PROPOSAL:
LEARNING DYNAMIC MOTOR SKILLS FOR VIRTUAL AND REAL HUMANOIDS

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PROPOSAL: LEARNING DYNAMIC MOTOR SKILLS FOR VIRTUAL AND REAL HUMANOIDS

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SUMMARY

As 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 yet a challenging problem which usually requires substantial amount of design efforts and optimization time due to its complexity. In this proposal, we introduce a set of technique for training various highly dynamic motor skills, such as jumping, rolling, vaulting, and landing, to 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 human 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 falling 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. Unlikely the existing techniques which usually consider the desired contacts as invariant features, we searches over a sequence of contacts to find the best falling motion which 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. Using our proposed system, we also train a real robot to perform dynamic motor skills such as rolling under enough consideration on noises over control and simulation.

By incorporating the propose 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 robotic. A wide variety of athletic, such as acrobatic or free running, demonstrate the efficient and artistic movements which involve the abrupt changes of momentum and contacts. Furthermore, these motor skills are transferred to virtual characters in animation and game 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 the safety, and demonstrate the self-expression.

In fact, developing dynamic controllers for virtual characters and real robots can be considered as related problems which can benefit each other. Since the control problems in two domains have shared properties, such as non-linearity, high-dimension, and disconstiuity, 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 requires 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 nice research direction, which is adopted in this proposal.

In 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 has been frequently applied to control problems: tracking the reference motion, or solving the space-time optimization problem under the 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 further 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 optimizzed, especially when the objective function is parameterized or concatenated for long term goals.

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 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.* [12, 38] 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.* [19] 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 [20, 29], or apply a hybrid method for synthesizing dynamic response to perturbation in the environment [26]. If the contact positions and timing are known, spacetime optimization techniques can also generate compelling dynamic motions [17, 7, 24, 31]. 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 [13], as well as using an abstract model to control a safe fall [8, 9, 39]. 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) [11], has been frequently applied to discontinuous control problems, such as biped locomotion [34, 35, 36], parkour-style stunts[18, 10], or swimming [32]. To compensate the expensive cost of sampling-based algorithm, different approaches have been proposed, including exploiting the domain knowledge [34, 35, 36] or shortening the problem horizons [28]. 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.[25]. 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 [37], and interface optimization [23]. The level of user interaction varies from simply selecting of the generated solutions [27] to directly editing the search parameters and constraints [30]. 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.* [16], it has been proven to be effective for training motor skills in numerous task domains, including object manipulation [2, 3, 33], navigation [14], full-body motion generation [15], 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 [22]. However, dynamic motor skills of humanoids have not been fully examined yet, except the only few works on the locomotion [21], which is our target domain in this proposal.

CHAPTER III

OPTIMIZATION OF FALLING AND LANDING MOTIONS

This section descries algorithm for generating natural and safe falling and landing motions of virtual and real humanoids. First, we develop 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 Falling and Landing Motion Control for A Virtual Character

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. 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.

3.1.1 Algorithm

3.1.2 Results

3.2 Multi-contact Falling Motion Control for a Humanoid Robot

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

REFERENCES

[1] *How to Land a Jump in Parkour, http://www.wikihow.com/Land-a-Jump-in-Parkour*, 2011.

[2] Atkeson, C. and Schaal, S., "Robot Learning From Demonstration," *ICML*, no. 1994, 1997.

[3] Calinon, S., Guenter, F., and Billard, A., "On learning, representing, and generalizing a task in a humanoid robot.," *IEEE transactions on systems, man, and cybernetics. Part B, Cybernetics : a publication of the IEEE Systems, Man, and Cybernetics Society*, vol. 37, no. 2, pp. 286–98, 2007.

[4] Chien, S., Rabideau, G., Willis, J., and Mann, T., "Automating planning and scheduling of shuttle payload operations," *Artificial Intelligence*, vol. 114, pp. 239–255, Oct. 1999.

[5] Edwardes, D., *The Parkour and Freerunning Handbook.* It Books, August 2009.

[6] Faloutsos, P., van de Panne, M., and Terzopoulos, D., "Composable controllers for physics-based character animation," in *SIGGRAPH*, pp. 251–260, Aug. 2001.

[7] Fang, A. C. and Pollard, N. S., "Efficient synthesis of physically valid human motion," *ACM Trans. on Graphics (SIGGRAPH)*, pp. 417–426, July 2003.

[8] Fujiwara, K., Kanehiro, F., Kajita, S., Kaneko, K., Yokoi, K., and Hirukawa, H., "UKEMI: Falling motion control to minimize damage to biped humanoid robot," in *Intelligent Robots and Systems, 2002. IEEE/RSJ International Conference on*, vol. 3, pp. 2521–2526, IEEE, 2002.

[9] Fujiwara, K., Kajita, S., Harada, K., Kaneko, K., Morisawa, M., Kanehiro, F., Nakaoka, S., and Hirukawa, H., "An optimal planning of falling motions of a humanoid robot," in *Intelligent Robots and Systems, 2007. IROS 2007. IEEE/RSJ International Conference on*, no. Table I, pp. 456–462, IEEE, 2007.

[10] Ha, S. and Liu, C. K., "Iterative training of dynamic skills inspired by human coaching techniques," *ACM Transactions on Graphics (Provisionally Accepted)*, vol. 33, 2014.

[11] Hansen, N. and Kern, S., "Evaluating the CMA evolution strategy on multimodal test functions," in *Parallel Problem Solving from Nature - PPSN VIII*, vol. 3242 of *LNCS*, pp. 282–291, 2004.

[12] Hodgins, J. K., Wooten, W. L., Brogan, D. C., and O'Brien, J. F., "Animating human athletics," in *SIGGRAPH*, pp. 71–78, Aug. 1995.

[13] Kalyanakrishnan, S., Goswami, A., Kim, J., KIM, Y., HURST, J., LIU, J., XUE, F., CHEN, X., KIM, M., GONG, L., and Others, "Learning to predict humanoid fall," *LEARNING*, vol. 8, no. 2, p. 245, 2011.

[14] Konidaris, G., Kuindersma, S., Grupen, R., and Barto, a., "Robot learning from demonstration by constructing skill trees," *The International Journal of Robotics Research*, vol. 31, pp. 360–375, Dec. 2011.

[15] Kulic, D., Ott, C., Lee, D., Ishikawa, J., and Nakamura, Y., "Incremental learning of full body motion primitives and their sequencing through human motion observation," *The International Journal of Robotics Research*, vol. 31, pp. 330–345, Nov. 2011.

[16] Kuniyoshi, Y., Inaba, M., and Inoue, H., "Teaching by showing: Generating robot programs by visual observation of human performance," in *Proc. of the 20th International Symp. on Industrial Robots*, pp. 119–126, 1989.

[17] Liu, C. K. and Popović, Z., "Synthesis of complex dynamic character motion from simple animations," *ACM Trans. on Graphics (SIGGRAPH)*, vol. 21, pp. 408–416, July 2002.

[18] Liu, L., Yin, K., van de Panne, M., and Guo, B., "Terrain runner: control, parameterization, composition, and planning for highly dynamic motions," *ACM Trans. Graph*, vol. 31, no. 6, p. 154, 2012.

[19] Liu, L., Yin, K., van de Panne, M., Shao, T., and Xu, W., "Sampling-based contact-rich motion control," *ACM Transactions on Graphics (TOG)*, vol. 29, no. 4, p. 128, 2010.

[20] Majkowska, A. and Faloutsos, P., "Flipping with physics: motion editing for acrobatics," in *Proceedings of the 2007 ACM SIGGRAPH/Eurographics symposium on Computer animation*, (Aire-la-Ville, Switzerland, Switzerland), pp. 35–44, 2007.

[21] Nakanishi, J., Morimoto, J., Endo, G., Cheng, G., Schaal, S., and Kawato, M., "Learning from demonstration and adaptation of biped locomotion," *Robotics and Autonomous Systems*, vol. 47, pp. 79–91, June 2004.

[22] Pastor, P., Hoffmann, H., Asfour, T., and Schaal, S., "Learning and generalization of motor skills by learning from demonstration," *2009 IEEE International Conference on Robotics and Automation*, pp. 763–768, May 2009.

[23] Quiroz, J., Louis, S., and Dascalu, S., “Interactive evolution of XUL user interfaces,” *Proceedings of the 9th annual conference on Genetic and evolutionary computation*, p. 2151, 2007.

[24] Safonova, A., Hodgins, J. K., and Pollard, N. S., “Synthesizing physically realistic human motion in low-dimensinal, behavior-specific spaces,” *ACM Trans. on Graphics (SIGGRAPH)*, vol. 23, no. 3, pp. 514–521, 2004.

[25] Scott, S., Lesh, N., and Klau, G., “Investigating human-computer optimization,” *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, 2002.

[26] Shapiro, a., Pighin, F., and Faloutsos, P., “Hybrid control for interactive character animation,” *Computer Graphics and Applications*, pp. 455–461, 2003.

[27] Sims, K., “Artificial evolution for computer graphics,” *SIGGRAPH Comput. Graph.*, vol. 25, pp. 319–328, July 1991.

[28] Sok, K. W., Kim, M., and Lee, J., “Simulating biped behaviors from human motion data,” *ACM Trans. Graph*, vol. 26, no. 3, 2007.

[29] Sok, K. W., Yamane, K., Lee, J., and Hodgins, J., “Editing dynamic human motions via momentum and force,” *ACM SIGGRAPH / Eurographics Symposium on Computer Animation*, 2010.

[30] Sreevalsan-Nair, J., Verhoeven, M., Woodruff, D., Hotz, I., and Hamann, B., “Human-guided enhancement of a stochastic local search: Visualization and adjustment of 3d pheromone,” vol. 4638, pp. 182–186, 2007.

[31] Sulejmanpašić, A. and Popović, J., “Adaptation of performed ballistic motion,” *ACM Trans. on Graphics*, vol. 24, no. 1, 2004.

[32] Tan, J., Gu, Y., Turk, G., and Liu, C. K., “Articulated swimming creatures,” in *ACM SIGGRAPH 2011 papers*, pp. 58:1–58:12, 2011.

[33] Ueda, J., Kondo, M., and Ogasawara, T., “The multifingered NAIST hand system for robot in-hand manipulation,” *Mechanism and Machine Theory*, vol. 45, pp. 224–238, Feb. 2010.

[34] Wang, J. M., Fleet, D. J., and Hertzmann, A., “Optimizing walking controllers,” *ACM Trans. Graph*, vol. 28, no. 5, 2009.

[35] Wang, J. M., Fleet, D. J., and Hertzmann, A., “Optimizing walking controllers for uncertain inputs and environments,” *ACM Trans. Graph*, vol. 29, no. 4, 2010.

[36] Wang, J. M., Hamner, S. R., Delp, S. L., and Koltun, V., “Optimizing locomotion controllers using biologically-based actuators and objectives,” *ACM Trans. Graph*, vol. 31, no. 4, p. 25, 2012.

[37] Waters, C. D. J., "Interactive Vehicle Routeing," *The Journal of the Operational Research Society*, no. 9, 1984.

[38] Wooten, W. L., *Simulation of Leaping, Tumbling, Landing, and Balancing Humans.* PhD thesis, Georgia Institute of Technology, 1998.

[39] Yun, S.-k., Goswami, A., and Sakagami, Y., "Safe fall: Humanoid robot fall direction change through intelligent stepping and inertia shaping," *2009 IEEE International Conference on Robotics and Automation*, pp. 781–787, May 2009.