ME 193B / 292B: Feedback Control of Legged Robots
A1 Quadruped Mini-Project

1 Motivation

In the previous mini-project on Cassie, you explored strategies to implement a robust balancing algorithm that can reject various perturbations. In this mini-project you will be going beyond balancing and towards locomotion. You will be implementing a control strategy for the A1 quadrupedal robot (Figure 1). ***Your goal is to move the A1 robot by a distance of*** 1 ***m in any direction in the xy-plane.***

Unlike the previous mini project, we will not have a leaderboard! Instead, we will be testing your developed controllers on hardware and you will receive a video of your controller in action on the real A1 robot. Please find more details in the following sections below.

2 Robot Model

The floating base model of the A1 robot consists of 18 degrees-of-freedom, with 3 actuated joints per leg – accounting for 12 DoFs. The remaining 6 DoFs correspond to the position and orientation (in Z-Y-X Euler angle representation) of the body. The three actuators at each leg correspond to (a) hip abduction, (b) thigh pitch and (c) calf pitch. Like any legged robot, the dynamics of the system can be represented by standard robot equations

$$D\ddot{q} + C\dot{q} + G = Bu + \Sigma_{i=1}^{n_c} J_i^T F_i, \tag{1}$$

where $q \in \mathbb{R}^{18}$, $\dot{q} \in \mathbb{R}^{18}$ are the configuration variables and their derivatives respectively, $D \in \mathbb{R}^{18\times18}$, $C \in \mathbb{R}^{18\times18}$, $G \in \mathbb{R}^{18}$, $B \in \mathbb{R}^{18\times12}$ are the system dynamics matrices, $u \in \mathbb{R}^{12}$ are the joint torques, $J_i \in \mathbb{R}^{3\times18}$ are Jacobians of the positions of the contact points, and $F_i \in \mathbb{R}^3$ are the contact forces. The order of the configuration variables are

Figure 1: A1 quadrupedal robot

$$q = \begin{bmatrix} x \\ y \\ z \\ \text{yaw} \\ \text{pitch} \\ \text{roll} \\ \text{front right hip abduction} \\ \text{front right thigh pitch} \\ \text{front right calf pitch} \\ \text{front left hip abduction} \\ \text{front left thigh pitch} \\ \text{front left calf pitch} \\ \text{rear right hip abduction} \\ \text{rear right thigh pitch} \\ \text{rear right calf pitch} \\ \text{rear left hip abduction} \\ \text{rear left thigh pitch} \\ \text{rear left calf pitch} \end{bmatrix}. \tag{2}$$

3 Problem Statement

The goal is to design a controller for the A1 quadrupedal robot to make it move a distance of 1 m (in any direction in the xy-plane). You could use any locomotion modality to achieve this: walking, trotting, hopping, bounding, galloping, jumping, etc. You are not limited to these locomotion modalities and could use less glamorous motions such as belly crawls, roll overs, etc.

Please note:

- You will receive a score for simulation based on the following metric:

$$s_{\text{sim}} = 10 + 65 \times \min(d, 1).$$

  Here, d is the distance travelled by your robot. In particular, if you make a submission (and your robot does not even move), you still get a score of 10. If your robot goes 1 m or over, you get 65 additional points. If your robot moves a distance between 0–1 m, you will get a proportional score. You should be able to find your simulation score from the output printed in the terminal after you run the code.

- For submissions whose simulation results are promising and have potential of working on the robot without damaging the hardware, we will run **exactly one** experiment with your controller. An experimental video and corresponding experimental log file will be sent back to you. You will get 0–25 additional points based on the following evaluation:

  + 5 points – If your code is deemed experimental worthy and deployed on the experiment.
  + 15 points – If your experiment achieves the task of moving 1 m.
  + 5 points – If your experiment behaviour is similar to that in your simulation.

- Max score possible on this project is 100 (= 75 + 25).

4 Installation

See https://drive.google.com/drive/folders/1pDtV79lxCbuzL6aE-vMOhN6ky4UPWMpK?usp=share_link for the installation instructions and usage of the code.

5 Strategies

There are several strategies for implementing locomotion controllers for quadrupedal robots. Some of them are listed below:

1. **Contact Force Control**: This is like the contact force control you saw in class and probably tried implementing on the Cassie Mini Project.

2. **Model Predictive Control (MPC)**: This is a popular choice of locomotion controller for quadrupedal robots. The robot dynamics are typically aproximated by a linearized rigid body model to obtain an MPC problem with linear constraints and a quadratic cost, which can then be solved in real-time. The MPC problem outputs desired contact forces, which can then be transformed through the Jacobian transpose [1], or through model-based whole-body controllers [2]. The MPC controller is typically coupled with Raibert-style controllers for footplacement.

   More recent work also focus on using nonlinear model predictive controllers that remove the simplifying assumptions of a linear rigid body model [3, 4].

3. **Reinforcement Learning:** There are several recent works using reinforcement learning to develop feedback controllers that are robust to model uncertainty [5, 6] and uncertainty in the environment (such as the terrain) [7, 8, 9].

4. **Hybrid Zero Dynamics (HZD):** The HZD method for bipedal robots can be extended to quadrupedal robots as well. See [10, 11, 12] for a few examples.

This is by no means an exhaustive list of potential approaches for locomotion controllers on quadrupeds is only a very small subset of existing works.

6 Submission Procedure

Please submit the following:

- A short video of your simulation. You can record your screen using your choice of screen recorder.
- A `log.npz` or `log.mat` file of your simulation generated from `run.py` under directory `project`.
- A zip file of your code. Your submitted code will be executed on the hardware (if your simulation data looks experimentally feasible) and you will receive a video of your experiment and corresponding log file. *Please ensure this zip file has all your files that will run on a fresh copy of the simulator.* If there is anything missing and we are unable to rerun your simulation, we won't be able to run experiments for you.
- Short document (PDF) on your approach and any feedback on this project (template on bcourses).

References

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