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Three-Level Tracking Method for Animating a 3D Humanoid Character

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Abstract**—**With a rapid growth in 3D graphics technology over the last few years, people are desired to see more flexible reacting motions of a biped in animations. In particular, it is impossible to anticipate all reacting motions of a biped while facing a perturbation. In this paper, we propose a three-level tracking method for animating a 3D humanoid character. First, we take the laws of physics into account to attach physical attributes, such as mass, gravity, friction, collision, contact, and torque, to bones and joints of a character. The next step is to employ PD controller to follow a reference motion as closely as possible. Once the character cannot tolerate a strong perturbation to prevent itself from falling down, we are capable of tracking a desirable falling-down action to avoid any falling condition inaccuracy. From the experimental results, we demonstrate the effectiveness and flexibility of the proposed method in comparison with conventional data-driven approaches.

Keywords**—**Character Animation, Forward Dynamics, Motion Tracking, PD Control.

I. Introduction

CONVENTIONALLY, it is a great challenge to handcraft a series of smooth and natural responsive motions [1], [2]. In practice, we expect a skilled animator that needs to have enough knowledge in the field of physics or robotics while he designs responsive motions of a human character. In this paper, we devise an adaptive forward dynamics simulator to be compatible with the 3D animation software in the skeletal format, such as Autodesk 3DS Max and MotionBuilder. The motion simulation results can be stored in a FBX format to export to other animation applications for further usages. First, we analyze the bipedal character to obtain the information of bones, joints, and motions. In order to attach physical attributes, including mass, gravity, contact force, collision, and inertia, to the static character body, we make use of Open Dynamics Engine (ODE) to re-construct the bipedal character in an ODE world space. Second, we take advantage of a Proportional-Derivative (PD) controller to let the character automatically track a reference walking motion in terms of calculating torque of each joint. Proportional-Derivative controller has been used successfully for the purpose of tracking reference motions stored in a database while simulating characters' current motions in different environments [3], [4]; in addition, PD controller has been also applied to work on characters with disturbances for keeping them in balance [5]-[7]. Conventionally, this controller is used to employ in robotics and Zordan and Hodgins [8] further took the controller into account to properly implement it in the field of computer animation. Now most of the studies about response motions take advantage of PD controller with an optimization method to search for target motions in the next time step [9] [10]. In particular, using PD controller needs to specify exact parameters that could be manually configured by using biometrics or experimental experience [11].

Instead of tracking all joints in a bipedal character, we propose a three-level tracking method to not only decrease the number of tracking joints but provide the believable and smooth responsive motions when the character suffers from different strength of external perturbations. With respect to the three-level tracking method, a bipedal character is divided into two parts, one is the upper body, and the other is the lower body [12]. When no perturbation is applied to a character, we directly simulate the motion of the upper body by means of animating the reference motion in the upper part, and carry out the PD controller to track the lower part of the reference motion. Once an external perturbation is occurred and the balance mechanism is under the control, the tracking depth of the upper body is calculated to react to the given perturbation. While the character confronts an unexpected perturbation and the balance control fails to cope with the unbalanced situation, we do not just give up the motion tracking to like a soft rag doll but provide the specified falling style to make the character fall down plausibly. The experimental results show that the proposed method is flexible and feasible to simulate responsive motions of bipedal characters with different perturbations. In comparison with the conventional data-driven methods, the proposed system only needs a few natural reference motions for tracking and it simulates the possible responsive motions in real-time with a high frame rate.

The remainder of this paper is organized as follows. Section II describes how to construct a physically-based bipedal character from a standard FBX file [13] according to the specification of Open Dynamics Environment (ODE) [14]. The three-level tracking method is proposed in Section III, and experimental results are show in Section IV. Finally, conclusion and potential future works are given in Section V.

II. Character Motion Simulation

In Fig. 1, the skeletal structure adopted in the system is an abstract model for representing humanoid characters [15]. The character's weight has default value of 70kg with 18 bones in

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which a symmetric and hierarchical form is constructed for simplicity. In addition, we need different types of joints to connect with 18 bones in terms of degrees of freedom (DOFs), and three kinds of joints are used to facilitate the bone connection. The first joint type is a ball and socket joint with three rotating DOFs, the second one is a universal joint with two rotating DOFs, and the last one is a hinge joint with a single rotating direction. After the definition of joint types, the rotating range of each joint is also constrained to be met with the physical motions of a human-like character. The flowchart of the proposed system is illustrated in Fig. 2.

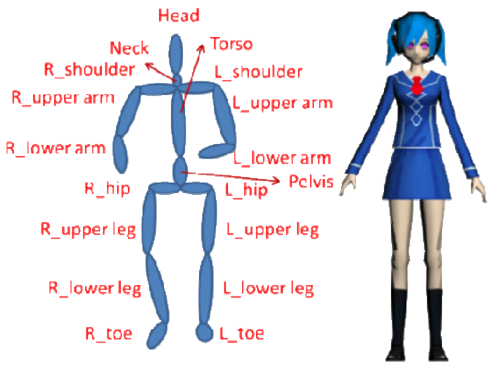

Fig. 1 The skeletal structure of a humanoid character

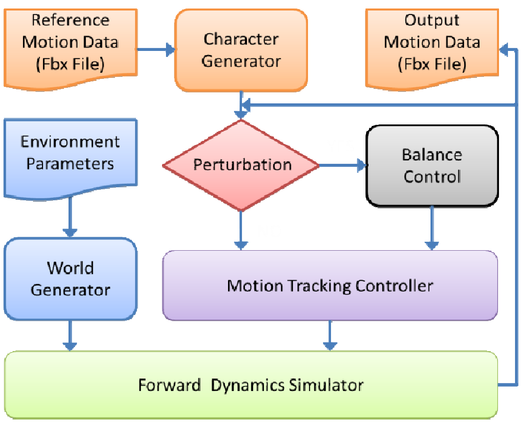

Fig. 2 The flowchart of the proposed system

Before the simulation, we calculated parameters of physical motions, such as joint accelerations, joint velocities, joint torque, root velocity, and root acceleration [16]. Equations (1) and (2) show the simple work for calculating both joint velocities and accelerations.

$$\dot{q} = \frac{q_j^N - q_j^{N-1}}{\Delta t} \quad (1)$$

$$\ddot{q} = \frac{q_j^{N+1} - 2q_j^N + q_j^{N-1}}{\Delta t^2} \quad (2)$$

where $\dot{q}$ and $\ddot{q}$ are joint velocities and accelerations respectively, and N is the joint number. Moreover, torque and rotations of each joint are restricted within a pre-defined maximum range in order to avoid an improper animation. We make confirm that a character does not have a behavior contrary to the common sense. The other physical parameters, such as contact forces, rigid body velocities and accelerations, and the COM velocity, were updated in every simulation loop, and we acquire some of these parameters with ODE.

In order to pursue approaching trajectories from reference motion data in real time, PD controller was applied here to yield appropriate joint torque on a virtual character.

$$\tau = k_p(q_d - q) + k_d(\dot{q}_d - \dot{q}) \quad (3)$$

In (3), k_p and k_d are the gain coefficients, q and $\dot{q}$ are the joint angles and joint velocities, q_d and $\dot{q}_d$ are the desired joint angles and joint velocities, and τ is the joint torque. The differences, including $q_d - q$and $\dot{q}_d - \dot{q}$, can give the tracking directions and magnitudes from the current poses to the desired poses. The gains control the weights for produced torque.

III. Three-Level Tracking Method

In this section, we describe the operation of the proposed three-level tracking method in detail. In practice, the number of simultaneous tracking joints is a critical factor to affect the computational cost of exerting a PD controller. When none of any external forces applied to a character, the proposed method solely concentrates on the lower body of the character in terms of reducing the number of tracking joints. If a perturbation is took place at a specific joint during tracking, we cope with the perturbation according to a variation in the joint velocity. Moreover, a strong perturbation could lead to an unexpected falling with an inaccurate posture. Accordingly, the proposed method takes advantage of the well-defined reference motions of falling down and carries out the motion transition to avoid any falling condition inaccuracy. The flowchart of applying the proposed method is illustrated in Fig. 3.

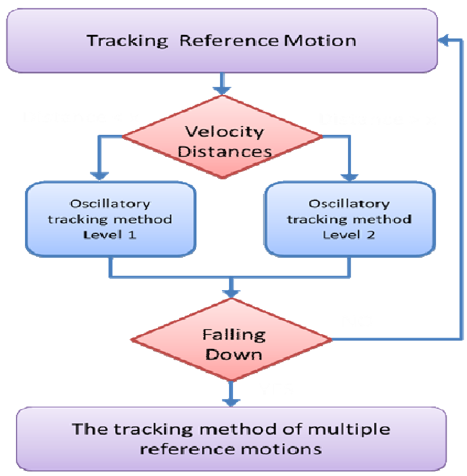

Fig. 3 The flowchart of applying the three-level tracking method

Using a PD controller to track reference motions of characters is a common technique in computer animation and robotics. However, the computational costs of motion tracking are enormous while tracking for the whole body of a character. We divide a skeleton of a character into six segments for simplifying the tracking of using the PD controller. The six segments are head, right arm, left arm, right leg, and left leg, as shown in Fig. 4.

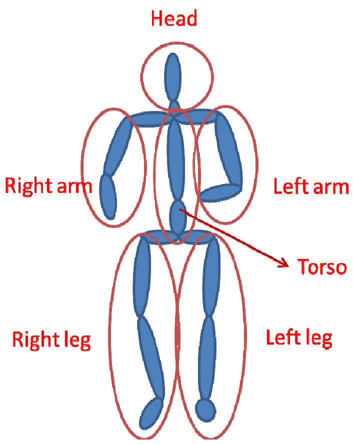

Fig. 4 The six segments of a human-like skeleton

There are three levels operated in the proposed method in order to handle different perturbations. In the first level, when a character does not face any external forces such that the proposed method directly simulates the motion of the character's upper body by adopting a specific reference motion. As for the lower body, the walking locomotion of the character is likely to be affected by frictional and contact forces, and we use PD controller to track the reference motion for keeping the correct walking locomotion. In the second level, as long as the character suffers from a slight perturbation at a particular part, the proposed method measures the variation in velocity for joints that belong to the same segment by (4). In (4), v_d is the variation in velocity of the i^{th} joint after hitting by an external force, v_r^i is the current velocity of the i^{th} joint after the perturbation, and v_f^i is the target velocity of the i^{th} joint in the reference motion. if the value of v_d^i is less than the pre-defined threshold, the proposed method only takes the affected segment into account to perform the motion tracking; otherwise, the torso segment needs to be incorporated withthe affected segment while tracking the motion of the character..

$$v_d^i = |v_r^i - v_f^i| \quad (4)$$

When the character meets a strong perturbation and does not preserve its boy balance; in other words, the character is forced to fall down accordingly. Meanwhile, if we still apply the PD controller to track the reference motion for keeping walking, it is obvious that the current locomotion of the character is quite inaccurate. In the third level, the proposed method prepares a few reference motions of falling down in advance and uses the linear interpolation as shown in (5) to smoothly transit the current walking motion to the target falling-down motion during the tracking phase [17], [18]. The purpose is to provide a natural and believable falling-down motion in simulating the motion of the character. In (5), M_i is the interpolated motion, M_s is the current walking posture, and M_r is the target fall-down motion. Additionally, four hitting directions are taken into consideration in determining which falling-down reference motion is used for tracking at this moment.

$$M_i = M_s * (1 - h) + M_r * h \quad (5)$$

IV. Experimental Results

In this section, we present experimental results to evaluate the proposed method. We make use of a few reference motions to acquire the required physical parameters; accordingly, we attach the value of the parameters into each joint to reconstruct a bipedal character for animating and reacting in a physical dynamic environment. PD controller has been used to track reference motions as closely as possible by means of calculating each joint torque from joint angles and velocities. As a result, the extra joint torque is applied to the specified joint to achieve the tracking operation in each time step. We take advantage of Open Dynamics Engine (ODE) to serve as the physics engine to simulate the physical dynamic environment, and we allow external perturbations to make a character change from an unstable posture to a balanced state. The experiments are divided into three parts. The first part is to set up a physical character in an ODE environment. Only gravitational and ground contact forces will be taken into consideration in this experiment. The second part is to show the simulation results when a small perturbation has been applied to the character. Finally, once the balanced state is out of control due to a strong perturbation, the character will fall down accordingly. The necessary physical attributes include bone mass, bone length, types of joints, and angle constraints of joints. The mass and length of each bone are listed in Table I, and DOFs and angle constraint of each critical joint are shown in Table II.

TABLE I
The Mass and Length of Each Bone

Bones	Mass (kg)	Length (m)
hip	4.3	0.097323
upper leg	6.6	0.457913
lower leg	3.2	0.475157
foot	1.0	0.150000
hip_to_torso	4.3	0.150000
torso	15	0.458223
neck	2.5	0.059140
hand	5.2	0.202566
shoulder	2.5	0.123588
upper arm	2.2	0.260867
lower arm	1.7	0.309095

TABLE II
The DOFs and Angle Constraint of Each Critical Joint

Joints	DOFs	Angle constraint of a joint		
		x	y	z
hip	3	-1.3 to 1.9	-1 to 1	-1 to 0.25
knee	1	0 to 2.5		
ankle	1	-0.75 to 0.75		
hip_to_torso	3	-0.6 to 0.6	-0.6 to 0.6	-0.6 to 0.6
hand	3	-0.6 to 0.6	-0.6 to 0.6	-0.6 to 0.6
shoulder	3	-1.7 to 1.7	-1.5 to 1.5	-1.5 to 1.5
elbow	1	-2.7 to 0		

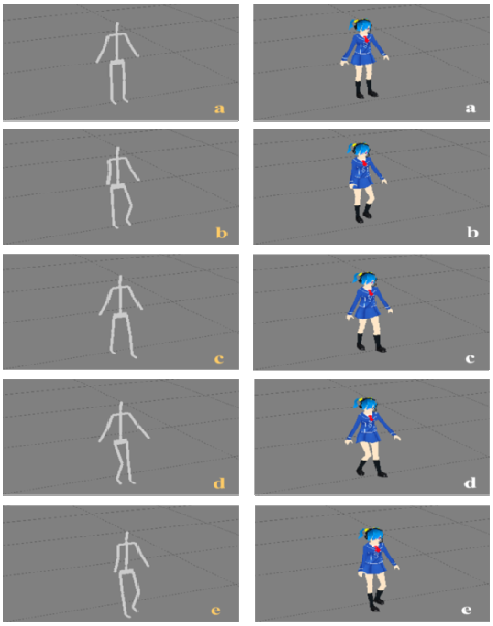

Fig. 5 To track a walking reference motion without any perturbation

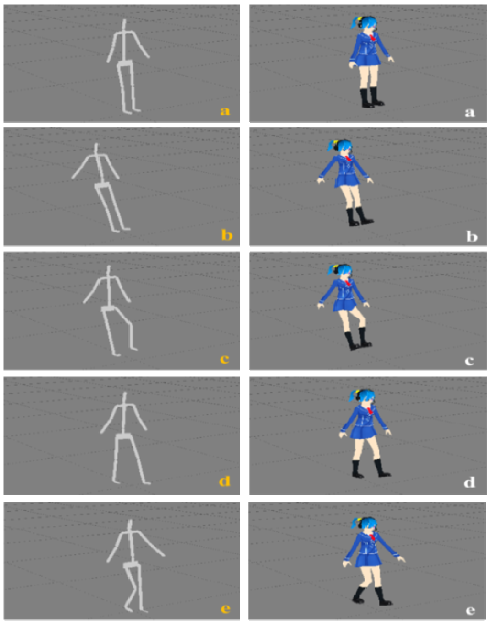

Fig. 6 To track a walking reference motion while pulling the right arm of the character

We experiment on the proposed three-level tracking method towards three kinds of force conditions, including no perturbation, a slight perturbation, and a strong perturbation. The reference motion adopted in this experiment is a handcrafted walking locomotion, and the keyframe length of the motion is 40. Fig. 5 demonstrates the simulation results of tracking the walking reference motion without applying any perturbation. Although the gravitational and contact forces of the ground have been applied to affect joint trajectories of the motion tracking, the character still sustains a smooth walking locomotion. In Fig. 6, we lightly pulled the right arm of the character towards its right-hand side, and then the motion tracking leads the character to return to the original walking locomotion. In the left of the Fig. 7, the character tried to use its two arms to hold the body by tracking a specific falling-down reference motion; on the other hand, the character was falling down freely due to the gravity, as shown in the right of the Fig. 7.

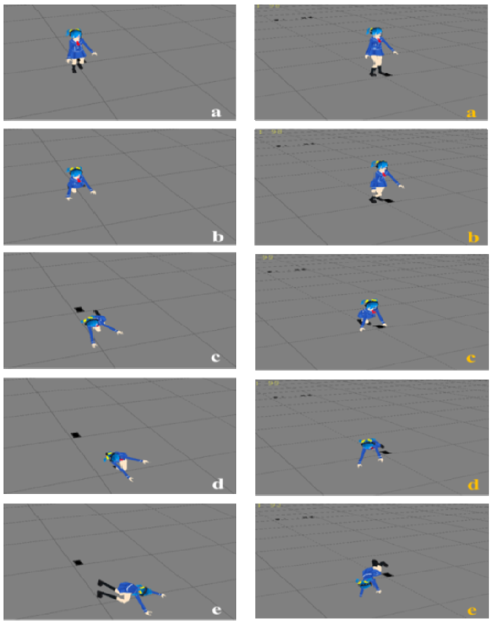

Fig. 7 (Left) The character tried to use its two arms to hold the body by tracking a specific falling-down reference motion. (Right) The character was falling down freely

V. Conclusion And Future Works

In this paper, we have proposed a three-level tracking method to not only animate a bipedal character smoothly but also provide a plausible response motion while reacting to varying environmental stimuli. Instead of employing data-driven approaches, we simply required a few reference motions for the purpose of tracking and we also followed the laws of physics to attach physical attributes to bones and joints of the human-like character. If the character did not suffer from any external forces, such as pulling or pushing, the method paid attention to the lower body of the character because the ground contact was the only force to affect the character's locomotion. Accordingly, PD controller has been applied to track a natural reference motion towards the lower parts of the character for reducing the considerable tracking costs. In the case of a strong perturbation, the character cannot prevent itself from falling down, and the proposed method has adjusted the falling posture to provide a believable falling-down motion and to eliminate motion inaccuracy from acting as a soft rag doll.

Balance maintenance is a significant research topic in simulating a human-like character in terms of using physical based approaches. In addition, how to control a character to fit in with an uneven terrain is another similar problem to tackle. In the future, we tend to concentrate on the above two topics to raise balance robustness and motion diversity of the proposed method.

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