SPRING-LEGGED LOCOMOTION ON UNEVEN GROUND: A CONTROL APPROACH TO KEEP THE RUNNING SPEED CONSTANT

[1]MICHAEL ERNST, [2]HARTMUT GEYER AND [1]REINHARD BLICKHAN

[1]Science of Motion, Friedrich-Schiller University Jena, Seidelstr. 20, 07749 Jena, Germany, email: {michael.ernst, reinhard.blickhan}@uni-jena.de

[2]Automatic Control Laboratory, Swiss Federal Institute of Technology Physikstrasse 3, 8092 Zurich, Switzerland, email: geyerh@control.ee.ethz.ch

We present a feedforward control for spring-legged systems in uneven terrain which keeps the running speed constant. The control uses the unique transformation between ground level and flight time to automatically adapt the system parameters during flight to the actual ground level without having to detect it. We further demonstrate how this control for constant speed running can simultaneously be combined with other control strategies in spring-legged systems to adapt their behavior to a desired locomotion task.

1. Introduction

In recent years, robots using spring-like leg behavior have increasingly been developed. This development was pioneered in the 1980s by Raibert and colleagues who introduced a legged hopping robot that balances on an air-spring [1]. In the 1990s robots using more than one compliant leg were introduced (e.g. Spring Flamingo [2], Scout II [3]). Today, spring-legged robots from hexapods (RHex [4], Sprawlita [5]) to quadrupeds (Tekken series [6], BigDog [7]) to bipeds (JenaWalker series [8], Kenken series [9]) exist.

Although more and more spring-legged robots are built, the theoretical potential of such dynamic locomotion systems has been explored to only a limited extent. Theoretical studies mainly focus on the stability of spring-like locomotion. For instance, based on the spring-mass model, it could be shown for the horizontal and sagittal plane that the running gait can be self-stable [10-12]. This stability analysis could later be extended to locomotion in three dimensions [13]. On the other hand, adding to the spring-mass model a clock that drives the rotation of the spring leg, it could be shown how a feed-forward rhythmic pattern can also stabilize dynamic running robots [14].

While the stability of dynamic locomotion is critical, other criteria may be of similar importance to legged robots. For example, although the self-stability of spring-legged locomotion can be maximized with a swing-leg control [12], this control introduces large variations in running speed if the legged system encounters large changes in the ground level. Such random variations in running speed will not be desired if legged robots have to cover a distance in the shortest possible time, or if they need to maintain a constant speed.

In this study, we investigate what alternative control strategies exist for spring-legged locomotion to keep the running speed constant on uneven ground. In particular, exploiting the spring-mass model's different parameters for steady-state solutions, we derive a swing-leg control strategy that keeps the running speed constant from step to step. Our control can be combined with other controls in spring-legged robots to adapt their behavior to the desired locomotion task.

2. Method

The spring-mass model and its parameters are well known [15, 16], (Fig. 1A). The model consists of a point mass attached to a massless spring. In running, the model alternates between ballistic flight and spring-loaded stance phases. Four independent parameters define the model dynamics, for example, the angle of attack α with which the spring leg touches the ground, the dimensionless spring stiffness K, the dimensionless forward speed F, and the apex height y, where y is the maximum height reached by the point mass during flight.

For all parameter configurations (α, K, y, F), the steady-state solutions of the model can be obtained by simulating its dynamics for a single step from one apex y_i to the next y_{i+1}. A steady-state solution corresponds to $y_{i+1} = y_i$. We implemented the spring-mass model dynamics in Matlab/Simulink (Mathworks, MA, USA), simulated for each parameter configuration a single step, and assumed that it describes a steady-state solution if the deviation $|(y_{i+1} - y_i)|$ was smaller than 10^{-3}m.

3. Results

Our goal is to identify a control strategy which keeps the running speed constant on uneven ground. Since for any steady-state solution the running speed at the apices i and $i+1$ is equal, we fix the parameter F and constrain our search for steady-state solutions to the parameter subspace (α, K, y). All these solutions automatically have the same running speed F. For four such running speeds F, the identified steady-state solutions are shown in figure 1B as four adjacent but separate domains in this parameter subspace.

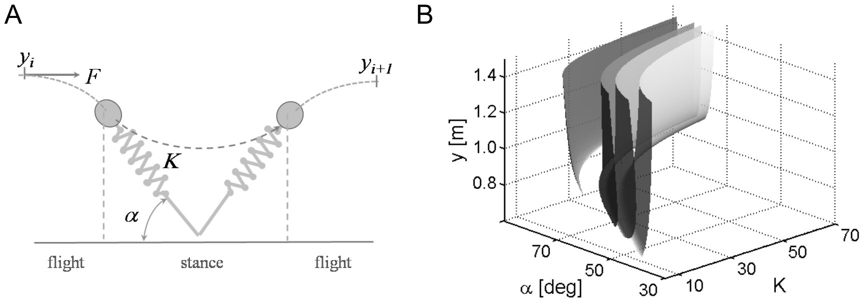

Fig 1. Spring-mass model and its parameter configurations for steady-state locomotion with constant running speed. (**A**) Schematic representation of the model and the four independent parameters (α, K, y, F). (**B**) From back to front, parameter subspaces of steady-state solutions for four different running speeds $F = v^2/(g\, L) = [0.41, 1.63, 2.25, 5.0]$. Note that L is the leg length, g is the gravitational acceleration. Note further that the dimensionless running speeds F correspond to absolute speeds v of [2, 4, 5, 7] ms^{-1} for a human sized running system.

For running on uneven ground, a control that keeps the speed F constant (for instance, $F = 2.25$) requires not only that the parameters (α, K, y) belong to the corresponding speed domain (second to front domain in Fig. 1B), but also that they have to match with the ground level. The apex height y cannot be chosen freely; it changes automatically with the actual ground level in each step. Therefore, the parameters α and K must be further constrained. To adapt these parameters to the current y, the ground level either must permanently be measured and embedded in a feedback control, or can more elegantly be encoded in a time law of a feedforward control during flight [12].

The feedforward time encoding exploits the fact that the time in flight from apex to touch down is uniquely coupled to the apex height y and the angle of attack α : t_{fall} = sqrt $[2/g \cdot (y - L \sin\alpha)]$. We use this equation to transform the parameter subspace (Fig. 1B) into a subspace that is independent of the apex height y. Figure 2B shows the result of this transformation for the parameter domain corresponding to $F = 2.25$. As long as the parameters α and K evolve with t_{fall} in this domain, the running speed keeps constant at $F = 2.25$, independent of the ground level encountered in each step. Thus, there is no single control but an infinite number of controls for constant speed running.

This variability can be used to combine different control strategies. For example, in figure 2B, the light curve along the domain combines constant speed running with a constant leg retraction rate in swing [17]. Because the constant leg retraction $\alpha(t) = \alpha_0 + \omega \cdot t$ defines the evolution of the angle of attack during swing, the spring-leg stiffness K must also be adapted in swing to maintain a constant running speed, resulting in the light curve along the parameter domain.

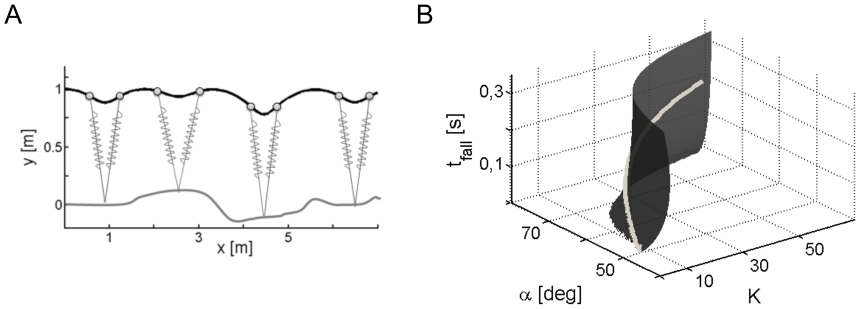

Fig 2. Constant speed running on uneven ground. (**A**) Schematic representation of the spring-mass model running on uneven ground. Note that, because the running speed is constant, the apex heights in flight must also be equal. (**B**) Time-dependent steady-state solutions for the speed $F = 2.25$. The model's parameters α und K must evolve with time in flight after apex, t_{fall}. The light curve along the domain shows one possible parameter adaptation [α (t), K (t)].

4. Discussion

Our results show that an infinite number of control strategies exists to let spring-legged systems run on uneven ground with constant speed. We used a systematic scan of the model's independent parameter space (Fig. 1) and the unique transformation between ground level and flight time to identify these strategies and to encode them in a feedforward control during swing (Fig. 2). The second step ensures that the actual ground level need not be measured from step to step. We moreover demonstrated that the control of constant speed running on uneven ground can be combined with other controls for spring-legged locomotion.

This flexibility in control is an important requirement. By itself, constant speed running is unstable. A small error in the time dependent parameters α (t) and K (t) will result in a drift from step to step away from steady-state solutions. To prevent an eventual fall of the spring-legged system, the constant running speed control either has to be adapted after some steps or an additional control has to be applied that returns the system to steady-state solutions. To include such an automatic return control, we are currently working on generalizing the unique transformation between ground level and flight time to other control strategies stabilizing spring-legged locomotion.

In conclusion, we identified control strategies for constant speed running on uneven ground, which can be combined with other control strategies in spring-legged robots to adapt their behavior to a desired locomotion task.

Acknowledgments

The authors would like to thank the German Research Foundation (DFG, Bl 236/15-2) for supporting this work.

References

[1] M. H. Raibert, *Legged Robots That Balance* (The MIT Press, 1986).
[2] J. Pratt, and G. Pratt, in Proceedings of the 36th Annual Allerton Conference on Communication, Control and Computing, 1998.
[3] M. de Lasa, and M. Buehler, in Proceedings of the 3rd International Conference on Climbing and Walking Robots, 2000.
[4] R. Altendorfer *et al.*, Autonomous Robots **11**, 207 (2001).
[5] J. E. Clark *et al.*, in Proceedings of ICRA, IEEE International Conference on Robotics and Automation, 2001.
[6] Kimura Lab (2009), http://robotics.mech.kit.ac.jp/.
[7] Boston Dynamics (2008), http://www.bostondynamics.com.
[8] Lauflabor (2008), http://www.lauflabor.uni-jena.de.
[9] ATR Computational Neuroscience Labs (2009), http://www.cns.atr.jp/~sangho/.
[10] J. Schmitt, and P. Holmes, Biol Cybern **83**, 501 (2000).
[11] A. Seyfarth *et al.*, J Biomech **35**, 649 (2002).
[12] A. Seyfarth, and H. Geyer, in Proceedings of the 5th International Conference on Climbing and Walking Robots, 2002.
[13] J. E. Seipel, and P. Holmes, The International Journal of Robotics Research **24**, 657 (2005).
[14] R. Altendorfer, D. E. Koditschek, and P. Holmes, The International Journal of Robotics Research **23**, 1001 (2004).
[15] R. Blickhan, J Biomech **22**, 1217 (1989).
[16] H. Geyer, A. Seyfarth, and R. Blickhan, J Theor Biol **232**, 315 (2005).
[17] A. Seyfarth, H. Geyer, and H. Herr, J Exp Biol **206**, 2547 (2003).