3

Sequence of the movement of the MMS model. The stance phase in the center of the image and the flight phase is on the sides of the image.

Figure 4

Left: Simplified diagram of a beam with joints for the study of the forces exerted on the trunk. Right: minimum and maximum bending moments.

Figure 5

x and y position and velocity of the (a) hip and the knee (b) of the MMS leg model and the (c) hip of the SLIP leg model in the galloping movement of the cheetah.

Figure 6

x and y position and velocity of the (a) hip and the knee (b) of the MMS leg model and the (c) hip of the SLIP leg model in the galloping movement of the horse.

Figure 7

Scheme of the deformation for the bending moments of the MMS leg model and SLIP leg model in flight phase.

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