# PROPOSAL:
# LEARNING DYNAMIC MOTOR SKILLS FOR VIRTUAL AND REAL HUMANOIDS

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Sehoon Ha

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# PROPOSAL:
# LEARNING DYNAMIC MOTOR SKILLS FOR VIRTUAL AND REAL HUMANOIDS

Approved by:

Professor C. Karen Liu, Advisor
School of Computer Science
*Georgia Institute of Technology*

Professor Greg Turk
School of Computer Science
*Georgia Institute of Technology*

Professor Jarek Rossignac
School of Computer Science
*Georgia Institute of Technology*

Professor Jun Ueda
School of Mechanical Engineering
*Georgia Institute of Technology*

Date Approved: 1 July 2010

# SUMMARY

As the technology of computer animation and robotics advances, controlling highly dynamic motions has been a great milestone for both virtual and real humanoid characters. However, developing controllers for dynamic motor skills is still a challenging problem, which usually requires substantial amount of design effort and optimization time due to its complexity. In this proposal, we introduce a set of techniques for designing controllers for various dynamic motor skills, such as jumping, rolling, vaulting, and landing, for virtual characters and real robots.

First, we introduce new algorithms to generate falling and landing motions, which are essential motor skills to ensure the safety of humans and robots. We propose an online algorithm to control falling and landing motions of virtual characters from a wide range of heights and initial speeds, which can potentailly cause huge damages. With the suggested algorithm, we demonstrate that simple momentum planning with the proxy model of inertia and feedback-based rules can generate the natural landing motions without large stresses on the joints. Inspired by the falling control of a virtual character, we develop an optimization algorithm for multi-contact falling motions of a real robot for minimizing the damage at the impact. Unlike the existing techniques that usually consider the desired contacts as invariant features, we search over a sequence of contacts to find the best falling motion that can handle a wider range of situations.

Second, we propose a human-in-the-loop (HITL) system to develop dynamic controllers under the guidance of a human coach. In this system, the user can provide a sequence of high-level instructions to iteratively train dynamic controllers of characters as if coaching a human trainee. To facilitate the mapping between high-level

instructions and control variables, we introduce a new representation of dynamic controllers, the "motor tree", which also enables flexible re-assembly and efficient re-optimization by preserving the invariant features of motor skills. Further, the optimization process is accelerated by utilizing the failed previous trials. By considering noise and uncertainty from real hardwares, we also train a real robot to perform dynamic motor skills such as rolling using our proposed system.

By incorporating the proposed techniques, we can produce highly-dynamic motions of virtual characters and real robots.

# CHAPTER I

# INTRODUCTION

Performing highly dynamic motions with agility and grace has been one of the greatest challenges in sports, computer animation, and robotics. A wide variety of athletics, such as acrobatics or free running, demonstrate the efficient and artistic movements that involve abrupt changes of momentum and contacts. Furthermore, these motor skills are transferred to virtual characters in animations and games to express the intention of designers and react to user interactions. Robotics, another application of dynamic controllers, also started to tackle the agile movements and demonstrated running, jumping, and landing motions with real hardwares. Despite the recent progress, learning dynamic motor skills still remains a very difficult problem because it needs to execute the task with great agility, ensure safety, and demonstrate self-expression.

In fact, developing dynamic controllers for virtual characters and real robots can be considered related problems, which can benefit each other. Since the control problems in two domains have shared properties, such as non-linearity, high-dimension, and discontinuity, an algorithm developed in one domain can be transferred to the other domain. However, control of real robots is more constrained due to the sensor uncertainty and hardware limitations, which usually require more robustness than control of virtual characters. Therefore, developing an algorithm in virtual environment to prove its full capability and transferring it to real hardwares would be a promising research direction, which is adopted in this proposal.

In the computer animation and robotics community, various categories of algorithms have been applied to control virtual and real characters. For generating a sequence of dynamic motion, two approaches have been frequently applied to control problems: tracking the reference motion, or solving the space-time optimization problem under physics constraints. Both methods demonstrated that a variety of motions can be achieved by solving the optimization problem which considers the entire sequence of motions. However, the optimization over the entire motion usually requires a long optimization time and also falls short of abilities for adapting the motion to new environments. On the other hand, abstract model based controllers can be interactively adapted to a wide range of situations by capturing the essential features of the dynamic motion. This approach shows the robust control over various motions, such as walking, balancing, and falling, but hard to consider the very detailed features such as the exact boundary of characters or a sequence of contacts. A sampling-based optimization for the parameterized controllers has proven effective for optimizing the motion within a realistic simulation environment, but it also takes a long time to be optimized, especially when the target motion is parameterized or concatenated. Instead, we want to introduce faster algorithms for developing dynamic controllers, which also can handle a wide range of situations.

In this proposal, we introduce a set of techniques to expedite the learning process of dynamic controllers for various dynamic motor skills. We first introduce a natural and safe landing controller for the characters and robots, which is essential for highly dynamic motions. After that, we propose an interactive syste to design dynamic controllers for humanoids. The rest of the sections are organized as follows:

## 1.1 Organizations

- **Optimization of Falling and Landing motions** In this proposal, we tackle the problem of controlling safe falling and landing motion for virtual characters and robots, which is a fundamental motor skill because highly dynamic motions involve the abrupt changes of contacts and can cause huge damages on the body parts. While absorbing the shock at the impact, a successful landing controller also should be able to maintain readiness for the next action by managing the momentum properly. For the virtual character, we introduce a fast and robust optimization algorithm for controlling falling and landing motions of virtual characters from a wide rage of heights and initial speeds. while reducing joint stress. Further, we develop a safe falling algorithm for a robot by planning a sequence of multiple contacts, which endures larger external perturbatations comparing to the existing methods.

- **Human-guided iterative training of dynamic motions** Also, we introduce an iterative training system for dynamic motor skills inspired by human coaching techniques, which uses human-in-the-loop (HITL) optimization for interactive training. In this system, the user only needs to provide a primitive initial controller and high-level, human-readable instructions as if coaching a human trainee. The virtual character interprets the provided instructions, accumulate the knowledge from the human coach, and iteratively improves its motor skills by optimizing control parameters. We propose a new hierarchical representation of controllers, the "motor tree" for interpreting the instructions and accumulating the knowledge on motions. In addition, we develop a new sampling-based optimization method, Covariance Matrix Adaptation with Classification (CMA-C), which efficiently solves the constrained problem by estimating the infeasible region from bad samples. The system is further extended by considering the hardware limitations and uncertainties to support training dynamic motions for robots. With the proposed system, we demonstrate the design process of comlex dynamic controllers including jumps, vaults, rolls, and flips.

# CHAPTER II

# RELATED WORKS

## *2.1 Control of Highly Dynamic Motions*

Designing controllers for physically simulated biped characters is a challenging problem due to its nonlinear dynamics and under-actuated control. Hodgins *et al.* [13, 39] showed that carefully crafted control algorithms can simulate highly athletic motions, including diving, tumbling, vaulting, and leaping. Faloutsos *et al.* [6] composed primitive controllers to simulate more complex motor skills, such as a kip-up move or a dive down stairs. Liu *et al.* [20] successfully tracked contact-rich mocap sequences using a sampling-based approach. They showed that vigorous motions with complex contacts, such as a dive-roll or a kip-up move, can be dynamically simulated, provided full body mocap sequences as desired trajectories. Other techniques directly edit ballistic motion sequences under the constraints imposed by conservation of momentum [21, 30], or apply a hybrid method for synthesizing dynamic response to perturbation in the environment [27]. If the contact positions and timing are known, spacetime optimization techniques can also generate compelling dynamic motions [18, 7, 25, 32]. In this work, we take the approach of physical simulation, but we seek for a more general and robust control algorithm such that the controller can operate under a wide range of initial conditions and allow for runtime perturbations. Furthermore, our controller does not depend on any pre-scripted or captured motion trajectories.

## *2.2 Control of Safe Falling Motions*

Safe falling and landing for bipeds is a topic that receives broad attention in many disciplines. Robotic researchers are interested in safe falling from standing height for the purpose of reducing damages on robots due to accidental falls. Previous work has applied machine learning techniques to predict falling [14], as well as using an abstract model to control a safe fall [8, 9, 40]. In contrast to the related work in robotics, our work focuses on falls from higher places. In those cases, control strategies during long airborne phase become critical for safe landing. We draw inspiration from kinesiology literature and sport practitioners. In particular, the techniques developed in freerunning and parkour community are of paramount importance for designing landing control algorithms capable of handling arbitrary scenarios [5, 1].

## *2.3 Sampling-based Optimization*

In character animation, a sampling-based method, Covariance Matrix Adaption Evolution Strategy (CMA-ES) [12], has been frequently applied to discontinuous control problems, such as biped locomotion [35, 36, 37], parkour-style stunts[19, 10], or swimming [33]. To compensate the expensive cost of sampling-based algorithm, different approaches have been proposed, including exploiting the domain knowledge [35, 36, 37] or shortening the problem horizons [29]. Based on the previous success of CMA-ES, we developed a new sampling-based algorithm resembles the evolution process of distribution

## *2.4 Human-in-the-loop Optimization*

Without human guidance, fully automated optimization algorithms sometimes produce undesired solutions due to unmodelled factors or unexpected situations. To fill the gap, researchers have developed semi-automatic systems which involve a human in the process to provide prior knowledge and guidance to the optimization.[26]. This type of optimization systems, called human-in-the-loop (HITL) optimization, have proven effective for various problems, such as space shuttle scheduling [4], vehicle planning [38], and interface optimization [24]. The level of user interaction varies from simply selecting of the generated solutions [28] to directly editing the search parameters and constraints [31]. Unlike most previous work which primarily focused on developing user interaction and visualization techniques for HTIL optimization systems, we develop new optimization algorithms that exploit the nature of HITL computation paradigm.

## 2.5 Learning from Demonstration

Learning from demonstration (LfD), also known as programming by demonstration, has been an attractive paradigm for training motor skills to robots. In this paradigm, a set of examples are provided by human teachers, and an optimal policy is generated from such examples. Since the early work of Kuniyoshi *et al.* [17], it has been proven to be effective for training motor skills in numerous task domains, including object manipulation [2, 3, 34], navigation [15], full-body motion generation [16], and so on. To increase the robustness, the learned motor skills are further generalized using machine learning techniques, such as gausian mixture model [3] or motion primitives [23]. However, dynamic motor skills of humanoids have not been fully examined yet, except the only few works on the locomotion [22], which is our target domain in this proposal.

# CHAPTER III

# OPTIMIZATION OF FALLING AND LANDING MOTIONS

This section describes algorithms for generating natural and safe falling and landing motions of virtual and real humanoids. In the prior project, we developed an online algorithm for simulated characters to generate natural falling and landing motions from different heights and initial conditions, while absorbing impact. In addition, we investigate a scenario of safe falling strategy for robots to protect themselves from large external perturbations by executing breakfall techniques.

## *3.1 Prior Work: Falling and Landing Motion Control for Character Animation*

In our prior work [11], we introduce a new method to generate agile and natural human landing motions in real-time via physical simulation without using any mocap or pre-scripted sequences. We develop a general controller that 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 (Figure 1). The character's motion is generated through a forward simulator and a control algorithm that consists of an airborne phase and a landing phase. During the airborne phase, the character optimizes its moment of inertia to meet the ideal relation between the landing velocity and the angle of attack, under the laws of conservation of momentum. The landing phase can be divided into three stages: impact, rolling, and getting-up. To reduce joint stress at landing, the character leverages contact forces to control linear momentum and angular momentum, resulting in a rolling motion which distributes impact over multiple body parts. We demonstrate that our control algorithm can be applied to a variety of initial conditions with different falling heights, orientations, and linear and angular velocities. Simulated results show that our algorithm can effectively create realistic action sequences comparable to real world footage of experienced freerunners.

**Figure 1:** A simulated character lands on the roof of a car, leaps forward, dive-rolls on the sidewalk, and gets back on its feet, all in one continuous motion.

## *3.2 Multi-contacts Falling Motion Control for a Humanoid Robot*

### 3.2.1 Problem Description

In this section, we propose to develop a safe falling controller for humanoid robots, which ensures the safety of the robots from the large external perturbations. Our approach is using the simulation samples for optimizing the controller to handle complex changes of contacts from highly dynamic fallings. By breaking a fall into a sequence of multiple contact, like “UKEMI” of Judo, we expect the robot to endure larger external perturbations. In addition, our simulation-based algorithm allows us to incorporate an arbitrary objective function so that we can prioritize the body parts to be protected.

The development of a safe falling controller requires design decisions on when to detect the falling and how to evaluate the damages from falling. In this proposal, we assume that the falling can be easily detected by observing acceleration of the center of mass and the falling controller will be activated after ?? seconds. Evaluating the damages from the falling might be an interesting problem to us, because it will dramatically affect the optimal control policy. We plan to measure the damages on the bodies and joints as contact forces and joint constraint forces, which might be scaled to select more important ones to be protected. Therefore, the objective function of our opitmization is accumulated body damages and joint stresses while ignoring the negligible value under the threshold.

### 3.2.2 Related Work

Safe falling and landing for bipeds is a topic that receives broad attention in many disciplines. Robotic researchers are interested in safe falling from standing height for the purpose of reducing damages on robots due to accidental falls. Previous work has applied machine learning techniques to predict falling [14], as well as using an abstract model to control a safe fall [8, 9, 40]. In contrast to the related work in robotics, we use simulation samples with detailed robot models to generate the optimal control policy. The main advantage of using simulation is that it can capture complex and arbitrary changes of contacts, which is hard to be formulated with an abstract model. We draw inspiration from kinesiology literature and sport practitioners. In particular, the techniques developed in freerunning and parkour community are of paramount importance for designing landing control algorithms capable of handling arbitrary scenarios [5, 1].

### 3.2.3 Algorithm

**Optimization for a single scenario** As the simplified version of the problem, we first develop the falling controll for a single scenario, which starts from the given initial state. For instance, the robot starts from its initial standing pose and being push its head backward for 0.1 second with 10N force. When we know the parameterization of the controller, optimizing control parameters for the given scenario can be easily solved by various optimization techniques, such as Covariance Matrix Adaptation (CMA) [12]). After solving one instance of the scenarios, we can use the solution as the guidance for the rest of the scenarios.

However, finding the proper parameterization of the controller is a very difficult problem which usually requires a lot of prior knowledge. In fact, there exist numerous control options in robotics, such as pose control, torque control, virtual force control using Jacobian Transpose, and so on. Even one of the option, a pose control has an infinite number of choices for representing its joint trajectories with splines. Indeed, the selection of control dimension has a huge impact on the result: we tested two parameterization of controller: a pose tracking with linear segments and bezier curves, which the latter has four times more degrees of freedom than the former. The optimization indicates that the bezier curve gives us much better results, which is one third of maximum impact comparing to the linear control.

Therefore, our short term goal is finding the proper parameterization of the controller. One intuition from the previous falling and landing project is momentum planning can be a simple and robust solution, so finding the proper momentum trajectory with an abstract model would be a promising approach. Another potential approach is incrementally finding the control parameterization. In this approach, we search over the optimal parameterization by mutating the control dimension with genetic algorithm. The value of each control dimension will be determined by solving the optimization problem with the standard technique, like CMA.

#### Policy generation for multiple scenarios

### 3.2.4 Results

#### Environment Setup

#### Preliminary Results

# CHAPTER IV

# HUMAN-GUIDED ITERATIVE TRAINING OF DYNAMIC MOTIONS

Resembles learning by demonstration,

## 4.1 System Overview

coaching and training

## 4.2 Controller

Our controller produces a torque

## 4.3 Instruction

our instruction are following:

# CHAPTER V

# TIMELINE FOR PROPOSED RESEARCH

- 2014, Apr: present proposal to committee
- 2014, Apr - May: setup a framework for real robots
- 2014, May - Sep: working on the robot falling project
- 2014, Sep: submit the robot falling paper to ICRA 2014
- 2014, Sep - Jul: working on the robot learning project
- 2015, May - Jul: write thesis
- 2015, Jul: defense thesis
- 2015, Sep: submit the robot learning project to ICRA 2015

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