Physical Simulation of Human Body Model Considering Joint Range of Motion

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Abstract

Recording dangerous motions using motion capture, the primary method used to acquire movements, remains burdensome for the performers. Physical simulation is considered an alternative but simulating a puppet that imitates a human being results in an unnatural bending of the joints. The range of motion of actual joints is complex and cannot be represented by simply setting a range for each axis. To solve this problem, we developed an improved physical simulation method consisting of passive restrictions on existing geometric joint ranges of motion and active restrictions to soften in advance the joint rotations that would exceed the range of motion. We implemented the proposed method using an open dynamics engine. Our experiments, involving the human body motions and the spherical rotational models that we developed, showed that the unnatural movements that occurred with the conventional method could be prevented using our methods.

Keywords: Computer Animation Physical Simulation Joint Range

1. Introduction

Reactive actions of humans in response to collisions are often required to be depicted in 3D animated content such as action games. Although these actions can be captured using motion-capture devices, They are dangerous and burdensome for actors. Physical simulation is another method for generating such motions, without requiring actors to perform any dangerous and burdensome tasks.

Simulating articulated bodies without considering the rotational ranges of joints as well as the actual range of motion in humans results in the generation of unnatural motions. In conventional physics simulations, constraints are applied on the rotational range for each axis of the joints. However, such a rotational range model cannot simulate the rotational range of human ball joints. For example, the unnatural motions of spherical joints are simulated, when each axis has an independent range of motion. Moreover, because humans avoid exceeding the rotational range by actively moving their joints, unnatural motions are generated in models without such a control mechanism.

The purpose of this research is to develop a physical simulation method that considers the rotational range of joints and active restrictions. Our method can be applied to generate human motions during physical interactions such as collisions and falls.

We improved conventional physics simulations of human bodies by introducing passive and active restrictions. In the passive restriction, the geometric range of rotation of a spherical joint [1] is adapted to the conventional rotational angle restriction. This is accomplished by dynamically updating the ranges of the joint rotation angles based on the geometrical range model and current rotational state. In active restriction, reactive control applies torque in the direction opposite to the rotational velocity to reproduce the human reaction to impact.

We implemented our method by using an Open Dynamics Engine (ODE) [2] that supports spherical joints and is rotational along each axis. Our experiments, involving the human body motions and the spherical rotational models that we created, showed that the unnatural movements that occurred with the conventional method could be prevented using our methods.

2. Related Work

2.1. Physical simulation

Zhao [3] attempted to limit the joint range of motion by using a physical simulation. In this case, the range of motion was limited by providing a range of rotation angles in the three rotating axes, with each range being independent of the others. In such a simulation, both one and two axes can bend to the maximum, which may generate unnatural motion. We used a geometric range of motion such that the range of the rotational angle of each axis was not independent.

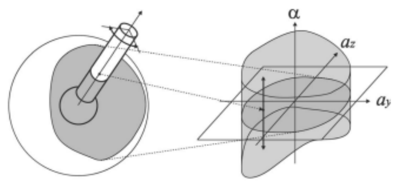

Figure 1: Motion range of a spherical joint projected onto (a_y, a_z, α) space : [1]

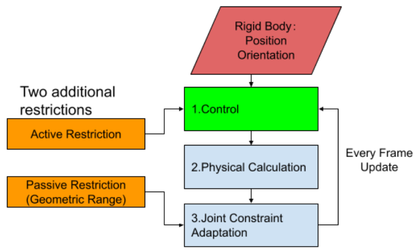

Figure 2: Improved Simulation

Zordan [4] proposed a method that combined a motion-capture-driven system with a physics simulation response. To some extent, this method relies on pre-prepared motion data. In this study, animations were generated solely through physical simulations.

2.2. Representation of rotation and range

Yamame [1] attempted to geometrically represent the range of joint motion. Rotation was represented in terms of points, and the geometric range of motion was defined in terms of polygonal regions, thereby generating animation from inverse kinematics based on these constraints. This rotational representation is also explained in this document, but details such as the parameter derivation are provided in [1].

The region space in Fig. 1 represents the geometric range of motion. Moreover, the position of a point in this space corresponds to the joint rotation. Point $a = (a_y, a_z, \alpha)$ representing the rotation was calculated from the link direction vector d and torsion angle α. The range of motion is represented by a polygonal area, which can be represented by triangular prisms.

3. Simulation Overview

Generally, human body physics simulations use an articulated body that mimics the human body. An articulated body comprises multiple rigid bodies connected by joints.

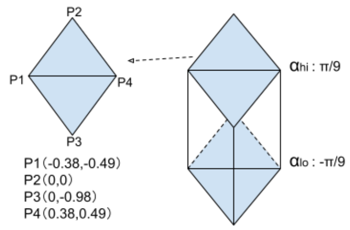

Figure 3: geometric range of motion

The simulation process is illustrated in Figure 2. In the control state, arbitrary forces and torques were applied to the rigid bodies based on a controller. The position and orientation of each rigid body were calculated using physical variation operations. Subsequently, the constraint conditions for each joint were adapted.

We implemented our simulation using the ODE that supports spherical joints and rotation constraints for each axis of rotation. For detailed descriptions of the parameters and functions, please refer to [2].

We added two restrictions in this simulation, as indicated by the orange boxes in Figure 2. Passive restrictions were imposed after applying the joint constraints to the controls. Active restrictions were used as controls.

4. Joint Restrictions

The proposed method aims to reproduce in a physical simulation the natural response of the human body to a given impact. The natural response involves rotation within the joint range of motion and active resistance to impact. To achieve this, we combined two types of constraints: passive and active restrictions. Passive restriction aims to correct rotation and adjust the human body to within the closest range of motion when it exceeds the range of motion. In contrast, active restrictions aim to actively inhibit the joint rotation where exceedance is likely to occur and apply a simplified force to replicate the human body's response to an impact.

4.1. Passive Restriction

Passive restriction uses the geometric rotational range of spherical joints [1]. Because many simulation engines, such as the ODE, support only rotational ranges for each axis of the spherical joints, our method dynamically supports the rotational ranges for each axis based on the geometrical range model and the current rotational state.

In our implementation, we used a simplified geometrical model that represents the range of (a_y, a_z) by a combination

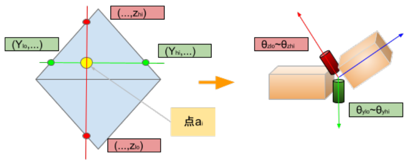

Figure 4: Geometric range to Amotor limits

of multiple triangles, as shown in Figure 3 and the range of (a_y, a_z) by constant maximum and minimum values because α is often independent of (a_y, a_z).

Based on our simplified geometrical model, (a_y, a_z), and given the current rotational state shown by the yellow circle in Figure 4, the rotational ranges around the y-axis θ_{ylo} and θ_{yhi} are determined by the horizontal segment that passes through the current state. Similarly, the rotation ranges around the z-axis θ_{zlo} and θ_{zhi} are determined by the vertical segment that passes through the current state.

4.2. Active Restriction

This method mimics the active human response by adding a reverse torque Tf in response to a sudden increase in rotational speed. Generally, such a reverse torque is applied in conventional control methods such as proportional-derivative control. However, normal reactive torques are often insufficient to respond to large impacts and suppress rotation over time. Therefore, our method detects a sudden increase in the rotational speed immediately after an impact and applies a counter torque.

The active restriction anticipates excessive joint rotation and applies T_f to control it. The input is the angular velocity around the three local coordinate system axes for each joint, and T_f was calculated and output when it exceeded a preset threshold value. Torque was applied to the joint as a control. Active restriction was applied to each joint as a control after the simulation loop was complete, and the current state of the articulated body was determined. The motion to which T_f was applied was calculated when the next simulation loop.

In this study, excessive rotation is considered to occur when the angular velocity ω around each axis of the joint rotation is greater than a certain threshold value t, and active restriction is applied according to the angular velocity. t is set for each of the three axes of rotation for each joint, and active restriction is applied when ω is greater than t. After measuring the angular velocity generated by the actual impact of a ball on any joint, we set t as the angular velocity, which is several times higher than the normal value of angular velocity, for example, in upright stance.

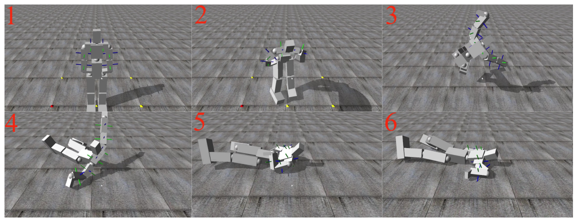

Figure 5: Ball collision with (a)

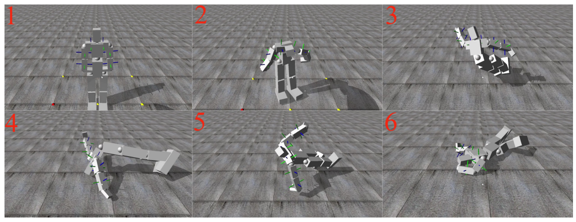

Figure 6: Ball collision with (b)

$$T_f = -kI\omega \tag{1}$$

The calculation of T_f for an axis is based on the calculation of a torque to cancel out the rotation that is about to exceed the ranges of motion. The calculation considers a torque that causes a rotation in the direction opposite to the current direction in proportion to the angular velocity ω that exceeds t on the axis of interest. The torque is calculated using Equation 1. k is a proportionality constant, and I is the moment of inertia of the single rigid body on which the joint rotation is based. In this case, the moment of inertia is considered in addition to the proportionality constant because the torque required for a particular rotation differs for each rigid body. k was assigned a value of 1, but adjustments were made through experimentation.

5. Experiment

To evaluate the effectiveness of the passive and active restriction models, we simulated the human body motions during physical interactions such as collisions with moving objects and falls. The floor, a ball for collision, and a slope for rolling the ball formed the scene, and normal gravity was applied.

A 17-jointed articulated body was used in the experiment. BVH(Biovision Hierarchy) is a format for storing the connections between the joints and body segments of the articulated body as skeletal information. In addition, information

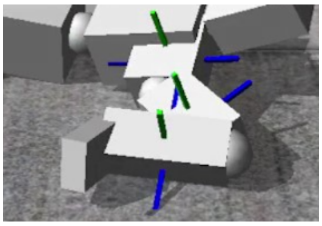

Figure 7: Unnatural example seen in (a)

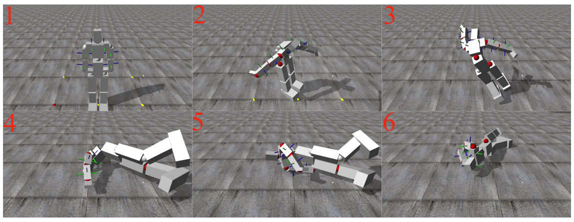

Figure 8: Ball collision with (b) and (c)

indicating the shape of each body segment is stored. Based on this information, it can be said that an articulated body is generated in the ODE scene. For the parameters of each point of the triangular column, which represented the range of motion of each joint, the base and height were set separately. The heights of the triangular columns representing the torsional angle range in the link direction were set to the angular range. Each point on the triangle was set to have an angular range of motion corresponding to the observed angular range of the maximum bending for a single axis. The active restriction threshold was also set to a speed that was considered excessive based on an analysis of the actual collision behavior.

In this experiment, we compared the results of the three methods.

(a) Rotational range for each axis of spherical joints (baseline method)

(b) Passive restriction (geometric range model for spherical joints)

(c) Active restriction

Figure 5 shows the simulation results with (a). Figure 6 shows the results with (b). Each figure shows the motion of the human body after collision with the ball in a series of images. In the results (a) some joints bent unnaturally, as shown by Figure 7.

Figure 8 shows the simulation results with (c). Figure 8 is the same as the situation in Figure 6 except for the addition of (c). Looking at frames 4, 5, and 6 in Figures 6 and 8, respectively, the behavior is such that the human body rotates strongly enough to float in the air in Figure 6, while the human body falls to the ground and rotates slowly in Figure 8. It is considered that the active restriction worked to suppress the rotation.

The geometric range of joints was simplified in this experiment. We are going to validate this method by setting a more accurate range of joints. In addition, because our implementation in this study relies on ODE, it sometimes become unstable. We are going to validate our method in other simulation engines.

6. Conclusion

In this study, we succeeded in generating movements in which the natural range of motion was preserved by restricting the range of motion of joints. This was achieved using a geometric range of motion in a physical simulation. In addition, the human body actively generates torque that cancels out the joint rotation. Although limited, the motion to resist the impact was successfully generated. For more realistic impact-motion generation, it is necessary to validate the model in the future by applying it to a human body-shape deformation model.

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