Improving energy efficiency of a bipedal walker with optimized nonlinear elastic coupling

Yinnan Luo*, Ulrich J. Römer*, Lena Zentner** and Alexander Fidlin*

**Institute of Engineering Mechanics, Karlsruhe Institute of Technology (KIT), Karlsruhe, Baden-Württemberg, Germany*

***Compliance Systems Group, Technische Universität Ilmenau, Ilmenau, Thuringia, Germany*

Abstract. This work introduces a method to improve the energy efficiency of a bipedal walking robot, using nonlinear elastic couplings between the robot's thighs. The robot model consists of five rigid segments which are connected by four revolute joints in the hip and knees. The joints are actuated by electric motors and the walking movement is generated and stabilized by a nonlinear controller. The optimum walking gaits and the optimum characteristic of the elastic coupling are identified via numerical optimization whereby the energy consumption of locomotion is minimized. Compared to the robot without elastic couplings, we find a mean reduction of the energy consumption by 78 % which is significantly better than the optimal linear coupling which only achieves mean savings of 62 %.

Method

Energy efficiency of locomotion is an important feature of bipedal walking robots. It essentially determines the walking distance that can be covered, since the energy storage of the robot e.g. a battery is usually limited. Our research focuses on improving the energy efficiency of bipedal walking movements on flat ground based on a five link robot model. In this model rigid segments are connected by four revolute joints, where electric motors provide the driving torques for the motion. In addition, the robot's thighs are coupled by an elastic coupling with a nonlinear characteristic that is described via cubic splines. A nonlinear controller based on the hybrid zero dynamics approach with polynomial reference trajectories produces and stabilizes the robot's periodic walking gaits, consisting of alternating single and double support phases. According to previous studies [1], the energy efficiency of the robot depends not only on its mechanical design parameters but also on its movements. This efficiency is assessed by the cost of transport (COT): the energy consumption of the electric motors divided by the walking distance and the weight force of the robot. Minimizing energy consumption during locomotion is formulated as a numerical optimization problem, which simultaneously optimizes the robot's gaits and its mechanical design parameter, in this case the nonlinear characteristic of the elastic coupling.

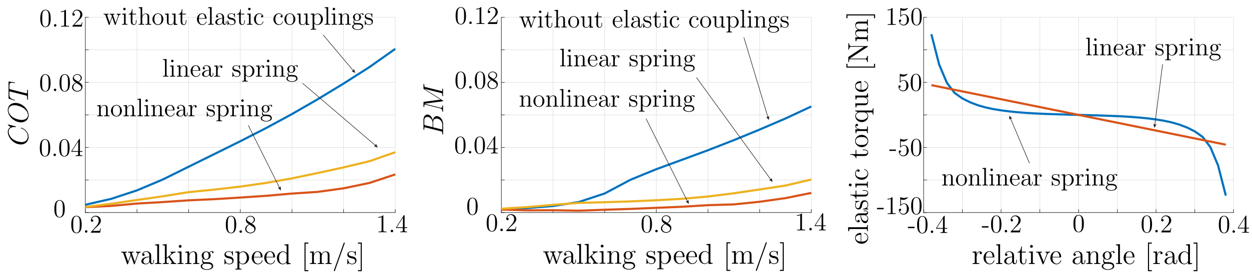

Figure 1: Left: Cost of transport in the speed range of 0.2 m/s to 1.4 m/s with and without elastic couplings. Middle: BM: Removed energy due to braking mode of the actuators (divided by the walking distance and weight force of the robot similar to COT). Right: Optimized characteristics of linear or nonlinear elastic couplings.

Results

The optimization is carried out for walking speeds in the range of 0.2 m/s to 1.4 m/s. Compared to the robot without elastic couplings, the mean energy consumption over all walking speeds can be reduced by as much as 77.67 % using the optimum nonlinear characteristic, compared to only 62.24 % for the optimum linear spring. The elastic couplings modify the natural frequency of the swing leg motion so that the resulting optimum walking gaits closely match the system's resonance motion. Since walking gaits of our model are limit cycles of the controlled robot system, the mean energy is constant. Therefore, the electric energy which is supplied in each step (this is optimized by minimizing the COT) is equal to the energy losses of the swing leg impact to the ground and the braking operation of the actuators, where the generated electrical energy mainly turns into heat. A detailed analysis of the system dynamics reveals that the nonlinear elastic coupling significantly reduces the actuator powers during the braking operation at the end of the swing phase before the impact. Instead of removing this energy from the system, it is stored as potential energy in the elastic couplings and used for accelerating again at the beginning of the next step.

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References

[1] U. J. Römer, C. Kuhs, M. J. Krause and A. Fidlin (2016) Simultaneous optimization of gait and design parameters for bipedal robots. *Proceedings of ICRA* 1374-1381.