

Open-loop control strategies in passive dynamic hopping

¹Marco Hutter, ¹C. David Remy, and ¹Roland Siegwart

¹Autonomous Systems Lab, ETH Zürich,

email: mahutter@ethz.ch, web: www.asl.ethz.ch

SUMMARY

We investigated control concepts for hopping motions of an articulated leg that is driven by series elastic actuators. A highly compliant spring in the knee joint allows the exploitation of periodic energy storage but creates a major control challenge by severely limiting the bandwidth of closed-loop position or force control. This is exacerbated by slow actuators, substantial delays, and the kinematic coupling in the articulated design.

With classic closed-loop control strategies failing, an adaptive open-loop control scheme is presented that, over a series of jumps, gradually modifies the motor inputs in order to maximize jumping height and minimize slippage.

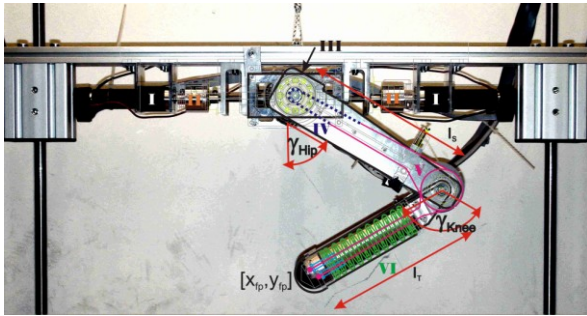


Figure 1: Experiments were performed on an articulated robotic leg with series-elastic actuation. The spring for knee actuation was included in the shank with a cable pulley system.

INTRODUCTION

To perform an efficient running, a robotic system must be equipped with elastic elements that temporarily store energy and recover it later in the gait cycle. To match the natural frequency of these elements with the hopping frequency of the robot low stiffness springs are required [1]. Series elastic actuation [2] is used to feed energy into the system and reject disturbances without impeding the underlying passive dynamic motion. However, the compliant elements act as mechanical low-pass filters which limits the controllability of the joint angles.

We build an articulated leg (Figure 1) with series-elastic actuation in the hip and knee joints, and developed control algorithms for one dimensional hopping using adaptive open-loop control strategies that circumvent the low bandwidth dilemma by considering the control task not as a time continuous problem but on a step-to-step basis.

METHODS

Three separate controller phases were defined for stance, flight, and pre-impact speed matching (Figure 2). The hopping motion is generated during stance [A] by

thrusting the knee motor with a desired angular velocity. The hip motor profile is adapted after every jump by estimating the spring compressions to ensure a purely vertical motion of the ground contact point and prevent slipping. During flight [B], the leg is simply brought into a predefined landing configuration where it is awaiting touch down. Damping and the nonlinear spring characteristics of the pulley system in the knee allow precise leg positioning by simply setting the actuator position to the desired joint angles. To prevent the generation of slipping at touchdown, the leg segments are accelerated to designated pre-impact velocities [C], which eliminate the tangential impulse at touch down. The controller was implemented in simulation and a robotic prototype.

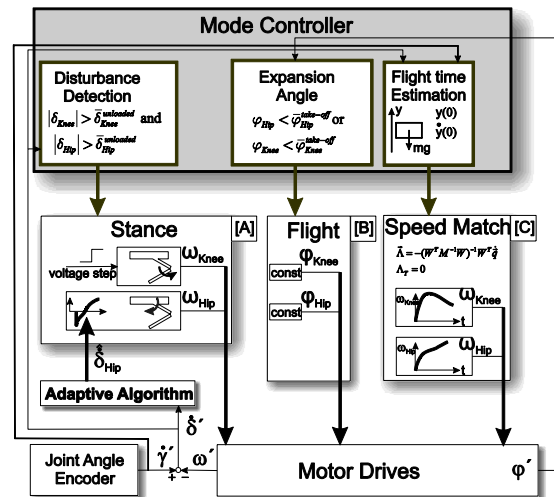


Figure 2: A three-phase open-loop control strategy generated motor trajectories for stance, flight, and pre-impact speed matching.

RESULTS AND DISCUSSION

The presented algorithm converged robustly towards a purely vertical, open-loop jumping motion without slipping. A steady limit cycle was reached within less than 3 jumps during which the controller adaptively generated open-loop motor trajectories for stance, flight, and pre-impact speed matching. These trajectories resulted in stable limit cycles and enabled periodic hopping for different loads and height levels.

REFERENCES

1. Farley, C.T., *Running springs: speed and animal size*, J. Exp. Biology, 185, pp. 71-85, 1993
2. Robinson, D.W., *Design and Analysis of Series Elasticity in Closed-loop Actuator Force Control*. PhD Thesis, Dep. Of Mech. Engineering, MIT, 2000