Nonlinear Modes for Efficient Robotic Locomotion

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I. BACKGROUND

Inspired by vertebrate animals, Articulated Soft Robots are mechanical systems with a rigid structure, and soft joints. It is intuitively clear that adding elasticity to a (possibly nonlinear) mechanism should improve its capability to perform oscillatory tasks - as for example various forms of locomotion. Yet, developing general techniques for exciting and sustain these nonlinear oscillations proved to be a quite hard task. Nonlinear modal theory [1] comes as a possible solution this challenge. Within this field Eigenmanifolds are defined as nonlinear extensions of the linear eigenspaces.

II. METHODS

Stabilizing Eigenmanifolds promises to be a robust way of exciting regular and efficient oscillations [2]. These surfaces can be obtained using continuation methods. We are currently working at a general approach to use this technique in locomotion. The proposed control paradigm based on nonlinear modes also leads to simplification of the control structure. Remarkably, a pure feedback control action plus energy regulation may be sufficient to achieve stable gaits [2]. Applications to this theory to locomotion have been limited so far to simple heuristics, however, preliminary experiments on a hopper and a quadruped have demonstrated that this idea is feasible and it generates useful gaits [3].

III. RESULTS AND DISCUSSION

Without requiring trajectory optimizations, stable efficient running can be achieved for all energy levels on the Eigenmanifold, each of them corresponding to a distinct speed. This is shown in Fig. 1, which depicts snapshots of a simulated two segmented leg hopper with springs in the joints changing its velocity by adjusting the mechanical energy. Fig. 2 shows the Eigenmanifold and the resulting trajectories during the locomotion phases. The simulations have also shown that the system is robust to considerable variations of the initial conditions, to substantial friction in the joints, and also to external forces acting during both stance and flight. Analyzing a system in terms of modes is also effective to investigate the optimal mechanical design to deliver the maximum efficiency for a range of speeds.

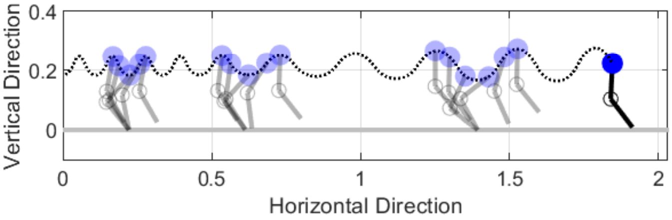

Figure 1. Snapshots of efficient and stable running of a two-segmented leg system exploiting a nonlinear mode and varying speed.

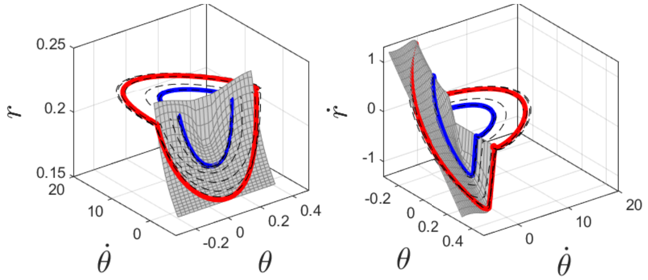

Figure 2. Evolution of the trajectories in state space. The manifold depicted in gray is the Nonlinear Normal Mode (NNM) associated with the mechanical system. Initially the systems orbits at low energy level (solid blue) and then progressively accelerates to reach a higher energy level (solid red), thus running stably at a higher speed.

IV. CONCLUSION

We are excited to propose and push forward this approach, which strives to interpret the complexity and concrete challenges of locomotion in terms of an abstract nonlinear theory of oscillations. This is of course just a preliminary contribution, and substantial work is still needed before reaching the desired performance. If this interpretation reveals to be correct, we believe that it could lay the foundations for the development of new methods and insights for robotic locomotion and beyond.

V. ACKNOWLEDGMENT

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