LEARNING DYNAMIC MOTOR SKILLS FOR VIRTUAL AND REAL HUMANOIDS

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LEARNING DYNAMIC MOTOR SKILLS FOR VIRTUAL AND REAL HUMANOIDS

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To myself,

Sehoon Ha,

the only person worthy of my company.

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I want to “thank” my committee, without whose ridiculous demands, I would have graduated so, so, very much faster. Can I?

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CHAPTER I

INTRODUCTION

Learning highly dynamic motions of athletes has been one of the greatest challenges for humanoids, from a virtual character in simulation to a real robot with hardware. The learned dynamic motor skills allow humanoids to generate more agile, efficient, and responsive motions that are useful in many applications. One notable advantage is that a humanoid can ovecome obstacles as swiftly and efficiently as possible using only its body. A robot in a diaster place is likely to encounter the uneven terrains and discontinuous gaps, which cannot be explored by regular locomotion without dynamic motions such as jumping or falling. In addition, dynamic motor skills maximize capability of humanoids under the given torque and joint limitations. If a virtual character in a sports game does not aquire athletic movements of elite sports players, a game will be boring and not appealing to users. A character can further adapt the acquired motor skill to the environment changes or user interactions under the valid physical assumptions, such as minimizing energy consumption. These advantages lead to the development of techniques to develop physics-based controllers for highly dynamic motions of humanoids in the various areas in academia and industry.

Virtual characters and real robots are two main subjects of motor control problems in computer graphics and robotics. Usually, virtual and real humanoids have different assumptions and limitations in terms of the sensor and actuator noises, maximum torque limits, contact dynamics, to name a few. However, it is also true that control problems of both subjects have common properties, such as non-linearity of the objective function, under-actuated characters, high-dimensional control parameters, and discontinuity due to the contacts. Therefore, principles and algorithms developed in one domain often can be transferred to the other domain. For instance, many optimization algorithms for finding the best control parameters [,,] have been successfully applied to the virtual characters and robots. Further, a virtual simulation of a robot is often used as a testbed for developing hardware compatible controllers due to the expensive cost and time-consuming trials. In this dissertation, I will discuss control of both virtual and real humanoids by demonstrating the different problem formulations and solutions. Further, I will explain how the optimization in two different systems can benefit each other.

However, developing effective controllers for dynamic motor skills requires a lot of manual efforts and computational resources due to their characteristics, such as abrupt accelerations and decelerations of momentum, frequent changes of contacts, and explosive usage of torques near limitations. Therefore, controllers must be able to generate efficient and feasible torque trajectories that can be applied to a wide range of initial conditions. In this dissertation, I thoroughly investigate a falling motion of humanoid as an example of highly dynamic motions, due to several reasons. First, it is a fundamental motor skill that protects the subject from severe injuries and connects the previous and next actions for fluent transitions. In addition, it is one of the most challenging motor skills because it accompanies huge changes of vertical momentum within a very short time window. Therefore, the development of falling controllers will make virtual characters and robots to execute the motion fluently, and its principles can be applied to the other highly dynamic motions with huge momentum.

Another difficulty arises when we optimize control parameters for dynamic motions. Typically, whole-body dynamic tasks typically have a cost function that is multimodal, non-linear, non-convex, and discontinuous due to an under-actuated system and discrete contacts. Further, control parameters are likely to be in a high dimensional space with small feasible regions that does not generate undesired behaviors.

These difficulties often require the most robust optimization algorithm. In computer animation, a robust black-box sampling-based method, Covariance Matrix Adaption Evolution Strategy (CMA-ES) [], has been frequently applied to discontinuous control problems, such as biped locomotion [], parkour-style stunts[], or swimming []. In this dissertation, I focus on improving the performance of the baseline algorithm, CMA-ES, for more difficult tasks with smaller feasible regions by training classifiers to exclude infeasible samples. I further extend CMA-ES for a parametrized motor skill, which is essential for operating a robot in the unpredictable environment.

Unlikely the optimization for virtual characters, a control policy search for hardware with many trials is often infeasible because conducting hardware experiment can be expensive and time-consuming. Moreover, an execution of a bad controller on a robot can potentially cause disastrous damage to the robot and enormous cost to repair. To reduce the number of trials on the hardware, a virtual simulation is used as a practical solution that provides a fast and safe evaluation of the control parameters. However, it suffers from *simulation bias* in which controllers developed for a virtual character do not work on hardware due to differences in the two systems. The *simulation bias* is hard to explicitly model because it can be caused by many reasons, such as different mass-distributions, sensor and actuator noises, command delays, and more. Therefore, a data-driven model-based policy search, which iteratively updates the simulation using collected hardware data, is a promising method to model the simulation bias. In this dissertation, I will discuss how to reduce the number of hardware experiments for robots using the proposed novel iterative model-based policy search that exploits the virtual simulation as a testbed.

I will present the following identified problems for developing controllers for highly dynamic motor skills.

1.1 Falling Strategies for Humanoids

Highly dynamic motions often accompany the abrupt momentum changes, which can cause large contact forces to characters. Therefore, how to manage falls is a fundamental motor skill to reduce damages to humanoids and achieve fluent transitions between motor skills. In this dissertation, I will discuss two different falling scenarios, for virtual and real humanoids. For a virtual character, I will describe a general controller that allows the character to fall from a wide range of heights and initial speed, which are inspired by falling of traceurs. For a real robot, a general falling strategy for handling various external perturbations is introduced, which is feasible to be executed by actual hardware. The effectiveness of the presented strategies will be validated in physics simulation, and experimentally tested on a small-size humanoid.

1.1.1 Falling and Landing Motion Control for Virtual Characters

Figure 1: A falling motion of Parkour.

In Chapter 3, I will show how to create an on-line controller for generating agile and natural falling motions of the virtual character that can land from various heights and velocities. The goals of the controller are to reduce the joint stress at the impact and get back on its feet to prepare the next action. Inspired by falling skills of Parkour(Figure 1), I formulate the falling problem with three phases, *airborne*, *impact*, and *rolling* based on the contact states. First, two sub-controllers are designed for the *airborne* and *rolling* phases and a regression analysis is conducted to find an optimal landing angle that can connect two sub controllers at the *impact* phase. I will demonstrate that the motion generated by the proposed controller induces smaller joint stress, which is still four times lower than a rag-doll motion at the worst cases.

1.1.2 Multiple Contact Planning for Humanoids

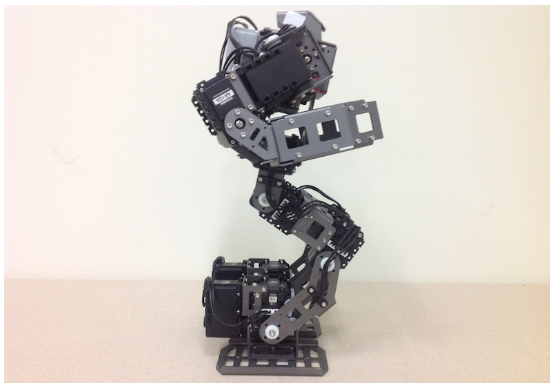

Figure 2: Hardware of BioloidGP robot.

Chapter 4 will describe a general algorithm which plans for appropriate responses to a wide variety of falls, from a single step to recover a gentle nudge, to a rolling motion to break a high-speed fall. Our multiple contact planning provides a unified framework that can represent many existing falling techniques [,,]. Then, I will show how to efficiently optimize the multiple contact falling strategy to the given initial state using a simplified model and dynamic programming. Finally, various scenarios will be tested on simulated humanoids and the actual hardware (Figure 2) to show that our algorithm plans various falling strategies with different contact sequences.

1.2 Learning of Dynamic Controller for Characters

Teaching a physically simulated character a new motor skill requires a lot of efforts from the controller designer, from the design of the control mechanism to the tweaking of low-level control parameters. To simplify the learning process, I will introduce an intuitive and interactive framework for developing dynamic controllers that is inspired by how humans learn dynamic motor skills through a iterative process of coaching and practicing. Further, we propose two optimization techniques that can extend the popular policy search algorithm, CMA-ES, to accelerate the convergence rate and to optimize a parametrized objective function.

1.2.1 Iterative Design of Dynamic Controllers

In Chapter 5, I will describe an iterative framework to design dynamic controllers using high-level, human-readable instructions, inspired by a training process of athletes that consists of interactive coaching and repetitive practices (Figure 3) To enable interactive coaching, I introduce "control rigs" as an intermediate layer of control module to facilitate the mapping between human instructions and low-level control parameters. During the practicing stage, control parameters are efficiently determined using CMA-ES, which will be further improved in the following chapters. The details of controllers development process using our iterative learning framework will be shown with example parkour motions.

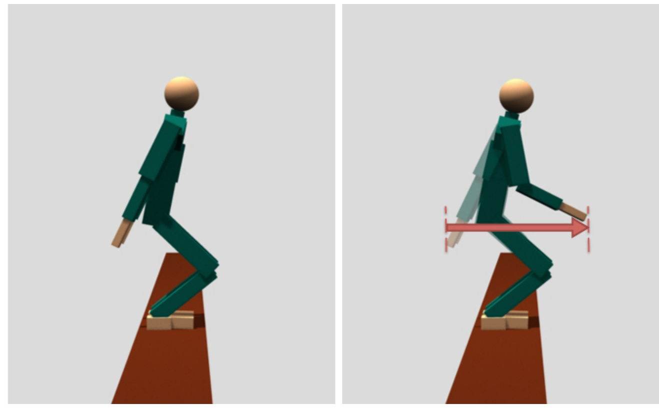

Figure 3: The proposed learning frame uses human readable instructions to teach motions.

1.2.2 Optimization with Failure Learning

A controller with many user constraints is difficult to optimize due to the relatively small feasible region. In Chapter 6, I will describe a new optimization algorithm for highly-constrained problems based on the observation of humans ability to learn from failure. The proposed algorithm, CMA-C (Covariance Matrix Adaptation with Classification) utilizes the failed simulation trials to approximate an infeasible region in the space of control rig parameters so that it can predict the quality of the samples, resulting a faster convergence than the standard CMA-ES.

1.2.3 Optimization for Parametrized Motor Skills

In Chapter 7, I will explain the optimization of parametrized motor skills. The parametrization of the learned motor skills is an essential ability because a robot can reinterpret the skill to a new situation, without learning from scratch. Instead of maintaining a single Gaussian distribution, the algorithm reduces the number of samples by evolving a parametrized probability distribution for a range of skills. I will test the algorithm on a simulated humanoid robot learning three parametrized dynamic motor skills, including vertical jump, kick a ball, and walk.

1.3 Model-based Learning for Virtual and Real Characters

Figure 4: Bongo Board balance toy.

In Chapter 8, I will describe an iterative approach for for learning hardware models and optimizing control policies with as few hardware experiments as possible. Instead of learning hardware models from scratch, the proposed approach only learns the difference from a simulation model. Similarly to the previous work, Gaussian Process is used to model the difference between dynamics of virtual and real characters based on the collected hardware data. To prove the concept, I will validate the algorithm on two different simulation models, one with perfect contacts and one with realistic contacts, by finding a balancing controller for a bipedal robot on a bongo board (Figure 4).

1.4 Contributions

The control and optimization methods discussed in this dissertation provide several contributions to the computer animation community. These contributions are as follows:

- **A falling and landing strategy for virtual characters** The falling strategy presented in the dissertation allows the character to fall from a wide range of heights and initial speeds, continuously roll on the ground, and get back on its feet, without inducing large stress on joints at any moment.

- **A multiple contact falling strategy for robots** I also introduce a new falling strategy that can optimize a sequence of contacts, which optimizes the number and locations of contacts for the given initial state.

- **An iterative learning framework for dynamic motor skills** Unlikely previous monolithic design processes in the literature, I proposed an iterative and interactive learning framework using human readable instructions. Starting from a basic controller, the proposed framework allows a user to easily train complex dynamic motion controllers within minutes, with only a few high-level instructions from the user.

- **An optimization technique for highly constrained problems** I introduce a novel efficient optimization algorithm, CMA-C, that is designed for the problem with many constraints and smaller feasible regions. The algorithm converges faster than the standard CMA-ES, by approximating the infeasible region using Supported Vector Machines.

- **An optimization technique for parametrized tasks** I introduce an efficient evolutionary optimization algorithm for learning parametrized skills to achieve whole-body dynamic tasks, which is much faster than the baseline algorithm, CMA-ES.

- **A model-based policy search for reducing hardware experiments** I propose an iterative approach for learning hardware model and optimizing policies with as few hardware experiments as possible by learning the difference between a simulation model and hardware.

In the next chapter, I will discuss the related work conducted by other researchers to address similar problems.

APPENDIX A

SOME ANCILLARY STUFF

Ancillary material should be put in appendices, which appear just before the bibliography.

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