Force Modulated Compliant Knee Control with Compliant Actuator for Stable and Efficient Hopping

Omid Mohseni, Andre Seyfarth, Maziar Ahmad Sharbafi
Lauflabor Locomotion Laboratory, Technische Universität Darmstadt, Germany.
mohseni, seyfarth, sharbafi@sport.tu-darmstadt.de

1 Introduction

Hopping as a key simplistic gait for understanding legged locomotion requires extensive knowledge of both mechanics and control. Achieving stable and efficient hopping, therefore, relies on a proper design in both aspects. The so-called Electric-Pneumatic Actuation (EPA) [1] is our proposed solution to this problem. EPA is in fact a variable impedance actuator that can adapt to different requirements of a given system. Having both an electric motor and a pneumatic artificial muscle (PAM) at its disposal, EPA offers precise control with high bandwidth and energy buffering capabilities, which are needed for efficient locomotion.
A locomotion task such as hopping requires consecutive energy harvesting (when hitting the ground) and energy injection (when rebounding off the ground) phases. These phases can be implemented either physically by the compliant elements in the system or virtually through the controller. On one hand, the PAM as a powerful actuator with muscle-like properties [2] in the EPA structure enables the physical implementation of these phases by adjusting the leg physical compliance. On the other hand, the electrical motor in the EPA enables controlling the leg stiffness virtually. The combination of these two then makes up a simplified version of physical impedance adjustment and reflex control, similar to what seen in the human neuromuscular system.
To investigate and benefit from the potential advantages of EPA, in this work, we target hopping in two hopper robots, called the EPA-Hopper-I (for 2D hopping) and MARCO-Hopper-II (for 1D hopping); see Figure 1. Inspired by the positive force feedback concept [3] here, we introduce the novel force modulated compliant knee (FMCK) method to control the electrical motors of the EPA system while using PAMs as parallel compliances to accompany the motors.

2 Robotic Setups

The EPA-hopper-I and MARCO-Hopper-II robots both have a segmented leg consisting of a thigh and a shank segment that mimics the human leg in the sagittal plane. The trunk in these robots is represented by the mass attached to the hip joint. The robots' hips are guided by linear bearings constraining motion to vertical translation. One main difference between the robot structures is that in the MARCO-Hopper-II, a Bowden cable between the hip and the foot defines the maximum knee extension and transfers the kinetic energy from the hip to the foot to enable hopping; which creates a 1D motion while EPA-Hopper-I can perform hopping in 2D as a result of its extra degree of freedom.

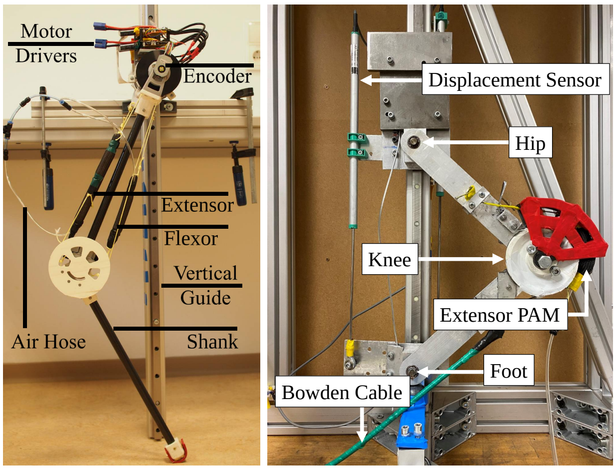

Figure 1: Robotic Setups: (left) EPA-Hopper-I with a two-segmented leg capable of 2D hopping driven by two electrical motors and an extensor pneumatic artificial muscles (PAM); (right) MARCO-Hopper-II with a segmented leg actuated by a series elastic actuator through the Bowden cable and a parallel PAM on the knee joint for 1D hopping.

3 Control Scheme

For generating stable hopping patterns, here we follow the idea of Force Modulated Control [4] which mimics a virtual adjustable spring that can be modulated by the ground reaction force (GRF) feedback. This GRF-based control has already been employed to generate human-like hip and ankle torques. Here, we employ this concept to tune the knee stiffness in the force modulated compliant knee (FMCK) controller as follows:

$$\tau = CF\left(\phi_0 - \phi\right) \tag{1}$$

where, τ, F, and ϕ are the torque generated at the knee joint by the motor, GRF, and the knee angle, respectively. This simple controller has two tuning parameters C and ϕ_0, representing the normalized stiffness and the rest length of the modulated spring, respectively. To implement the controller, the hopping sequence is divided into flight and stance sub-phases. In EPA-Hopper-I, during the stance phase, the

FMCK controller is employed to control the knee while the hip motor is set free. And in the flight phase, knee and hip joints are position controlled to predefined target angles using PD controllers. In MARCO-Hopper-II, in the stance phase, the positive part of the FMCK output torque is tracked by a PD controller while the negative part is neglected. As the actuator in this robot cannot control the leg during the flight phase, the actuator is controlled to be at the right position with a desired speed at the next touch down.

4 Results and Discussions

4.1 EPA-Hopper-I

The experiments on EPA-Hopper-I were carried out in two cases of with and without the extensor PAM (P_{ext}). The results were then compared based on the hopping height, energy consumption, and efficacy. For this robot, the hopping height (h) is defined as the difference between the maximum hip height and a predetermined hip height at touchdown. The energy consumption (EC) is computed as the summation of both knee and the hip absolute work during stance and flight phases. And, the efficacy (ρ) criterion is measured as twice the leg's potential energy divided by the energy consumption as $\rho = 2mgh/EC$, where g is the gravitational acceleration and m is the robot mass which is 2.87 kg. After searching for appropriate control parameters, we set the FMCK parameters to $C = 0.07$ and $\phi_0 = 0$. Also, to compare the effects of the extensor PAM, we set the the initial air pressure inside of it once to zero and once to 6 bar. The results of the experiments are summarized in Table 1. An insight into the table reveals that the proposed FMCK controller can stabilize the hopping motion regardless of the presence of PAMs. The addition of PAM, however, is shown to increase the hopping height while decreasing the energy consumption. As a result of these two outcomes, the efficacy of this hopping case is $\rho = 26.6\,\%$ which shows an improvement of 7.2%. These results show that the addition of PAM to the robot can support the motors to consume less energy and also help improve the overall performance.

4.2 MARCO-Hopper-II

To assess the effects of the parallel PAM on the efficacy (ρ) of MARCO-Hopper-II ($m = 2.72$ kg), we carried out the experiments for nine experimental conditions: generating three desired hopping heights (6, 10, and 14 cm) with three different PAM pressures (0, 4, and 6 bar). The averaged efficacy of 100 hops (10 experimental trials with 10 hops in the steady state condition) are plotted in terms of PAM pressure for all the experimental conditions in Figure 2. It is shown that the addition of the PAM can increase the efficacy. For low hopping heights (e.g., 6 cm) higher PAM pressure or equivalently stiffer artificial muscle is more effective in increasing the efficacy whereas a PAM with moderate stiffness is more efficient for hopping higher heights (e.g., 14 cm).

Table 1: Experiment results of EPA-Hopper-I summarizing the effects of PAM pressures on hopping performance.

Metric / PAM	h [cm]	EC [J]	ρ [%]
$P_{ext} = 0$ bar	17.89	40.59	24.85
$P_{ext} = 6$ bar	19.16	39.68	26.62

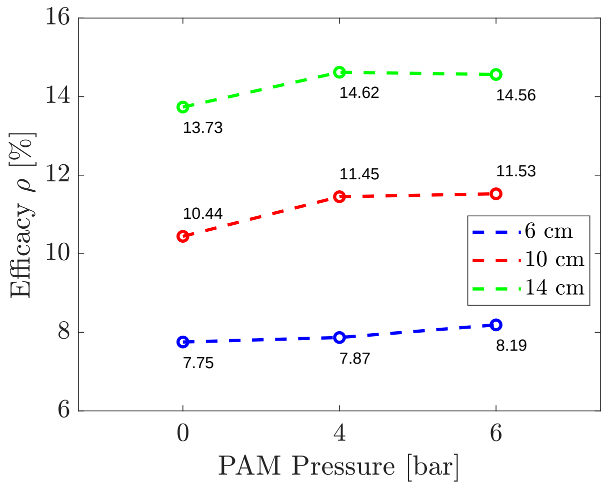

Figure 2: Effect of PAM on efficacy of MARCO-Hopper-II. Mean of efficacy over 100 hops using the optimal FMCK parameters is shown for three desired hopping heights.

5 Conclusions

In this work, we employed the electric-pneumatic actuation (EPA) system towards achieving stable and efficient hopping in two hopper robots with different levels of complexity. We presented a GRF-based controller - named FMCK - for control of the knee joint via the electrical motors in the EPA and utilized PAM in a parallel configuration to examine its influence on the efficacy of hopping. As an outcome, it was observed that the proposed controller can stabilize hopping and the incorporation of PAMs can improve the efficacy of hopping. Furthermore, validation of the results in two robots (one capable of 1D hopping and the other 2D) highlights the extendability of the EPA design to more complex legged locomotors.

References

[1] Maziar Ahmad Sharbafi, Hirofumi Shin, Guoping Zhao, Koh Hosoda, and Andre Seyfarth. Electric-pneumatic actuator: A new muscle for locomotion. In *Actuators*, volume 6, page 30. Multidisciplinary Digital Publishing Institute, 2017.

[2] Omid Mohseni, Ferréol Gagey, Gouping Zhao, Andre Seyfarth, and Maziar A Sharbafi. How far are pneumatic artificial muscles from biological muscles? In *2020 IEEE International Conference on Robotics and Automation (ICRA)*, pages 1909–1915. IEEE, 2020.

[3] Hartmut Geyer, Andre Seyfarth, and Reinhard Blickhan. Positive force feedback in bouncing gaits? *Proceedings of the Royal Society of London. Series B: Biological Sciences*, 270(1529):2173–2183, 2003.

[4] Maziar A Sharbafi and Andre Seyfarth. Fmch: a new model for human-like postural control in walking. In *2015 IEEE/RSJ International Conference on Intelligent Robots and Systems (IROS)*, pages 5742–5747. IEEE, 2015.