Toward efficient, fast, and versatile running robots based on free vibration

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1 Introduction

Despite the impressive demonstrations of energy efficient legged robots in the past, there are still a number of challenges remained to compete with legged locomotion of biological systems. In order to optimize energy efficiency of a legged robot, we typically need to sacrifice versatility: our robots have usually limited locomotion speed, lack of behavioral diversity, complex mechanical designs, and limited scalability in terms of weights and sizes [1, 2, 3]. From this perspective, we have been exploring an alternative design strategy of hopping/running robots that are not only simple and efficient, but also capable of exhibiting variations of locomotion behaviors.

To the best of our knowledge, the most efficient hopping/running robot is the ARL Monopod, which can achieve the cost of transport 0.2 at 1.2m/s [4]. This is a very impressive achievement by optimizing many components including actuators, transmission, weight distribution, moment of inertia, and motor control, and the result is almost comparable to human running efficiency (i.e. human running is known as the cost of transport 0.1-0.2; [1, 3]). However, there are still a number of challenges that need to be solved: our robots are still not significantly better than animals (in terms of efficiency and speed); our design strategy does not scale to different sizes and body weights [2, 3]; and our robots can achieve only one kind of gait/motion pattern.

2 Hopping and Running with Free Vibration

The innovation of this project is the use of free vibration in legged robot locomotion. Free vibration designates oscillatory motion patterns of an elastic mechanical structure when actuated at the resonance frequencies. Locomotion robots can benefit from free vibration in many ways [5]. First, the robot can be very simple (as well as light and cheap) because free vibration does not need many motors and sensors to induce basic behavior patterns. Second, we do not need large actuation forces to induce these behavior patterns, which makes the system not only simple, cheap, and light but also energetically efficient. Third, we can build light leg structures because the legs need to be just elastic without motors which resulted in smaller energy loss in impacts. Fourth, a system can have many modes of free vibration which can be controlled through different resonance frequencies. This can be used to induce different behavioral patterns. And fifth, this design and control strategy works in a small robot as well as a large and heavy one.

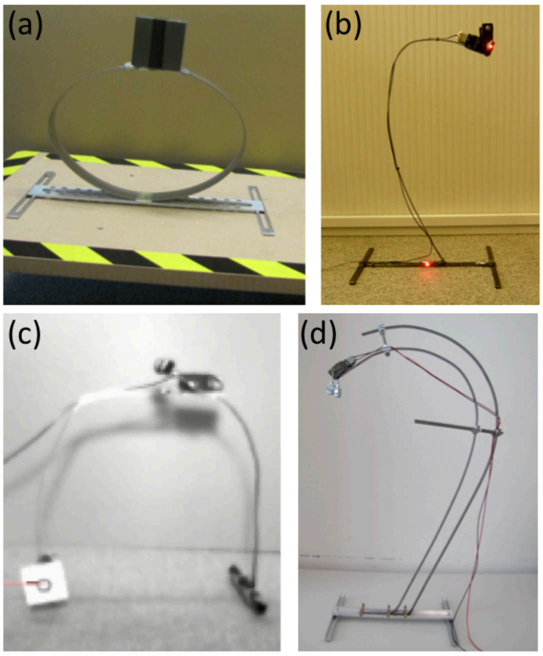

Figure 1: Prototypes of hopping and running robots based on free vibration. (a) passive hopper, (b) hopping robot with a single rotational motor, (c) running robot based on an arched elastic curved beam, and (d) hopping robot with parallel beams for variable stiffness.

The main challenge of this approach, however, is to identify the principles of design and control: it is not trivial to design a mechanical structure that exhibits desired locomotion behaviors when externally oscillated at resonance frequencies, and we often need a number of design iterations to achieve robust locomotion. In this presentation, therefore, we introduce some of our preliminary exploration of different mechanical structures that exhibit self-stabilizing locomotion behaviors based on free vibration, and explain modeling and analysis of these systems.

Figure 1 shows four different types of hopping/running robots that we developed in our laboratory in order to systematically analyze the relation between free vibration and energy efficiency of locomotion. We started with a series of simple passive systems which hop down a slope at the resonance frequency, and measured the mechanical cost of transport. In this case, the negative work generated by damping, friction and impact during the locomotion process can be reflected onto the angle of slope. Even with a relatively small “leg length”, the robots could achieve locomotion with the specific resistance of approximately 0.1 - 0.2, while we should be able to optimize the weight, spring stiffness, and leg length to further improve the efficiency.

The basic design of this passive hopping robot can be also transformed into an actuated one simply by adding a pair of small rotational masses (Figure 1(b)). We have explored a number of different designs by employing this approach, and we found that, even with a small electromagnetic motor with a relatively small gear reduction, they are able to achieve large hopping height and forward velocity. The main benefit of this design approach lies in the fact that energy loss at the ground impact can be very small because of the long and light leg structure while hoping relatively high [5, 6].

Another locomotion strategy can be achieved in an arched-structure shown in Figure 1(c), which usually exhibits a running behavior similar to quadruped bounding. Compared to the previous model, this robot is more stable and faster locomotion owing to the two supporting feet, although the dynamics is slightly more complex. After the careful analysis of a few different designs of this type, we found that the running behavior is also based on the free vibration of the body structures. Furthermore, we also found a few interesting cases of body designs in which the robots exhibit different “gait patterns” similar to walking and pacing, for example.

And currently, we are also exploring how we can actively control the proposed locomotion strategy because it is not trivial to harness the free vibration dynamics for desired body trajectories. Figure 1(d) shows one of our initial attempts in which the robot is able to adjust its leg stiffness by adjusting the gap between two parallel beams. Although we still do not fully understand the basic control principles of such dynamic robots, we are investigating how to control the locomotion velocity and stride lengths by actively varying basic body design parameters (e.g. body segment length, weight distribution, and visco-elasticity of legs). This exploration will then be extended for controlling different gait patterns such as walking, hopping and running, in the future.

3 Open questions

One of the most exciting questions is whether this approach can practically go beyond conventional efficient locomotion machines. Considering the fact that the conventional efficient robots waste most of energy in the electric motors and transmission, the proposed approach could improve the energy efficiency significantly due to the unique actuation principle. So far the lowest cost of transport was 0.4 achieved by one of our hopping robot without careful optimization of the system. We expect that, by investigating the scalability of this approach especially for larger sizes and weights, we should be able to improve cost of transport by increasing the body weight, and locomotion velocity by increasing leg length.

An additional open challenge is behavioral diversity. We have so far found that one robot is capable of multiple free vibration modes each of which exhibits a distinguishable gait pattern. It is, however, still not fully understood how we can design and control a set of desired locomotion patterns in different environments. It is a particularly challenge problem to investigate how to achieve trajectory control in the proposed locomotion framework based on free vibration.

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