The Influence of ground inclination on the energy efficiency of a bipedal walking robot

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One of the major tasks in developing bipedal walking robots is to improve energy efficiency of their locomotion. In this paper a method for extending this research by considering ground inclinations is introduced. The investigated robot is driven by electric motors in its revolute joints. Robot's gaits for different walking speeds are generated via numerical optimization, minimizing energy consumption during locomotion. Energy efficiency can be increased for differently inclined grounds where the robot utilizes its natural dynamics and gravity.

1 Introduction

In regard to the wide range of bipedal robots' applications, the complexity of the environments should be considered. For instance, bipedal walking movements on an inclined ground are investigated on different humanoid robots [1, 2]. While these researchers focus on stabilizing the motion in different environments, the goal of our study is to improve the robot's energy efficiency, which is mainly determined by its mechanical design parameters and the movements influenced by a controller. Through optimization of these factors a high energy efficiency can be achieved according to simulations [3, 4]. In this paper, we simulate bipedal walking movements on grounds with upward and downward inclinations to extend available methods for the development of bipedal walking robots with the ability to move in many environments with high efficiency.

2 Method

We consider the robot model in Fig. 1(a) which consists of five rigid segments that are connected by four revolute joint with electric motors as actuators; the thighs are connected by a linear torsion spring with stiffness k. Periodic walking includes alternating single and double support phases. In the single support phase, the swing leg is in a unilateral contact with the ground and subject to static friction; the double support phase is modelled as an impact where the former swing leg touches the ground and the former stance leg lifts off. As the robot is modelled with point feet, no torque is transmitted between the stance leg and the ground. This contact is subjected to unilaterality and static friction and is modelled as an unactuated revolute joint. The ground inclination is described by the angle β, as depicted in Fig. 1(a). A positive β produces an upward slope, otherwise a downward slope. The model from [4] is extended to account for the tilted normal and tangential force components as well as for the height of the stance leg foot in the double support phase.

The robot's gaits are described through trajectories of its joint angles, which are created and stabilized by a hybrid zero dynamics based controller [5]. This control approach utilizes the robot's natural dynamics instead of suppressing them, and thus allows for a high efficiency. The resonance frequency of the mechanical system can be modified by the torsion spring [6]. In related previous works, minimizing the energy efficiency is formulated as an optimization problem. The input of electric power at each motor is considered for the calculation of the energy consumption per distance and weight (the cost of transport), which is used as the criterion to assess the energy efficiency. If any motor is driven as a generator, the electric power is negative and assumed to be ignored in previous works [7]. However, the change in potential energy due to the ground inclination has a strong influence on the required energy to be supplied by the actuators. In the case that the robot walks downwards so slowly that the required energy for walking is majorly supplied by gravitational potential energy [8], the solution in numerical optimizations is not unique. To avoid this ambiguity, we introduce a modified objective function that evaluates the generated electrical energy from motion. Furthermore, we assume that only $20\,\%$ of this can be recovered since there are losses in the electric circuit from the battery and controller to the motors / generators which is not modelled. To find energy efficient walking gaits, we minimize the cost of transport $c = E_{\mathrm{supp}} / (\ell\, m\, g)$ which we define as the energy E_{supp} which is supplied by the actuators during one step, divided by the step length ℓ and the robot's weight $m\, g$.

The investigated robot model is symmetrical and has a total body mass of 9.00 kg and a total body height of 1.15 m. Its thigh length and shank length are both 0.30 m. In order to analyze how the energy efficiency is improved through coupling robot's thighs by a torsion spring in different environments, this study is carried out for different walking speeds from 0.2 m/s to 1.4 m/s on the ground with inclination angles from -10° to 10°. The stiffness of the torsion spring as well as robot's gaits are optimized simultaneously to achieve a high energy efficiency.

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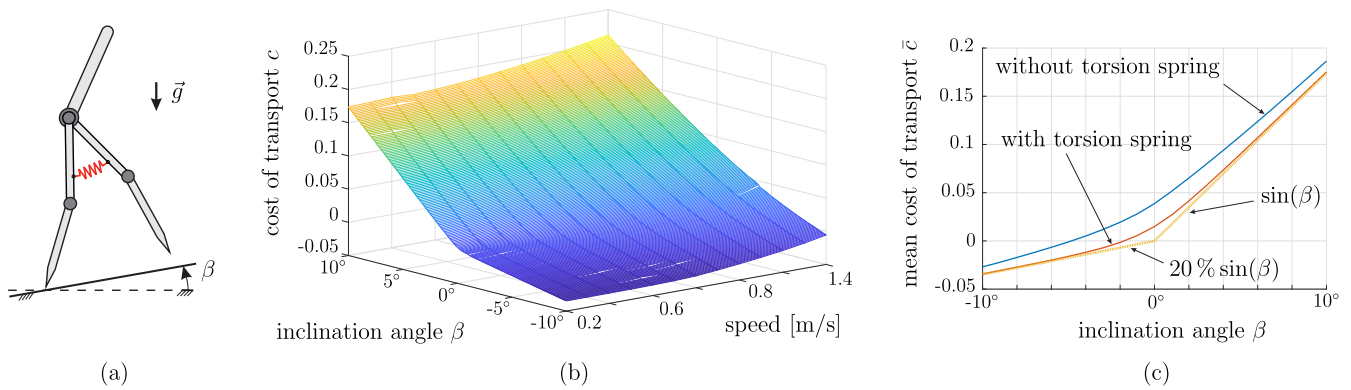
Fig. 1: (a): Five segment robot model with a torsion spring. (b): Cost of transport c in generator operation without torsion spring. (c): Mean cost of transport $\bar{c}$ of speed range from 0.2 to 1.4 m/s with and without torsion spring.

3   Results

The consideration of a part of the generated electrical energy (20 %) prevents that multiple solutions with $c = 0$ arise for negative inclinations. The numerical optimization problem has therefore a unique solution. Due to the small range of investigated inclination angles in Fig. 1(b), the energy consumption almost linearly depends on conditions of walking speed and inclination. Gravitational potential energy becomes a main energy source which drives the robot to walk downwards with a high efficiency using its passive dynamics, which is also described in [9].

Since resonance of the mechanical system can be modified through coupling the robot's thighs by an additional linear torsion spring, the energy efficiency can be increased via numerical optimization for different walking scenarios as depicted in Fig. 1(c). Compared to a flat ground, additional potential energy of gravitation due to inclination regulates the cost of transport c: on the one hand c is at least increased by $\sin(\beta)$ for climbing a slope; on the other hand c is reduced by $20\,\%\sin(\beta)$ during walking downwards as part of generated energy from gravity is reused. A high energy efficiency which asymptotically approaches these physical limits can be achieved using a linear torsion spring, while the robot utilizes gravity and its natural dynamics for walking.

The optimized stiffness of the torsion spring essentially depends on the walking scenarios, where the robot has different step lengths and postures generated by optimal trajectories of its joint angles. At larger walking speeds the torsion spring has a bigger active operating range according to simulations: on a flat ground, the spring's maximal deflection reaches to 19.1° at a walking speed of 1.4 m/s and 3.6° at a walking speed of 0.2 m/s. In general, the effect of the stiffness is small at low walking speeds. The torsion springs give neither large advantage nor disadvantage in such a situation. Therefore, the main contribution to the calculation of the optimal stiffness is made by the walking scenarios with moderate or high velocities. The result then enables to achieve high energy efficiency in all considered situations.

4   Conclusions

The presented study shows the dependence of the optimized energy efficiency of a bipedal walking robot to small ground inclinations, which is an extension of former researches on improving energy efficiencies of bipedal walking robots. Due to inclinations the potential energy directly influences the least cost of transport c, which are asymptotically approached by a robot with an optimal torsion spring between its thighs. The robot is able to walk efficiently utilizing gravity and its natural dynamics on an inclined ground.

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