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SWING LEG CONTROL FOR ACTUATED SPRING-MASS ROBOTS*

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In this paper we present a control strategy for spring-mass running robots that maintains a consistent running gait on uneven terrains, while prioritizing a limit on the peak forces on the leg. The peak forces are a problem for real machines, potentially exceeding the peak forces of an actuator and leading to a fall, or even breaking robot components. Our control strategy relies on an actuated spring-mass model which is described in section 2. Our controller chooses a leg angle and a leg length during the flight phase, relying entirely on passive dynamics during the stance phase to have symmetric gait and not suffer from high leg forces during the stance phase.

Keywords: Actuated SLIP model, Running robot.

1. Introduction

The planar spring loaded inverted pendulum (SLIP) has been widely used in literature as a model for walking[1,2] and running.[3,4] The stability of this simple model in running[5] explains how animals can run robustly and efficiently in real world. Schmitt et. al.[6] added a very simple controller to the passive SLIP model and made the system more robust.

Very recently Ernst et. al.[4] proposed a flight phase control strategy for running on uneven terrain that leads to steady state running. In their method, the leg angle is chosen such that a steady state running is produced during the stance phase. This control strategy does not require any work during the stance phase, but the leg force is increased dramatically.

Our motivation for this study comes from the response of animals to hidden disturbances[7] as is shown in Figure 1. For them, too, peak leg force appears to be a concern. Ground-running birds carefully limit their leg peak forces when encountering unexpected drop perturbations by extending their

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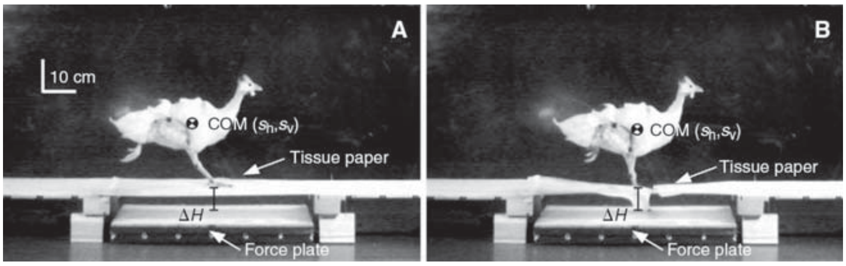

Fig. 1. By extending their leg length and adjusting their leg angles, guinea fowls reject hidden disturbances without suffering from high leg forces.[7]

legs and adjusting their leg angles[7] (Figure 1).

Inspired by the behavior of animals in running, we intend to investigate the effect of the leg length on the dynamics of running. Therefore, a leg actuator is added to the SLIP model[8] to control the length of the leg during the flight phase (Figure 2). The observation of animals' behavior shows that in the level running, the CoM trajectory is close to a symmetric path. When they encounter hidden drops in the ground, their leg length increases to fill the unknown hole height and their leg angle is adjusted to reject the disturbance robustly and efficiently. The steady state running (equilibrium gait) for the SLIP model can be obtained when the leg touch-down angle is the same as the leg lift-off angle and also the CoM velocity components are the same.

2. Methods

The model that we use here is an actuated version of the SLIP model which is shown in Figure 2. The leg actuator is in series with the spring to control the leg length during the flight phase. We keep the motor locked during the stance phase, therefore the dynamics of the system will be entirely passive (SLIP model) in stance phase. The motor inertia and maximum motor torque are considered for the leg actuator to model a realistic electric motor. In addition to the leg length control we assume, like previous studies,[4–6] that the leg angle can also be controlled during the flight phase.

Previously, Ernst et. al.[4] proposed a method to have symmetric gait (steady state running) by only adjusting the leg angle during the flight phase. Figure 3 shows the CoM trajectory of the SLIP model with this control policy. To implement this control policy on a real robot, we need to generate a look-up table which gives us the appropriate touch-down angle

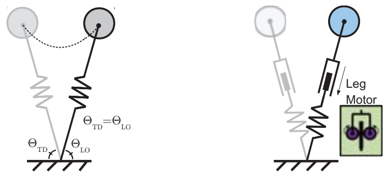

Fig. 2. **Left:** The passive SLIP model **Right:** The actuated SLIP model.

with respect to the vertical component of the CoM velocity. Unfortunately, the peak leg force during the drop increases too much using this control policy. Simulations show that the increase in the peak force in drop gait is about 33% of the steady state value. This increase may break the leg or the transmission of the robot.

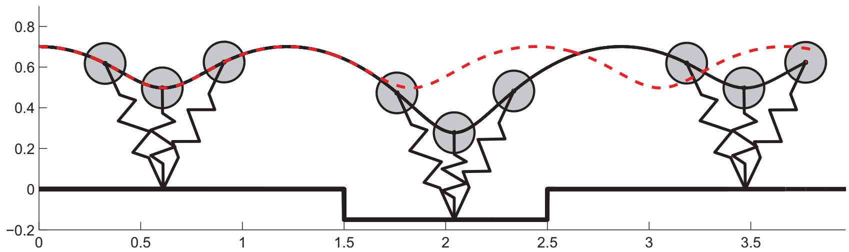

Fig. 3. CoM trajectory of the SLIP model adjusting the leg angle with constant leg length to have symmetric gait.[4]

The control policy used by animals uses the leg extension in addition to leg retraction. Therefore, at each instant (means constant vertical velocity during the flight phase) we look for the relation between the leg length and the leg angle that leads to a symmetric gait for SLIP model. Moreover, we monitor the change in the peak leg force in the stance phase. We need to expand the previous look-up table that Ernst et. al.[4] proposed. In the new look-up table different leg lengths should also be included. Therefore, the required leg angle in each instant is obtained based on the falling time (or vertical velocity) and the current leg length by interpolating among the look-up table data. Since the system is purely passive in stance phase, the well known SLIP model equations of motion are used in stance phase.[2,6]

In Figure 4 the relation between the leg length and the leg angle is shown for different vertical velocities to have equilibrium gait. Each point (pair of leg angle and leg length) on the lines leads to an equilibrium gait for the corresponding vertical velocity. The numbers on the curves show the peak leg forces at those points. It can be seen that to have symmetric gait, the peak force is nearly constant for different leg lengths (numbers along each curve in Figure 4). It means if the leg length extends while the leg angle is being adjusted concurrently (like animals do), the peak force in the stance phase does not vary too much. The whole point is that the leg extension compensates for the hole height and therefore, a symmetric path with nearly constant peak force is generated during the stance phase.

In summary we can design the controller as follows: if the vertical velocity passed the usual value at touch-down; the leg actuator should extend the leg towards the ground. Based on the current leg length at each moment the leg angle should be adjusted using the curves in Figure 4 or the look-up table that was mentioned earlier.

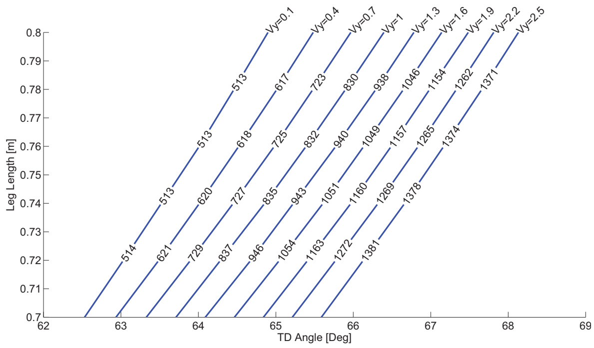

Fig. 4. Leg length vs leg angle for equilibrium gait policy with different vertical velocities. Numbers on the lines show the peak leg force [N] during the stance phase at that point. The peak forces are nearly constant along each curve.

Two different scenarios that may happen during the running are shown in Figure 5. When the vertical velocity of the CoM is less than or equal to the usual value of the vertical velocity at touch-down, the motor does not work and only the leg angle is adjusted to generate symmetric path in stance phase (if there is any step up in the ground). If the vertical velocity of the CoM passes the usual value of the vertical velocity at touch-down it means the robot encounters a step down in the ground. Therefore, the leg actuator extends the leg towards the ground. Because of the existence of the motor inertia and maximum torque, the toe reaches the ground with some delay. Meantime, the leg angle is adjusted based on the current leg length to have symmetric gait in stance phase whenever it hits the ground.

Fig. 5. **Left:** The leg actuator does not work on even ground (no leg extension, only leg angle adjustment during the flight phase) **Right:** The leg actuator extends the leg, the leg angle is adjusted concurrently based on the current leg length.

In our simulations, we assume that the motor has inertia and maximum torque limit. Any leg mass can also be included in motor inertia. In this case, the important physical limitations are considered in the results. To accomplish the simulations, following characteristics are chosen for the model.

Parameter	Description	Value
m	robot mass	$30.0kg$
k_{leg}	leg spring stiffness	$4500\frac{N}{m}$
T_{max}	maximum motor torque	$850N.m$
I	motor inertia	$2.78kg.m^2$
G	Gear ratio	$50:1$
v_{0x}	initial horizontal velocity	$2.5\frac{m}{s}$
h_0	initial CoM height	$70cm$
δ_{gnd}	ground disturbance	$-15cm$

3. Results

The CoM trajectory of the robot controlled with the policy described in section 2 is shown in Figure 6. When the vertical velocity of the CoM becomes greater than the vertical velocities at touch-down in previous strides, the leg actuator starts extending the leg towards the ground. At each moment, based on the new leg length and new vertical velocity the required touch-down angle is calculated from the look-up table. Figure 7 shows the leg force profiles for three cases. As can be seen in the figure, the increase in the peak force with the proposed control policy is only 11% more than the undisturbed case. This increase is due to the small increase in the vertical velocity of the CoM while the motor tries to hit the ground. The increase of the peak force due to the Ernst et. al.[4] method is about 33% more than the undisturbed case.

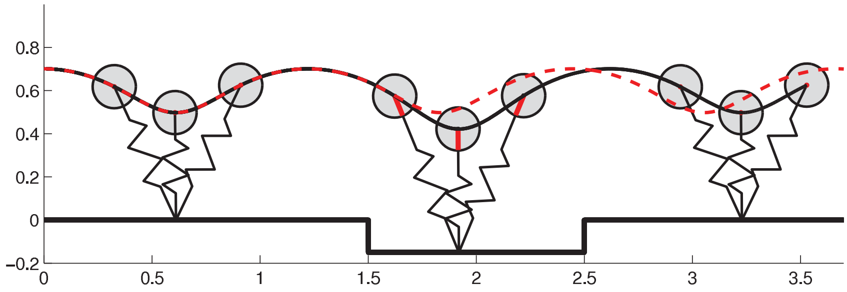

Fig. 6. The actuated SLIP model rapidly extends the leg and adjusts the leg angle concurrently. The red line on the leg at the drop gait is the increased leg length.

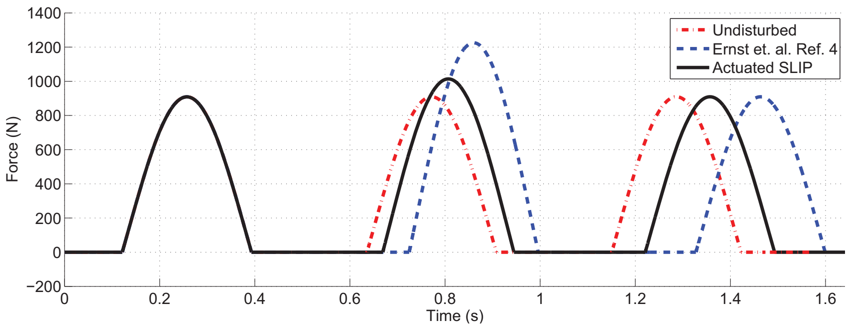

Fig. 7. Leg force profiles show the peak force increases only 11% if the leg is rapidly extended. This increase is due to the physical limitations of the motor like motor inertia. Without leg extension, increase in leg force would be 33%.

4. Conclusion

In this paper we proposed a bio-inspired control strategy for the flight phase that leads to steady state running but more importantly keeps the leg force nearly constant in the presence of disturbances. The proposed control policy comes from the fact that if the leg length extends while the leg angle is being adjusted appropriately (like animals do), the peak force in the leg does not increase too much. It means the leg extension partially compensates for the drop and the leg angle is updated to generate the symmetric path. It should be noted that the small increase in the leg force in our simulation is due to the physical limitations of the motors that prevent them to act instantaneously.

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