A sagittal plane hexapedal running model: Towards robust locomotion with feed forward actuated serial elastic hips and serial elastic telescoping legs

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1 Motivation

Being able to slowly traverse rough terrain with our torque controlled, actively compliant walking hexapod [3], we are aiming at a new design that includes passively compliant elements in order to achieve increased mechanical robustness and dynamic locomotion capabilities. For this purpose we return to the analysis of conceptual models like the planar hexapedal runner with massless legs and serial elastic actuation. We believe that fast locomotion basically can be modeled as coupled nonlinear oscillations of a hybrid dynamical system. Our goal is to identify some of the core elements that result in self-stabilization and disturbance rejection of a periodically excited mechanical system in the context of rapid hexapedal locomotion.

2 State of the Art

Up to today, many researchers addressed the identification and anlaysis of hexapedal running and the underlying structure of its great robustness by experiments with insects [9] and robots [6, 2] as well as by modeling and simulation [1, 5, 7, 8, 4]. Hereby, a large variety of feed forward controlled models with different levels of complexity exist that try to capture the behavior observed on insects. These models range from simplified sagittal and horizontal plane models towards full 3D implementations with various combinations of passive elastic, active elastic or purely active rotating hips and telescoping legs (detailed list of references is omitted due to limited space). While for horizontal plane locomotion the lateral leg spring model [7, 8] reveals closely matching translation and rotation behavior the analysis of sagittal plane models as well as full 3D models often neglects pitch and roll dynamics. To the best of our knowledge the analysis of limit cycle behavior of coupled translation and rotation of a running hexapod that includes pitch and roll dynamics remains an open problem to be solved in future.

3 Approach

In our approach we model the sagittal plane hexapedal runner as a body with mass m and mass moment of inertia J, six massless, serial elastically actuated, telescoping legs and collinear placed, serial elastically actuated hips. All actuation is modeled as feed forward periodic change of the force free length of the linear prismatic leg springs and the linear rotational hip springs. Hereby, the legs are grouped in two tripods that are actuated $180°$out of phase at a single frequency. Currently, no passive dampers are modeled and damping is actively provided by the serial elastic actuators. In our approach we want to clarify if linear serial elastic actuators combined with the posture dependent kinematic nonlinearities and periodic excitation are sufficient to establish self-stabilizing locomotion.

4 Current Results

For our model with a mass of 1 kg, a mass moment of inertia of 0.01 kgm^2 and a nominal COM height of 0.12 m, we have performed simulation studies and found distinct parameter sets that result in stable periodic forward locomotion. Within a relevant range, the average forward velocity (1.06 m/s to 2.96 m/s) is approximately proportional to the frequency of feed forward excitation (5 to 15 Hz). Each tripod shows sequential touchdown of the feet following the sequence: hind leg, middle leg, front leg. We observed no distinct flight phase but a double stance phase with partially overlapping tripods. Further, we found that all legs have similar vertical ground reaction forces while they specialize in exhibiting horizontal forces. Hereby, the front legs dominantly brake while the hind legs dominantly accelerate the body. The middle legs do both, they first brake and then accelerate. The locomotion limit cycle appears to be attractive with respect to a broad range of initial conditions. Additionally, the model rejects 20% step up and 30% step down disturbances as well as force impulses larger than 10 times the body weight. Being strongly disturbed or starting at rest the horizontal ground reaction forces of the model sometimes exceed limits imposed by ground friction constraints. Including a second order friction model for the

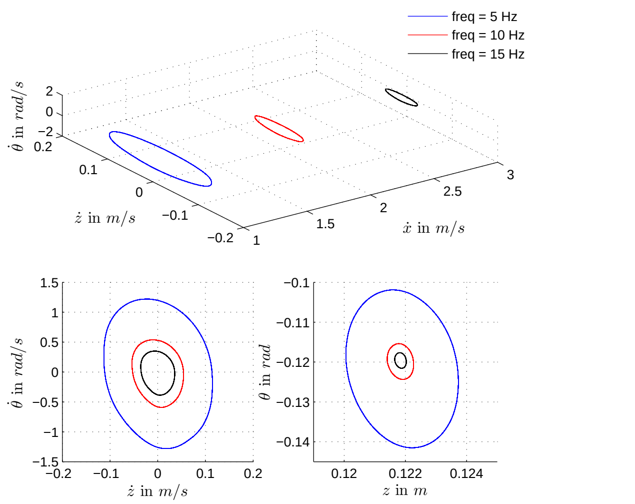

Figure 1: Limit cycles for three different feed forward actuation frequencies

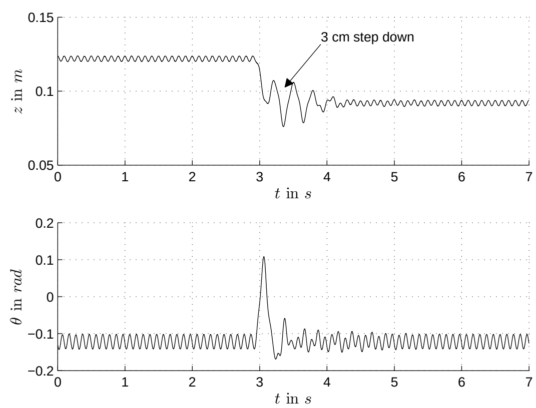

Figure 2: Vertical center of mass and pitch angle trajectories for running at 5 Hz feed forward controlled periodic actuation across a 3 cm downward step; (negative pitch angle for upward tilted front)

foot contact points the horizontal forces remain bounded with respect to the appropriate friction forces and no severe influence on the self-stabilizing behavior was found. For our model the springs seem to mainly influence the proper phasing of energy exchange rather than enhancing efficiency.

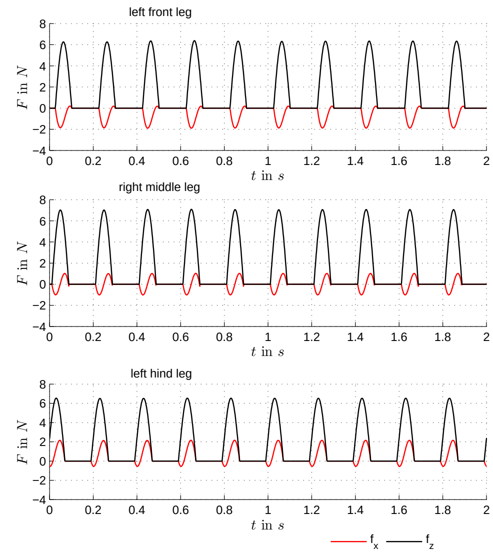

Figure 3: Foot forces of the left tripod for running with approximately 1 m/s at 5 Hz feed forward controlled periodic actuation

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