Towards limits of energy efficiency in legged locomotion

Fabio Giardina and Fumiya Iida

Legged locomotion in nature is often found alongside intricate leg structures, muscles and tendons acting as elastic actuators, lightweight bones to provide structure, and clever control strategies to reject environmental disturbances. Understanding the interplay of these components is a challenge and impedes engineers to build robots capable of demonstrating similar feats to their animal analogue. Particularly, animals tend to excel most of today's robots in terms of cost of transportation, i.e. energy used divided by the travelled distance x and weight w. Mechanical robots based on passive dynamics have shown that the complex walking behaviour may be reproduced with simple realisations, without losing beneficial energy efficiency [1]. Can similar systems be found for hopping or running locomotion? In this abstract we are going to present our efforts to understand energy efficient hopping locomotion by reducing theoretical and physical model complexity.

Focusing on the morphology of the robot body rather than control, the curved beam robots [2] exploit induced vibrations in the elastic beam structure to produce locomotion behaviour. They have been found to be highly energy efficient while maintaining a simple mechanical structure and an even simpler open-loop control strategy. Although the curved beam behaviour can be approximately modelled with a linear spring, the physical robot is tricky to build as the curvature, thickness and material of the beam need to be chosen carefully. Attempting to improve controllability of the motor input while keeping the complexity of the system low, the curved foot hopping model was formed [3]. Two rigid bodies and parallel elastic actuation performed similarly to the more complex flexible robot, but scalability of locomotion speed and motor input were enhanced. The model lead to the first curved foot hopping robot CHIARO, showing efficient and self-stable locomotion characteristics [3], [4].

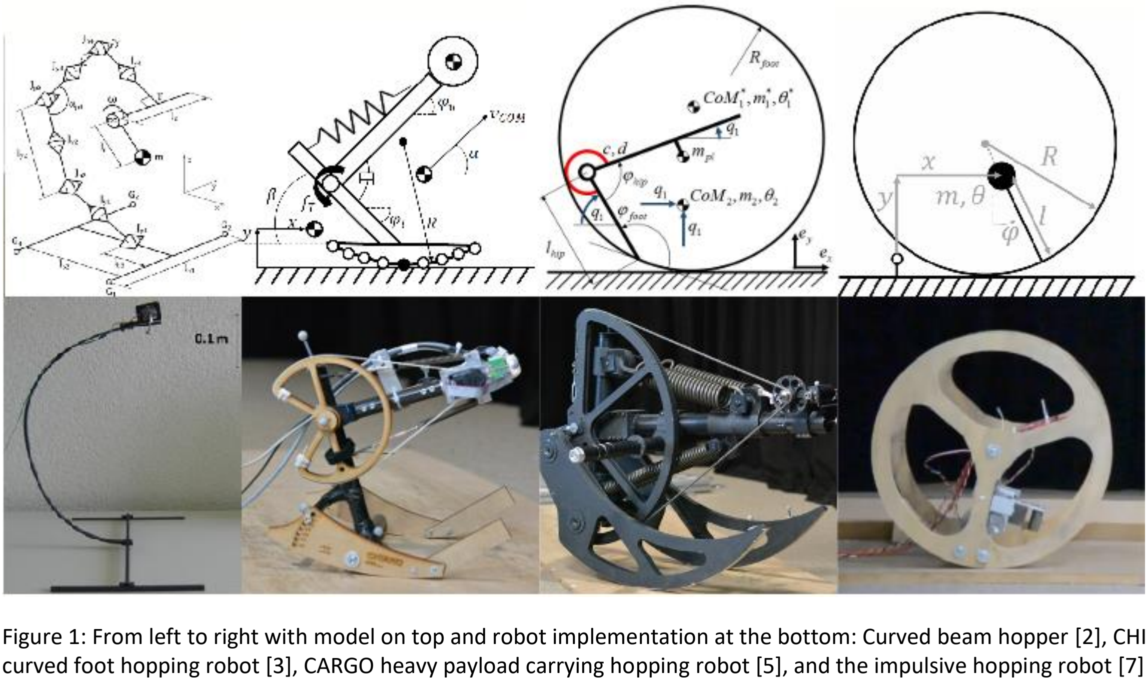

Figure 1: From left to right with model on top and robot implementation at the bottom: Curved beam hopper [2], CHIARO curved foot hopping robot [3], CARGO heavy payload carrying hopping robot [5], and the impulsive hopping robot [7].

Due to the simple structure of the curved foot model, the system is easily scaled in terms of size and mass, as demonstrated with the robot CARGO [5]. The 30kg robot can carry payload of up to 150kg with minimal changes in the open-loop control strategy, mainly owing to the parallel elastic actuation setup with four strong springs suspending the payload. The cost of transport of CARGO was found to be around 0.1 with a payload of 150kg which is the lowest we have achieved with any of our robots so far.

The two-rigid-body with parallel elastic actuation approach was simple, but further cuts in complexity seemed possible. The system was reduced to one rigid body, comprising of a wheel with off-centred mass. On the control side, rather than continuous energy input through the motor throughout the gait cycle, energy injection was modelled to occur only at one well defined point during the cycle through an impulsive force. The model was completely freed from elasticity and vibration based actuation and only impulsive forces are causing changes in total energy. Even though the model only considers rigid body collisions without springs, SLIP-like [6] stance phase trajectories, leg retraction, and energy efficient locomotion emerge naturally when the impulse and control law are chosen in accordance to model mass and rotational inertia properties [7]. Design is simplified to choosing the foot radius and mass-inertia distribution, and control to timing, direction and magnitude of energy injection. The model predictions are closely matching trajectories of CARGO and can explain traits of animal locomotion when inertial parameters and energy consumption are chosen correspondingly [7]. A real-world implementation of the impulsive hopping robot is still pending, but first attempts have confirmed the concept.

Building on the template with impulsive actuation we are going to present some theoretical limiting factors for efficient hopping locomotion, thoughts about the definition of legged locomotion, and stability considerations as predicted by the model.

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