Robotic spring-mass walkers – potential and limitations

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1 Introduction

As spring-like leg behaviour in human running was observed in a number of studies [1] the spring loaded inverted pendulum (SLIP) model was initially proposed as a template model for running and hopping [2]. Based on the model behaviour a number of predictions were made concerning the ability to reproduce dynamics of walking gaits [3], stability measures and stabilisation strategies [4] as well as energetics of gait [5].
Compliant mono- and bipedal robot hoppers and runners have been around since the the 1980ies [6] and there have been attempts to implement SLIP-behaviour in running robots. To the best of our knowledge there had been no bipedal robotic spring-mass walker so far. This study presents experiments made with a bipedal walking robot mimicking the SLIP-model gait and testing model predictions on CoM-motion and acting forces. The implementation of similar tests on the advanced biped ATRIAS is discussed.

2 The robot

A simple seven-segment, nine degree of freedom (DoF) planar biped was used in this study. The robot is equipped with metalgear DC-motors at both hips and both knees driving four actuated DoFs. The joint angles are determined using built-in servo-potentiometers. In addition, the robot trunk has three passive DoFs (two prismatic, one revolute). The robot's shanks are equipped with one prismatic joint each and a linear spring acting in line with this linear DoF. As the knee is kept straight during stance phase the whole structural leg, i.e. the physical connection between hip and ground, acts compliantly. Naturally the leg itself is not massless. However we have distributed the mass such that a significantly higher share is concentrated in the trunk. The robot is mounted on a 0.9 m long beam rotating around a concentric pivot point and restricted to planar motion in the sagittal plane.
The robot is controlled by a simple state machine implemented in MATLAB REAL-TIME WINDOWS TARGET triggered by a ground contact sensor. It swings the leg forward in flight phase and retracts the hip during stance.

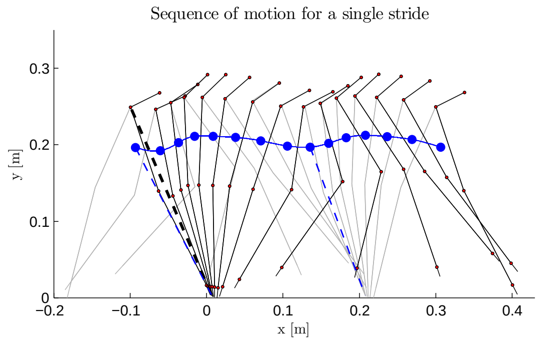

Figure 1: Sequence of a single stride, the initial stance leg is indicated in black, the swinging leg in grey. Positions of markers on the initial stance leg are indicated as small circles. The position of the CoM for every frame displayed is indicated by a large circle, the CoM-progression by the connecting line.

3 Experiments

The robot walked continuously on the circular track, its motion was recorded using a ten-camera motion analysis system recording at 500 frames per second. Nine successful trials were selected for analysis, a trial was considered successful when at least 50 s of continuous motion were captured. For all trials sensor data of the robot, i.e. joint angles of driven joints, motor voltage and current and ground contact, were recorded synchronously.

4 Results

Alltogether 1254 steps were analysed, each trial consisting of 58-79 strides. A representative sequence of motion of a single stride is shown in Fig.1. The progression of hip and CoM after touch-down shows clear leg compression as response to the impact. The reducing distance between knee and foot marker are good indicators of the changing leg length for the structural leg. The spring decompresses towards apex. In final stance hip and CoM drop but without much leg compression until the trailing leg's touch down. Over one stride the CoM shows a sinuous progression of two periods. Interestingly after swinging forward the leading leg starts to retract before it touches down. This behaviour was not programmed but results from the tilting trunk.
The force acting on the CoM calculated from the CoMs ac-

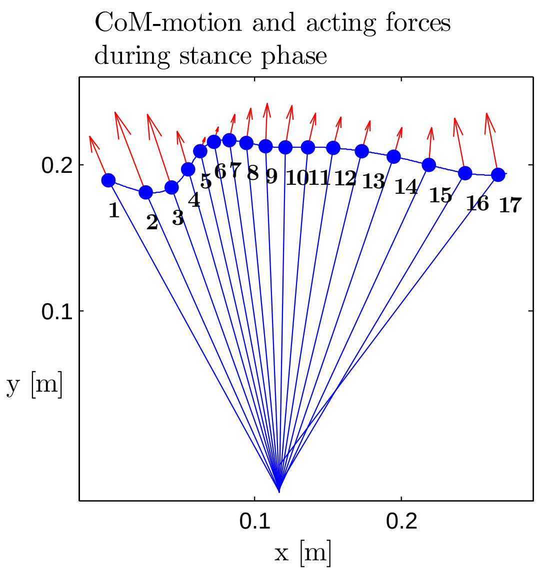

Figure 2: Forces acting on the CoM in stance are indicated with arrows pointing in the effective direction of the force at this instant. The length of the arrow corresponds to the relative magnitude of the force. CoM-position and leg orientation are indicated for different instants during stance phase.

celeration are exemplarily indicated in Fig.2. During initial spring compression force is acting mainly in the direction of the leg indicating an explicit contribution of the compression spring for the absorption of touch-down impact (T1-4). Later the leg is merely counteracting the gravitational force, only a small second compression is observed (T8-11), the force direction is slightly modulated by the hip motor, accelerating the CoM forward. In terminal stance the braking force of the contralateral legs touch-down is observable (T16-17).

5 Discussion

The robot has shown continuous motion, often over more than 60s. According to [7] we can consider the robot to locomote outside the time-limited basin of fall and thus be stable in its pure descriptive sense of not falling. The robot shows a gait that can be considered as walking presuming an event-based definition of one leg being permanently in contact with the ground while for each leg stance and swing phases follow repetitively. The CoM-trajectory resembles the predicted progression, i.e. touch-down in the late descending period, deflecting the vertical motion towards apex in single support and a following descent towards the next touch-down of the contralateral leg. Unlike the simulation model the functional leg length, i.e. the distance between CoM and footpoint, can exceed the leg length at touch-down as a result of the robots geometry, i.e. the CoM is moving ahead of the actual hip joint that pivots around the footpoint, and the swinging leg influences the CoMs motion. Friction and damping that are found in all real-world systems have to be considered for relevant design-engineering and functional deductions.

6 Future work

ATRIAS, a bipedal robot currently built at the Dynamic Robotics Laboratory, develops this concept further - making use of the passive dynamics of a compliant leg but adding actuation into the leg axis. This allows for compensating losses and mimicking SLIP-behaviour closer. This allows for additional investigations on robotic spring-mass walking and to take advantage of control strategies proposed and tested on the spring-mass-model.

7 Acknowledgement

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