Template Models of Bipedal Locomotion: The SLIP Model

Analysis and Modeling of Locomotion

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Introduction

Modeling and control of legged locomotion has been the field of interest and research from both biology and robotics viewpoints to understand the underlying locomotor mechanisms, as well as take inspiration to build efficient and powerful robotics platforms. Studies have been done at different levels of abstraction from very simplified models to sophisticated neuro-mechanical models [4]. For animal and human running gaits, the Spring-Loaded Inverted Pendulum (SLIP) has been proposed as an archetypal model, which is able to predict correctly ground reaction forces and center of mass trajectories [4]. The SLIP model is a two-state hybrid dynamical system consisting of a point mass attached to a massless springy leg. In this assignment session, we provide a tutorial and a SLIP model which simulates the dynamics of running systems. By following the steps, you can learn how these simple models can be used to explain the principles of running/walking dynamics and stability.

> You are only required to deliver answers to the questions labeled "deliverable." You may work in groups of two students. Limit your answers to 3 pages of text in total (excluding figures). Only one student needs to upload the assignment in PDF form to the moodle before the deadline. Mention your group members on top of the pdf.

Get Started

Download the SLIP_Assignment folder from moodle and unzip it. This Tutorial is provided in Matlab and is based on an open-source gait-creation framework designed and published by David Remy [3]. We have slightly changed the codes and added some Steps to fit them with the questions you are going to answer in this session.[1] To launch the tutorial follow the steps below:

- Set the "Current Folder" in your Matlab session to this directory: SLIP_Assignment/Models/SLIP.
- Run initTutorial in your Matlab Command Window.

Your Tutorial should now be initialized and ready to be used. If so, you will receive a confirmation message in your command window. Now you are prepared to follow the exercises below and for any of them you will be asked to run one of the provided functions.

Explore parameters

Play around with the system parameters and explore how they influence the simulated hopping leg behavior. Basically you have to explore the role of the following parameters:

[1]For more details please see: http://www.asl.ethz.ch/people/cremy/personal/GaitCreation

- **Physical properties** of the system such as mass, size, spring stiffness, etc.
- **Initial conditions** for the state variables of the system such as initial velocity and initial height.

The main goal is to choose a set of parameters able to guarantee as many as possible steps before the SLIP falls over. To make this search easier for you, we have selected most of the parameters for the first step. The only parameters that you need to explore at this step, are the *angle of attack* and the initial *forward speed*. Run the command "help exe_1" in Command Window. You will choose first what angle of attack and second what forward speed you want to command to the leg. The second option is just for visualization. Using the function "exe_1", go through the following Steps:

- Enter the highest value for the angle of attack i.e. $\alpha = 90$ and zero value for the initial speed $dx = 0$. Observe how the leg behaves!
- Now give some other angle of attack to the leg but keep the initial speed still zero. What do you observe? Try to see how you could make the leg hop forward by playing only with the angle of attack.
- Now keep the angle of attack fixed to some value which you have found reasonable in the previous step and this time only change the forward speed. Try some values between 0 and 15 (as a hint!). Write down the solution which gives you the highest number of successful steps. You will need it later! (Note that the maximum number of steps simulated is set to 20).

Exercise 1 - Observation on the system behaviour

Deliverable 1:
1) Why is this system a hybrid system? What are the different phases of the motion? Write down the forces applied to the center of mass at each of these phases (Hint: remember the lecture notes!).
2) Which type of empirical rule can be used to associate the angle of attack, forward speed and stiffness in order to obtain a better gait?
3) Is the SLIP able to reach a non-stationary stable hopping on up/down slopes? Why?

Exercise 2 - Examine the Running Stability

The idea in this exercise is to examine the effect of certain parameters on the running stability in a more systematic way. To do that you basically need to select two important parameters from the above-mentioned sets; the *system parameters* and the *initial conditions*. In this exercise you will do a systematic grid search on two main popular sets of parameters [2]. Follow the Steps below:

- **Step 2-1:** Do the systematic search for the combination of parameters K and α (spring stiffness and angle of attack). The main codes are provided in the tutorial but to use them you need to have a good solution from exe_1 (with at least 10 successful steps)! Whenever you are ready, follow these steps:
  - Run the command help exe_2_1 in your command window to get the function description.
  - Using the function exe_2_1, first you are asked to enter the value of dx (forward speed) of your good solution.
  - Next you should select the boundaries you suggest for α and k. (Hint: again use your solution from the exploration of parameters and distribute the boundaries around its k and α value.)
  - Select the number of sample points you want to use for the systematic search. You can start with low numbers (like 10 for both) when you are exploring the good boundaries. But once you have found the good boundaries, increase the number of sample points to have a finer search.
  - After each systematic search you do, you can ask for its graph and based on that improve your guess for the boundaries.

- **Step 2-2:** Now it's time to perform the systematic search for this combination (stiffness and initial velocity). Follow the same steps as *Step 2-1* but this time with exe_2_2.

> **Deliverable 2:**
> 1) Plot a good graph (with several successful solutions) from Step 2-1;
> 2) Explain the trend you observe in the graph (give hint on how to choose the range of variables to see a nice J shape) and its meaning from a biomechanics perspective;
> 3) Plot a $dx - K$ map from Step 1-2 and explain the behavior you observe;
> 4) By doing the same procedure for up and down slopes, 4.1) what can you argue about adapting the spring stiffness for these cases?
> **BONUS:** Do you think counting the number of steps is a good measure of stability? Suggest a Score Function that could be used in the systematic search in order to investigate the stability of bipedal system and explain why. Implement such a Score Function and apply it in the systematic search. Are your results comparable to what you expected? Why?

Exercise 3 - Studying the Return Map

In this exercise, we introduce another method to examine the stability of the running gait, this time based on dynamical systems concepts and tools. This method is a well-known method for stability analysis of the periodic dynamical systems, called *Poincaré* or *Return Map*. For more details on this method please refer to the lecture notes as well as the reference [5].

The goal of this exercise is to show you how the concept of Poincaré or return map can be used for stability analysis of a periodic dynamical system. To do that in the first step you learn how to extract this map and how to interpret it. We also discuss for which variables of the system you should apply this method. For each Step, run the corresponding command e.g. "exe_3_1" for Step 3-1. You will be asked to enter the properties (dx, angle of attack and spring stiffness) of one of the good solutions you have found in "exe_2_1" or "exe_2_2". If you don't have a good gait, go back to those exercises, find a good one and come back here.

- **Step 3-1:** In the first Step, you will plot the return map for 10% boundaries around your selected gait (in terms of initial conditions). Describe how one can plot such graph. This graph is a useful tool to extract the periodic solutions of the system. Explain how the fixed points are found and how you can detect if the fixed points are stable or not. You will also get a second graph which represents the eigenvalues of the system. Hint: ignore multiple stars, there exists only one intersection.

- **Step 3-2:** One important point about this method is that you should consider and apply it for all the **independent** state variables of the system which are periodic. For instance, the system under study here has two periodic state variables; body height (y) and forward velocity (dx). Therefore, you need to examine the stability condition for both of these variables. In this Step, you extract the return map for the 'dx' (forward speed) variable. Run exe_3_2 and repeat the same steps as Step 2-1.

> **Deliverable 3:**
> 1) How can the graphs of Steps 3-1 and 3-2 help you to analyze the stability of the fixed points? and how are they related together?
> 2) Include the results from both previous Steps as well as a stable sequence of hopping in your report;
> 3) Discuss the concepts of periodicity, stability and basin of attraction with their definition and examples.
> 4) In this task, we assume that you have examined the stability of the fixed points for the running gait you have selected. Now, for such a gait you should show the notion of stability by starting off from the fixed point and visualising how the hopping leg converges to the stable solution. You can show it either on the return map plot or by running the animation and plot.

- **Step 3-3:** Running animals and humans show a retraction of their limbs just prior to ground contact. Such an observation can be easily reproduced by a feedforward control added on top of the spring loaded inverted pendulum (SLIP) model through the automatic adaptation of the angle of attack as a consequence of disturbances (which can affect both the forward speed and the stance-limb stiffness). In the function exe_3_3 consider the effect of the rotational behavior of limbs in the running stability: the function takes as first argument, the retraction angle (deg), as second argument the commanded forward speed (m/s) and as last one the constant angular leg velocity (rad/s).

Deliverable 4:
1) Test the exe_3_3 function with the following parameters: (60, 6.8,0.05). Now increase the rotational velocity *wr* gradually up to 0.25 rad/s. What do you observe? Which is the main effect of the leg retraction? How can such a behavior be explained in terms of return map analysis?

References

[1] P. Holmes, R.J. Full, D. Koditschek and J. Guckenheimer, The Dynamics of Legged Locomotion: Models, Analyses, and Challenges, SIAM Review, **48**, 2006.

[2] A. Seyfarth, H. Geyer, M. Gunther and R. Blickhan, A movement criterion for running *J. of Biomechanics*, **35**, 649655 (2001)

[3] C. Remy, K. Buffinton, and R. Siegwart,"A matlab framework for efficient gait creation", International Conference on Intelligent Robots and Systems, 2011.

[4] P. Holmes, R.J. Full, D. Koditschek and J. Guckenheimer, The Dynamics of Legged Locomotion: Models, Analyses, and Challenges, SIAM Review, **48**, 2006.

[5] A. Seyfarth, Hartmut Geyer and Hugh Herr, Swing-leg retraction: a simple control model for stable running, J. Exp. Biol., **206**, 2003.