Can we design controllers for bipedal robots based on simple models (templates) of their dynamics?

Harold Roberto Martinez and Juan Pablo Carbajal[1][2]

1 Introduction

The development of biped machines, inspired by human locomotion, is an interesting subject in engineering science. In order to understand the principles involved in biped locomotion, researchers have proposed several mathematical frameworks ([1, 2]).All these models have provided technical knowledge of biped locomotion that has been applied in the development of many energy efficient biped machines ([3–5]). However, the construction of biped machines capable of exploiting passive dynamics in different gaits remains an unsolved engineering challenge. In this study we propose a controller of the angle of attack (α in Figure 1) that exploits the passive dynamics of a compliant leg to develop stable patterns of locomotion and gait transitions in a defined range of energy extending the analysis of [6]. We adopt the spring loaded inverted pendulum (SLIP) model to represent running and walking. The controller naturally emerges from the identification of stable regions of locomotion as well as unstable regions.

2 Methods

We followed the framework described in [6], that publication contains a full description of the mathematical model and a preprint is freely accessible via arxiv.org. All initial conditions are given in the s-chart (single stance phase) defined by the section $\mathscr{S} : \theta = \pi/2$, i.e. only one leg touching the ground and oriented vertically. We define a running gait $\mathscr{R}$ as a trajectory that switches from the $\mathscr{S}$ section to the ff-chart (flight phase) and back to the $\mathscr{S}$ section. The walking gait $\mathscr{W}$ and a grounded running gait $\mathscr{GR}$ are defined as a trajectory that switches from the $\mathscr{S}$ section to the d-chart (double stance phase) and back again to $\mathscr{S}$ section. The results are visualized using the values of the length of the spring r and the radial component of the velocity that, in $\mathscr{S}$, equals the vertical speed $\dot{r} = v_y$.

In a physical platform it is required that a suitable angle of attack for locomotion exists in a definite interval, since real sensors and actuators have a finite resolution and are affected by noise. For this reason, the area of the $\mathscr{S}$ section where the system can take another step, selecting an angle of attack from an interval of reasonable length is important. This area is the viability region of a gait. The viability region is represented with $V^i(\Delta\alpha)$, where $i \in \{\mathscr{R}_\alpha, \mathscr{GR}_\alpha, \mathscr{W}_\alpha\}$ (running, grounded running and walking respectively), indicating that the angle can be selected from an interval with length $\Delta\alpha$ or greater.

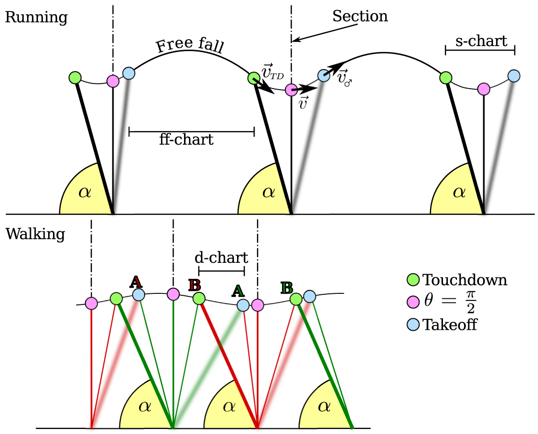

Figure 1: Evolution of the SLIP model for running and walking. The mass is represented with a filled circle. The color of the fill indicates touchdown event(green), takeoff event(blue), and the crossing of the section(fuchsia). The landing leg is pictured with a thick solid line, and the leg at takeoff is represented with a blurred line. Due to the passive properties of these models, control is necessary only during the swing of the leg, i.e. during free fall while running and from point A to B while walking.

3 Results

We call landscapes, to the region in the $\mathscr{S}$ section that corresponds to the viability region $V^i(\Delta\alpha)$ of a gait, or the transition region (set of initial conditions from where the system can go from one gait to another). Here, we present the results of the analysis on the data collected from the model for 9 different energies. Based on the properties of the landscapes, we look for the different aspects that can be exploited to define the best possible way to induce a gait transitions or to select a gait. We explore all the possible transitions and the intersections of the $V^i(\Delta 2^\circ)$ regions $(\{(R \to GR), (R \to W), (GR \to W), (GR \to R), (W \to GR), (W \to R), (R \wedge GR), (R \wedge W), and (W \wedge GR)\})$. We se-

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[2]The authors are with the Artificial Intelligence laboratory, Department of Informatics, University of Zurich, Andreasstrasse 15 8050 Zurich Switzerland { martinez,carbajal } @ifi.uzh.ch

lect the area in the $\mathscr{S}$ section as the comparative measure for all the landscapes. Fig. 2 shows the area as a function of the energy. We observed that all transitions are possible for energies above 810 J. Finally, Fig. 2 shows that though the area of $V^i\,(\Delta 2^\circ)$ regions grow with energy, their mutual intersections are still smaller than the areas of regions of transitions. Therefore automatic transitions (i.e. intersection of $V^i\,(\Delta 2^\circ)$ regions) are a scarce resource for a controller.

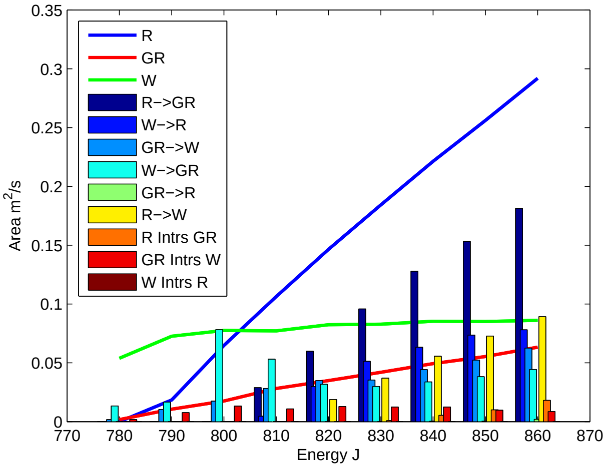

Figure 2: Area of the regions $V^i\,(\Delta 2^\circ)$, and all the possible transition region inside the regions $V^i\,(\Delta 2^\circ)$ for different energies. Solid lines represent the area of the $V^i\,(\Delta 2^\circ)$, running is shown in blue, red is Grounded running, and green is Walking. The bars represent the area of the transition region (represented with the right arrow) in the region $V^i\,(\Delta 2^\circ)$, and the area of the intersection (denoted 'Intrs') between all the different patterns of locomotion.

3.1 Controller

The landscapes compress the relevant information of the system. The viability region $V^i\,(\Delta 2^\circ)$ defines the initial conditions in which is better the execution of a particular gait i. The transition regions $\{(R \to GR), (GR \to W), (W \to GR), (W \to R), (R \to W)\}$ offer the biggest area in the $\mathscr{S}$ section to induce a gait transition. The controller collects these landscapes for a pertinent range of energies. Landscapes at intermediate energies can be interpolated. All together, this is a compact representation of the locomotion process, using the same language to describe, walking, running and gait transitions. The selection of the angle of attack is based on the landscape and a simulation of the SLIP model. The landscape defines the gait to use, meanwhile the simulation allows the system to explore all viable angles of attack, and the future states in the $\mathscr{S}$ section. Among other interesting combinations, the controller could output policies based in the selection of r, v_y, or r and v_y in the $\mathscr{S}$ section. To illustrate the use of such approach we generated a sequence of angles that keeps the value of r constant for 5 steps and then takes the system to $v_y = 0$. The angle sequence obtained is

$$\alpha = \left(71.0920, 86.8140, 71.0920, 86.8140, 71.0920, 81.5100^3\right), \quad (1)$$

where the exponent indicates how many times the angle was used. The section crossing are shown in Fig. 3. It can be seen how for the first 5 steps (task: keep r constant) the procedure generates a policy with two intercalated angles. When the task is to find a symmetric gait, the procedure finds the angle that maps the system to a gait with zero vertical velocity at mid stance. Fig. 4 shows the trajectory of the system and Fig. 5 shows an example of three transitions for a given initial condition. The trajectory has a total of 26 steps and the angle sequence is

$$\alpha = \Big(81.8860^5, 88.5000, 62.4000, 72.3500, 71.1000^3, 71.0000, 74.4000, 72.1300, 74.0000^4, 78.0000^2, 76.5000, 69.0000, 81.7280^4\Big) \quad (2)$$

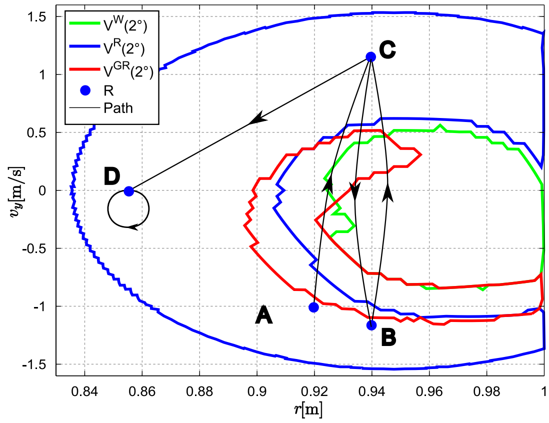

Figure 3: Section crossings of trajectory generated by control policy (Eq. 1) at 860J. The angle sequence keeps r constant (section crossings B and C) for the first 5 steps and then puts the system into the stable region (section crossing D). The Regions $V^i\,(\Delta 2^\circ)$ are shown in colors. Blue is running, red is grounded running and green is walking.

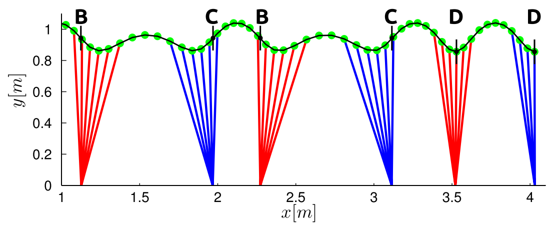

Figure 4: Trajectory generated by control policy (Eq. 1) at 860J. The center of mass of the system is shown with a green dot. Straight lines represent the spring, when not shown the system is free falling. Black markers show the section crossings, the labels are consistent with the ones in Fig. 3.

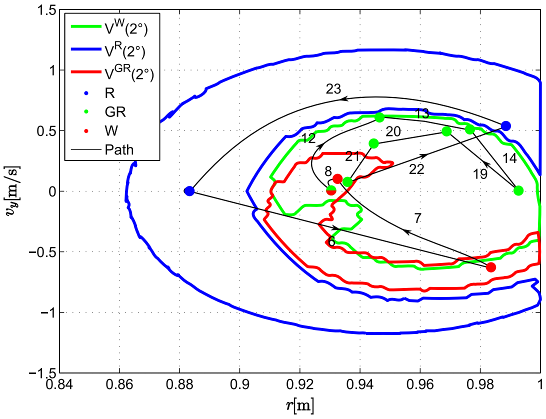

Figure 5: Transition sequence generated by control policy (Eq. 2) at 820J(Figure 6 of [6]). The plot shows a trajectory with three transitions. The Regions $V^i\,(\Delta 2^\circ)$ are shown in colors. Blue is running, red is grounded running and green is walking. The sequence starts in the running region and after some steps star the transition. Steps numbers are shown next to the arrows.

4 Discussion outline

Discrete maps between sections (such as the $\mathscr{S}$ section) allow us to understand more easily the behavior of the system by reducing the dimensionality of the representation of fundamental properties, e.g. 2D regions of viability instead of 3D volumes. The $\mathscr{S}$ section is represented with three variables (r, v_y, E). For this reason, a task in this section can be described in terms of desired r or v_y. The viability regions, are an effective tool to design a controller because they takes into account constraints given by real actuators and senors, i.e. imprecise actions.

As it is shown in Fig. 3, the controller will produce bistable policies in which the angle alternates to satisfy the control criteria (e.g. r constant), or constant angle of attack policies when the condition is $v_y = 0$. To achieve this, the controller has to perform two activities. First, based on the state on the $\mathscr{S}$ section, it has to select the gait and the angle of attack to keep the agent stable. Thus, the controller needs to have the knowledge of all the $V^i\,(\Delta 2^\circ)$, and the desired $\Delta\alpha$ to identify which gait has to be selected (the angle of attack can be selected based on the gait model). Second, the controller has to be able to produce gait transitions when it is needed. Hence, the transition regions should be also known by the controller and, with a model of the gait, the angle of attack required can be selected. We expect that this approach can be used to handle uneven terrain, given that these irregularities could be modeled (under certain restrictions) as a change in the energy of the walker.

In this study, we reported a richer set of possible gait transitions for 9 different energies $E \in [780\text{J}, 860\text{J}]$, extending the findings in [6]. The controller naturally emerges from the landscapes defined by the transition regions and the viability regions. The controller exploits the passive dynamics of the system, which reduces the amount of energy needed to control the system. We show that the landscapes can be a useful tool to easily understand the dynamics of the system. If a real robot dynamic can be approximated by the SLIP model, then the results presented herein bring new ideas that can be used to develop a plausible control mechanism for locomotion.

5 Format

Oral presentation

References

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