Stabilising Quadruped Robot under Disturbances

Jiayi Wang

March 7, 2018

1 Introduction

[1]

2 Problem Description

3 Literature Review

4 Work Plan

5 Conclusion

6 Introduction

7 Problem Description

- **Exploitation of Swing-leg Natural Dynamics** During both even-terrain and uneven-terrain locomotion, quadruped robots have to periodically swing their legs. Current robot control strategies govern the leg swing behavior in a human-engineered way that the robot legs are forced to track predefined leg swing trajectories (i.e. ellipse-like curves)[2, 3, 4, 5]. This is particularly energetically inefficient, since the natural dynamics of the legs are not exploited but canceled. More specifically, the leg swing behavior can be divided into two phases. In the first phase, the robot should lift up chosen feet. After the robot feet arrives at a certain height and travels a forward distance, the robot feet should start touching down, which is regarded as the second phase. Actually, this touching down phase can be completely driven by gravity without any active actuation of joints. However, due to the fact that current control strategies always actively control leg swing behaviors, the effects of gravity are canceled, resulting in unnecessary energy consumption.

- **Utilisation of Elastic Springs in Compliant Legs** Some state-of-the-art quadruped robots such as StarlETH and ANYmal commonly have compliant legs. The compliance is introduced by elastic springs which are in series attached to actuator outputs. These springs bring an important feature that they can temporarily store energy when robot's feet collide with the ground, and then release the stored energy to help robot's feet to take off. If properly used, this temporary energy storage feature will further improve the energy efficiency of quadurped locomotion. Unfortunately, none of the control strategies in [6, 2, 3] have addressed the ways of utilising these springs for improving the energy efficiency.

- **Determination of Proper Robot Footprints and Postures in Uneven-terrain Locomotion** In uneven-terrain locomotion, except leg swing behaviors, there are other factors which can potentially affect energy efficiency. These factors are robot footprints and robot postures. The robot postures include both robot torso and stance leg postures. For a joint torque-controllable robot walking on uneven terrains, the determination of these factors in motion planning phase directly relates to how much foot contact forces should be exerted from the robot legs to the environment in order to drive the robot to move forward while maintain stability. If the robot footprints are selected at inappropriate positions or the robot is ill-posed, the robot will probably need to exert large foot contact forces to the environment by generating large joint torques, leading to high energy consumption. However, no research has attempted to plan the robot footprints and postures for uneven-terrain locomotion in an energetically efficient manner, thus leaving a blank research area.

8 Methodology

In this section, we will propose two methods for improving the robot control strategies from the previously defined aspects. These two methods are called model-based approach and model-free approach. Further, we will suggest the detail work-flows describing how we can improve the control strategies by the proposed methods. At last, we will identify the robot platform for this project, along with its benefits being introduced.

8.1 Proposed Methods

- **Model-based Approach** The model-based approach refers to the ways of building accurate models to describe how the robot should behave to achieve certain goals. The model-based approach is particularly applicable for increasing the energy efficiency by exploiting swing-leg natural dynamics and utilising elastic springs in compliant legs, since what we want are models to describe how robot legs should swing in order to reach reduced energy consumption. To achieve the goals, potentially, we can establish models based on rigid body dynamics, classical control theory and optimal control techniques. However, the model-based approach has limitations that it cannot solve the problem defined in the third aspect, which is determining proper robot footprints and postures for achieving efficient uneven-terrain locomotion. The reason is that it is hard to find a model which can directly tell how the energy efficiency is related to the selection of robot footprints and determination of robot postures.

- **Model-free Approach** The model-free approach here refers to use reinforcement learning algorithms to train the robot to automatically acquire efficient locomotion skills. Particularly, among various of reinforcement learning algorithms, in this project, we plan to apply deep reinforcement learning to approach the goal, since the deep reinforcement learning algorithm has demonstrated potentials for learning complex robot control skills[7]. In contrast to model-based approach, the model-free approach can solve problems without building models. As a result, the problem defined by the third aspect can be tackled by the model-free approach that we can train the robot to learn how to select footprints and determine robot postures during uneven-terrain locomotion, with having as less energy consumption as possible. Further, the model-free approach is also an alternative method for finding solutions to exploit the swing-leg natural dynamics and utilise the springs in compliant legs.

8.2 Detailed Work-Flows

- **Exploitation of Swing-leg Natural Dynamics** At the beginning, we plan to investigate how to use model-based approach to increase the energy efficiency by exploiting the swing-leg natural dynamics. At first, we will focus on the investigation of touching down phases. More specifically, we would like to build a model to predict where the robot swing legs will land, under the condition that the swing legs are only driven by the gravity, and given the robot feet velocities and swing leg postures at the time when the touching down phase starts. Afterwards, we will build another model which can lift up swing legs to reach desired staring robot feet velocities and swing leg postures of touching down phases by using as less joint torques as possible. Further, if we combine these two models to become a complete one, we will be able to figure out how to use minimal amount of joint torques to swing robot legs to arrive desired positions by taking swing-leg natural dynamics into account.

  When it comes to use model-free approach to address the problem, we can train the robot to learn a sequence of joint torque commands to control the swing-leg behaviors, with setting the learning objective as swinging the legs towards desired positions by using as less total amount of joint torques as possible. Moreover, in order to ensure the gravity will be fully exploited, during the learning process, any large joint torque command generated in touching down phases should be strictly penalised.

- **Utilisation of Elastic Springs in Compliant Legs** For investigating how to utilise elastic springs in compliant legs for temporary energy storage purpose, we will again start with using the model-based approach. At first, we propose to develop a model to estimate how much potential energy will be stored into the springs, given the detail information of how a robot foot collides with the ground, including the angle of attack, velocity and acceleration of the robot foot. Afterwards, we will establish another model to minimise joint torques for taking off robot legs, with the help of releasing the energy stored in springs. Eventually, by combining these two models together, we expect to demonstrate a successful reduction in the energy consumption during locomotion. Further, in order to fully utilise the temporary energy storage feature of springs, we advice to edit the motion profiles which define how robot leg should swing to maximise the potential energy being injected into the springs.

  As indicated before, we can also use model-free approach to train the robot to learn how to utilise the springs. To achieve this goal, we will still train a sequence of joint torque commands which are responsible for regulating swing-leg behaviors, with the learning objective setting as maximising the total energy being injected into springs while using as less joint torques as possible.

- **Determination of Proper Robot Footprints and Postures in Uneven-terrain Locomotion** In this section, we will present the work-flow of training the robot to learn how to determine proper robot footprints and postures for achieving efficient uneven-terrain locomotion. Firstly, we will train the robot to learn how to efficiently stand on various types of uneven terrains. After training, given terrain models and robot footholds, the robot should be capable of determining proper robot torso and stance leg postures in a way that the robot can stably stand on the given terrains with requiring minimal foot contact forces or joint torques. Next, we will continue to train the robot to learn footprint selections for tracking predefined robot trajectories. Once the training is finished, it is expected that the robot can select new footprint positions, under the condition that the robot can stably move forward as much as possible while requiring as small foot contact forces or joint torques as possible. Eventually, with these two trained strategies being combined, the robot is expected to traverse various of uneven terrains with reduced energy consumption.

8.3 Robot Platform

This project will consider ANYmal as the research platform, since it is driven by highly compliant SEAs (Series Elastic Actuators) which have springs being inserted in between of the gearbox outputs and joints. The springs in SEAs enable important benefits such as impact rejection, joint torque control capabilities and the temporary energy storage feature, which make ANYmal best suits for this project.

9 Conclusion

This proposal aims at increasing the energy efficiency of both even-terrain and uneven-terrain quadruped locomotion by improving robot control strategies. In order to achieve the goal, we defined three aspects that may increase the energy efficiency, and have been neglected by previous robot control strategies. These three aspects are exploitation swing-leg natural dynamics, utilisation of elastic springs in compliant legs and determination of proper robot footprints and postures in uneven-terrain locomotion. Further, in order to tackle the energy efficiency problem through these identified aspects, we proposed two methods, model-based approach and model-free approach. We expect that the energy efficiency of quadruped locomotion will be effectively increased after the completion of this project. Further, the proposed solutions can be also applied to increase the energy efficiency of other legged systems. For instance, humanoid robots. A potential robot system for validation could be Valkyrie[8], a state-of-the-art humanoid robot designed for moonshot missions.

References

[1] Jaehwan Park and Jong Hyeon Park. Impedance control of quadruped robot and its impedance characteristic modulation for trotting on irregular terrain. *IEEE International Conference on Intelligent Robots and Systems*, (1):175–180, 2012.

[2] Marco Hutter, Hannes Sommer, Christian Gehring, Mark Hoepflinger, Michael Bloesch, and Roland Siegwart. Quadrupedal locomotion using hierarchical operational space control. *The International Journal of Robotics Research*, page 0278364913519834, 2014.

[3] Christian Gehring, Stelian Coros, Marco Hutter, Michael Bloesch, Markus A Hoepflinger, and Roland Siegwart. Control of dynamic gaits for a quadrupedal robot. In *Robotics and Automation (ICRA), 2013 IEEE International Conference on*, pages 3287–3292. IEEE, 2013.

[4] J Zico Kolter, Mike P Rodgers, and Andrew Y Ng. A control architecture for quadruped locomotion over rough terrain. In *Robotics and Automation, 2008. ICRA 2008. IEEE International Conference on*, pages 811–818. IEEE, 2008.

[5] John R Rebula, Peter D Neuhaus, Brian V Bonnlander, Matthew J Johnson, and Jerry E Pratt. A controller for the littledog quadruped walking on rough terrain. In *Proceedings 2007 IEEE International Conference on Robotics and Automation*, pages 1467–1473. IEEE, 2007.

[6] Ludovic Righetti, Jonas Buchli, Michael Mistry, Mrinal Kalakrishnan, and Stefan Schaal. Optimal distribution of contact forces with inverse-dynamics control. *The International Journal of Robotics Research*, 32(3):280–298, 2013.

[7] Timothy P Lillicrap, Jonathan J Hunt, Alexander Pritzel, Nicolas Heess, Tom Erez, Yuval Tassa, David Silver, and Daan Wierstra. Continuous control with deep reinforcement learning. *arXiv preprint arXiv:1509.02971*, 2015.

[8] Nicolaus A Radford, Philip Strawser, Kimberly Hambuchen, Joshua S Mehling, William K Verdeyen, A Stuart Donnan, James Holley, Jairo Sanchez, Vienny Nguyen, Lyndon Bridgwater, et al. Valkyrie: Nasa's first bipedal humanoid robot. *Journal of Field Robotics*, 32(3):397–419, 2015.