Simulating Muscle-Reflex Dynamics in a simple Hopping Robot

Andre Seyfarth¹, Karl Theodor Kalveram¹,² und Hartmut Geyer¹,³

¹ Locomotion Laboratory, University of Jena, Germany,
² Institute of Experimental Psychology, University of Duesseldorf, Germany,
³ Media Lab, Massachusetts Institute of Technology, Cambridge, USA
andre.seyfarth@uni-jena.de

Abstract In legged systems, springy legs facilitate gaits with subsequent contact and flight phases. Here, we test whether electrical motors can generate leg behaviors suitable for stable hopping. We built a vertically operating sledge actuated by a motor-driven leg. The motor torque simulates either a linear leg spring or a muscle-reflex system. For stable hopping significant energy supply was required after midstance. This was achieved by enhancing leg stiffness or by continuously applying positive force feedback to the simulated muscle. The muscle properties combined with positive force feedback result in spring-like behavior which enables stable hopping with adjustable hopping height.

1 Introduction

Design and construction of legged robots are constrained by the properties of actuators, for instance by the specific torque-current and speed-torque relationships of motors, or the gear induced friction. In order to improve the efficiency and stability of the gait patterns (e.g. walking, running, hopping), often spring-like structures are introduced in walking machines. Thereby it is assumed that mainly the tendons in the biological muscle-tendon-joint system contribute to the observed elastic behavior of legs. When simulating muscle-reflex dynamics [1], however, we found that the reflex-driven muscle itself can behave spring-like even if the tendons are completely stiff. Hence, quasi-elastic limb behavior does not necessarily require passive elastic-compliant structures within the body.

The present paper is concerned with one-legged hopping on place with subsequent contact and flight phases. Can such a hopping pattern also be considered to emerge from pure muscle-reflex activity?

To test this hypothesis we built a simple hopping device called Marco hopper. Marco consists of a body and a motor-driven leg moveable in the vertical direction.

The question is, what types of force generation laws produce force patterns which move the body during stance such that alternating flight and stance phases occur. The advantage of Marco is that different types of force generation laws can easily be selected and applied via the motor. Explicitely, we do not intend
to get hopping by control, that is to say, by prescribing a desired trajectory to
the sledge and/or rod and enforcing the Marco to keep that trajectory using
negative feedback and/or feedforward control. We rather aim at self-stabilizing
oscillations which only use intrinsically given and peripherally measurable states
of sledge and rod to shape ground reaction forces resulting in stable hopping.

The purpose of the paper, therefore, is to demonstrate conditions and require-
ments which provoke or impede stable bouncing of a hardware hopper, without
using a pattern-based movement controller.

2 Methods

2.1 The Marco Hopper

Figure 1(a) shows the technical realization of the Marco hopper. A sledge repre-
senting the body slides through ball bearings on a vertical rail. A rod repre-
senting the leg is attached to the sledge and is allowed to move up and down
relative to the sledge. On the sledge, a motor is mounted. It drives the rod via
a toothed wheel fixed on the motor shaft, which in turn scrolls a toothed belt
attached to the rod. If the rod’s foot has ground contact (stance phase), the
sledge can be accelerated upward by an appropriate current through the motor.
Without ground contact (flight phase), the common centre of mass of sledge and
rod follow the laws of free fall. Below the rod’s foot point a ball consisting of
Adiprene (a highly damping material) is attached. This shock absorber attenu-
ates impacts on the ground plate which could damage the device. A Maxon DC
motor ADS50/5 with a build in gear box (gear ratio 1:14) actuates the rod. The
weight of the sledge is 1.3 kg, the weight of the rod is 0.5 kg. The gear enhances
the inertia of the rod by 1.9 kg, and the friction force by 6 N. That means that
the gear makes the rod with respect to the sledge a very inert and stiff device,
as indicated by the fact that the rod sticks on the sledge and is not pulled down
by gravitation if the sledge is lifted up.

The motor is driven by a Mattke MAR24/6Z power amplifier adapted to
current control. Here, the current through the motor is strictly proportional to
the input voltage of the amplifier, regardless of the motor speed. Because the
amplifier automatically counterbalances the electro-dynamical back EMV of the
motor, the force exerted by the motor can be read from the input voltage into
the amplifier.

Three sensors capture the state of Marco: A POSIMAG system measures the
y-position $y_S$ of the sledge, a tachometer coupled to the gear’s drive side measures
the y-velocity $dy_L/dt$ of the rod, and a strain gauge on the ground plate beneath
the rod measures the contact force. The length $y_L$ of the rod is computed by
numerical integration of the tachometer signal. The scaling is chosen such that
$y_S$ agrees with $y_L$ during stance, and that at the deepest position of the sledge
both $y_S$ and $y_L$ reach zero.

Data conversion is managed by the Meilhaus AD/DA computer interface card
ME2600i. The data are processed by Matlab/Simulink and RealTime Workshop.
2.2 How to make Marco hopping

Principally, stable hopping is achievable only if the energy losses of the bouncing system can be compensated. The question is, whether the energy supply is scaleable in such a manner that overcompensation or undercompensation can be avoided, or at least balanced out on average over several hopping periods.

Regarding a hopping mechanical systems, energy can be enhanced only in the ground contact phase (stance phase). Midstance, that is the point of time at which the rod reaches the minimum length respectively the sledge the deepest position, sections the stance phase into two parts, stance1 before and stance2 after midstance. Obviously, (positive) energy supplied in stance1 cannot refill the energy reservoir, because the additional energy is consumed by braking the sledge, and only prevents the sledge to fall as deep as it would have fallen without...
Figure 2. Models of energy supply in Marco. The explicit numerical values of the selected parameters refer to Figure 3.

that energy supply. In contrast, energy supplied in stance2 can contribute to upwards acceleration of the sledge, such that the kinetic energy at the end of the contact phase can be managed to reach or exceed the kinetic energy at the beginning of the contact phase. Therefore, energy feeding should be asymmetrical with respect to midstance: During stance2, the energy fed into the system should be greater than during stance1.

2.3 The force generating laws

The force generating law of the leg during ground contact is, according to the Hill-type muscle model, modeled as a product of basically three variables (Figure 1(b)): The lowpass filtered stimulation \( s \) which results in the activation \( a \) of the driving system, the force-length relationship \( F_L \) which describes the force as dependent on the deviation of the rod's actual length \( y_L \) from a reference length \( y_0 \), and the force-velocity relationship \( F_V \) which maps the force as dependent on the velocity \( dy_L/dt \) by which the length of the rod changes [1]. Usually, these variables are on hand in a normalized fashion. Therefore, a fourth factor representing the maximum isometric force \( F_{max} \) is then needed for the overall adjustment. Here, \( F_{max} \) was set to 1 because we didn't apply any normalizations.

It should be mentioned that in an elastic object the notation "reference length" refers to the rest length, that is the length the object would attain without being exposed to external forces. In Marco, the reference length \( y_0 \) of the rod is arbitrarily chosen to \( y_0 = 0.11 \text{ m} \). Notice that the real muscle is stretched in the ground contact phase, whereas the rod exerts force in the compressed mode, so the sign in the \( x \)-axis of the force-length curve is inverted for usage in Marco. For energy supply, an additional input called \( \Delta s \) is provided by which an extra stimulation can be added upon the basic pre-stimulation \( s_0 \).
Figure 3. Four hopping experiments: (a-c) Simulated leg stiffness during contact and (d) simulated muscle-reflex system. Leg stiffness is increased with time: (a) at midstance or continuously in a linear (b) or quadratic fashion (c). Shortly before ground contact the leg was somewhat shortened to attenuate the landing impact.

3 Four models for energy supply and results

We derived from the basic model of Figure 1(b) four submodels which differ with respect to the manner by which the energy admitted in stance 2 is made exceeding the energy supplied in stance 1. The models are sketched in Figure 2. In all models, the same force-length relationship was applied using

$$F_L = \begin{cases} y_0 - y_L & \text{if } y_0 - y_L \geq 0 \\ 0 & \text{else} \end{cases}$$

(1)

The force-velocity dependency was set to 1, hence, it had no influence. In model 4, however, a second curve with a nonlinear decay was selected.

Model 1: Here, the behavior of a mechanical spring, which is essentially given by Hooke’s law, was the force generating law. The stimulation s can therefore be
interpreted as the stiffness of this spring. If the basic stimulation is held constant, the maximum potential energy of this spring is given by

\[ W + \Delta W = (s_0 + \Delta s)/2 \cdot (h - y)^2, \] (2)

where \( h \) denotes the deepest position of the sledge attained in midstance, \( y \) the position the sledge will attain when the ground contact is lost and the flight phase starts, and \( \Delta W \) the increase of energy if the stimulation is enhanced by \( \Delta s \) during stance2. The value of \( h \) is measured and held back by a Simulink unit when the sledge velocity goes, coming from negative values, through zero. In our system, \( y \) is expected to reach at least the reference length \( y_0 \) which is 0.11 m. So we determined the ‘stiffness’ enhancement during stance2 by

\[ \Delta s = 2 \Delta W/(h - y)^2, \] (3)

where \( \Delta W \) is the amount of energy we wished to inject into the system. Model 1 was operated with \( s = 180 \, \text{N/m} \) and \( \Delta W \) ranging from 3.0 to 2.4 \( \text{Nm} \). These parameter values induced stable hopping, whereby the apex heights decreased from 0.15 to 0.14 m. At \( \Delta W = 2.2 \, \text{Nm} \), however, hopping ceased after two jumps. Figure 3(a) shows the result for \( \Delta W = 3.0 \, \text{Nm} \).

**Model 2:** In this version, we increased linearly the stimulation \( \Delta s \) to be added to the basic stimulation \( s_0 \) during the complete stance phase, starting with zero at the beginning of ground contact. We applied gains ranging between 4000 and 6000 \( \text{N/m} \), but we did not succeed in achieving stable hopping. In Figure 3(b) the result for a gain of 6000 \( \text{N/m} \) is sketched.

**Model 3:** Here we increased the stimulation \( \Delta s \) quadratically with respect to time (model 3 in Figure 2). With gains between 60 kN/m and 125 kN/m stable hopping could be achieved. Figure 3(c) visualizes the result with a gain of 100 kN/m.

**Model 4:** In this approach we implemented a muscle-reflex mechanism, namely, a positive force feedback. The feedback signal was delayed with times between 20 and 50 ms during the complete ground contact phase of the rod. The force-length relationship was the same as in the models 1-3 The force-velocity relationship was either given the value 1 during stance as in the other models or an exponential dependency on velocity after midstance:

\[ F_V = \begin{cases} 
 e^{-2\frac{dy_L}{dt}} & \text{if } \frac{dy_L}{dt} \geq 0 \\
 1 & \text{else}
\end{cases} \] (4)

Both versions of the force-velocity dependency resulted in stable hopping patterns, as expected from previous simulations. For the exponentially dropping force-velocity relationship, a force-feedback delay of 30 ms and a gain of 140 N/m the result is given in Figure 3(d). For \( F_V = \text{const} = 1 \), however, the slope in stance2 was steeper and produced a more asymmetrical positional trajectory of the sledge with a slightly higher apex (not shown).
4 Discussion

The purpose of this study was to demonstrate how stable hopping can be generated in a robot leg: It demands to replace the lost energy. This can be performed in different ways. The common feature of the tested models was that the energy supply after midstance exceeded the energy supply before midstance.

Model 1 generated stable hopping pattern with the lowest activation difference between the two stance phases. The apex height was clearly dependent on $\Delta s$, the stimulation added upon the basic stimulation $s_0$ during stance2. Supply models 3 and 4, too, produced stable hopping with apex heights scaleable through gain changes. Supply model 3, applying quadratic stiffness change, achieved the highest apices. Model 4, governed by positive force feedback, achieved higher hopping frequencies than model 3, hence, the apex height was smaller in model 4.

The advantages of models 3 and 4 compared to model 1 are, that no measurements are necessary to determine the instant of midstance and the minimum height of the sledge. The hopping oscillations are completely selfpreserving. The movement patterns are simply determined by the gain in the feedback loop. The disadvantage of models 3 and 4 is that in stable hopping considerably higher activation values occur than in model 1, which may overdrive the amplifier respectively the muscle.

The outstanding feature of model 4 is that its built-in muscle-reflex mechanism, the positive force feedback, is capable of generating stable and scaleable hopping patterns even in a robot.

At last it should be noted that the limited ranges in gain parameters and hopping heights are likely due to the very high energy losses caused by the extremely high friction in the gear, and also due to the necessity to avoid overdriving the power amplifier.

Acknowledgments

This study was supported by grants SE1042/2 and KA417/24 of the German Research Foundation (DFG).

References