Energy-efficient planning using approximated step-to-step dynamics for traversing stepping stones

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***Abstract*—This paper presents a framework for energy-efficient motion planning of dynamically balancing legged robots on stepping stones. One of the main issues of current approaches for solving this problem is slow online computations of controllers which make the real-time implementation of such approaches difficult. In this paper, we propose a motion planning algorithm that incorporates both terrain cost and energy cost while uses an approximated model of step-to-step dynamics (Poincaré map) for fast computation of the controllers. Our simulation results show that the proposed framework based on approximated step-to-step dynamics allows the robot to successfully traverse stepping stones and significantly reduces the computation time of the controllers.**

***Index Terms*—Poincaré map, motion planning, stepping stones**

I. Introduction

One of the main advantages of legged robots over wheeled or tracked systems is that they require contact points with the ground, making them suitable for traversing rough terrain such as stepping stones. Yet current approaches for foot step planning on this terrain type are not computationally efficient, making the real-time implementation of such approaches hard. In this paper, we propose a framework based on approximated Poincaré map to realize energy-efficient dynamic gaits over stepping stones with reduced computation time for controllers.

II. Methods

A. Closed-form approximation of the Poincaré map

To find an approximation of the Poincaré map, we first choose a range of initial states, $\mathbf{x}_i$, and controls, $\mathbf{u_i}$, (inputs) on the Poincaré section, and then find the states of the system at the next step, $\mathbf{x}_{i+1}$, (outputs) by numerically integrating the equations of motion. Next, the outputs are curve fitted to the inputs using quadratic functions to find an approximated model of the Poincaré map.

B. Motion planning

We describe the motion planning of a hopper model on stepping stones as follows. We create a terrain with stepping stones, and assign different cost values for stepping stones and ditches. The cost value of placing the foot on stepping stones is set to zero, but a positive large value on ditches. In order to have a convex cost function for the whole terrain, we assume that the cost function for parts of the terrain covered by stepping stones is described by straight lines ($y = 0$) and the cost function for parts of the terrain covered by ditches described as the combination of two cubic polynomials with a maximum positive value in the middle of each ditch. We also consider Mechanical Cost Of Transport (MCOT) as an energy metric for the cost of locomotion on stepping stones. MCOT is defined as the mechanical work done per unit weight per unit distance traveled. Thus, the total cost is the sum of terrain cost and MCOT. Then we solve a trajectory optimization problem with the total cost as an objective function subject to the approximated Poincaré map over a fixed horizon for a given number of steps ($N = 1, 2, 3, ...$). We choose the number of steps, N^*, that gives zero terrain cost and the lowest total cost. Then we use the fist M steps (M-step execution) of N^* to simulate the system. After the robot traverses M steps, we repeat the process until the robot reaches the end of the terrain.

III. Results and Discussion

Fig. 1(a) shows the terrain cost profile that consists of straight lines and cubic polynomials corresponding to stepping stones and ditches, respectively. Fig. 1(b) illustrates the footholds on the stepping stones. As seen, it takes 5 steps for the hopper model considered here to efficiently traverse the terrain with one-step execution without placing the foot on the ditches. We also carried out simulation for two-step execution. The results show that two-step execution led to lower total cost compared to one-step execution. Our simulation results also show that approximated Poincaré map substantially reduced the computation time of the controller while providing sufficient accuracy.

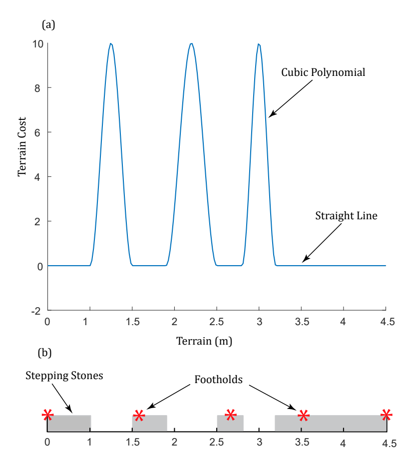

Fig. 1. (a) Terrain cost. (b) Stepping stones and footholds.