Data-Driven Human Motion Synthesis Based on Angular Momentum Analysis

Ping Hu, Qi Sun, Xiangxu Meng, Jingliang Peng
School of Computer Science and Technology, Shandong University
Emails: {peggyhu0315,nowhereman.sq}@gmail.com, {mxx,jpeng}@sdu.edu.cn

***Abstract*— In this paper, we present a novel method for real-time synthesis of human motion under external perturbations. The proposed method is data-driven and based on angular momentum analysis. When an external force is applied on the virtual human body, we analyze the change in the joints' angular momentums in a short period of time, predict the human body response, find an appropriate motion sequence from the pre-built motion capture (MoCap) database, and make a smooth transition between the current and the retrieved motion sequences to obtain the synthesized motion. The most important contributions of our method include that we propose a complete momentum analysis solution for the human body and that we make effective MoCap data organization based on the major characteristics of the body motion and the external force. As a result, realistic and real-time human motion synthesis is achieved, as experimentally demonstrated with the walking, the running and the jumping sequences.**

I. Introduction

Although computer animation has been in fast development for its attractive visual effects and promising application in video games, movies and other media, lifelike character animation synthesis is still a challenging area because of the complexity of human motions. Human motions are so complex that it is very difficult to realistically simulate them purely using computational methods. As such, MoCap techniques have been increasingly used to produce realistic human body animations. It is coming widely accepted that a versatile human motion synthesis system should take advantage of both computational methods and MoCap techniques. In such a system, physics and mathematical methods can be used to simulate human body response to the environmental factors and MoCap data can be utilized to model realistic human motions. This is also the focus of this work, and the goal of this research is to develop a complete solution for real-time and realistic simulation of human motion under external perturbations.

The human motion synthesis system that we develop is composed of two parts, off-line MoCap preprocessing and online human motion synthesis, as shown in Fig. 1. During the off-line preprocessing, we capture various motion sequences of a subject. While the subject acting each motion sequence, we exert at a certain body joint an external force of a certain strength and the subject's real response is captured. For each thus-captured raw MoCap sequence, the off-line preprocessing automatically computes its angular momentum file, detects the frame with sudden change (corresponding to the exertion of the external force) and writes that frame number in an index file. In the online process of human motion synthesis, an initial MoCap sequence is used to animate a 3D virtual human body; when an external force is applied through user control, the system predicts the angular momentum of every joints in upcoming frames and locates a subset in the MoCap database to reduce the search range; by comparing the predicted frames and the frames of the MoCap sequences in the subset, a best-matching sequence is extracted and used for simulation of the human motion after the perturbation.

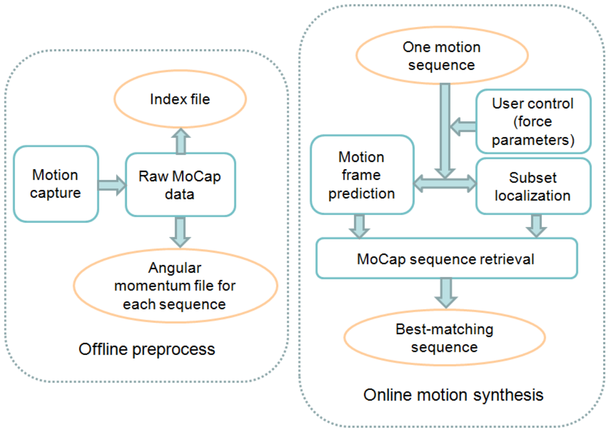


Fig. 1. System architecture.

The distinguishing contributions of our proposed human motion synthesis scheme mainly include:

- We propose to use angular momentum analysis to simulate the change of joints' angles under a sudden external force. This angular-momentum-based simulation yields physically faithful prediction of the subsequent frames after the perturbation, which further enables accurate retrieval of the optimal sequence from the MoCap database.
- Good acceleration is achieved in the motion retrieval process with quick subset localization, owing to the effective organization of the organization of the MoCap sequences according to motion types and external perturbation features. Different from the complex training-based classification approaches adopted in many recent works, our method is simple and effective.
- Our current system successfully simulates not only walking, but also running and jumping, in contrast to many related works that only simulate walking. This suggests universal applicability of our method for generic motion

types.

II. Related Work

There are mainly four categories of approaches in processing sequences of humanlike animation [1]: kinematics, dynamics, hybrid and motion editing. Our research focuses on synthesizing natural-looking animation. From this perspective, related works can be sorted into two categories: those editing motion data directly and those synthesizing animation based on physical models.

A variety of algorithms have been proposed in editing motion data directly [2][3][4]. Image filtering is introduced in motion extraction [3]. A directed graph is built for creating new motion sequences [4]. One work [5] takes angular momentum into consideration, but only focuses on the sagittal plane in which the human model is walking and ignores the underlying constraints in the data. As a result, the animation generated is limited by the pre-recorded data.

The other class of algorithms that process the data based on physical models [6][7][8][9] can compensate for the limitations with the direct motion editing approaches. Hof, Gazendam, and Sinke [10] used the inverted pendulum model [11] to simulate human walking motion. Some of these works can use a dynamics engine as the controller to simulate physically-valid animation [7][8], while others control the virtual character motion via principles of physics [9].

All of the above-mentioned works that are based on MoCap data processing focus mainly on two points: searching for the best sequence in the database and blending it to the current motion sequence minimizing the discernable inaccuracies. Whereas very few published works, if any, have tried to directly make a prediction of the character's relative angular momentum of each joint when an external force is exerted. We try to set foot in this aspect and have received gratifying outcomes in real-time and realistic human motion synthesis.

III. Angular Momentum Analysis

Human body skeleton is composed of a certain number of bones and joints. The joints form a hierarchy and each joint can be located by its coordinates in the local frame relative to its parent joint.

When analyzing the joint rotation, each segment of the human body can be simplified as a rigid stick model. For a rigid stick, its moment of inertia with respect to an arbitrary axis, Q, can be described as follows [12]:

$$\mathbf{L} = I \cdot \omega = (I_x\omega_x, I_y\omega_y, I_z\omega_z) \tag{1}$$

where $\mathbf{L}$ represents the angular momentum, ω represents the angular velocity, I is the stick's moment of inertia, and I_x, I_y, I_z are principal moments of inertia which represent to the three coordinate axes in an orthogonal frame, respectively. According to the definition of angular momentum when influenced by an external force, a rigid stick rotates according to the following formulae:

$$\tau = \mathbf{r} \times \mathbf{F} \tag{2}$$

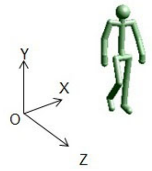


Fig. 2. Orthogonal frame used in our system.

$$\tau = I \cdot \dot{\omega} \tag{3}$$

where τ represents the torque of the external force, $\mathbf{F}$ represents the external force, $\dot{\omega}$ represents the derivative of ω, and $\mathbf{r}$ is the position vector, pointing from the coordinate origin to the exertion point of the external force. Meanwhile ω and θ meet the condition:

$$(\omega_x, \omega_y, \omega_z)^T = (\dot{\theta_x}, \dot{\theta_y}, \dot{\theta_z})^T \tag{4}$$

According to the angular momentum conservation principle in physics, a normal walking human body, seen as an entirety, stays on dynamic stability [10], in which both the momentum and the angular momentum of the whole body are conserved. The angular momentum of the body will change when an external force occurs causing a torque. Even if an external force is exerted on the root joint, the hip joint, it still causes one or more torques, and then some bones' angular momentums may change because not all bones are put in the same direction. As affected by an external force, the angular momentum can be calculated as:

$$\triangle\mathbf{L} = \mathbf{r} \times \mathbf{F} \cdot \triangle t \tag{5}$$

$$\mathbf{L_{t'}} = \mathbf{L_t} + \triangle\mathbf{L} \tag{6}$$

where $\triangle t$ is the time duration. Equation (5) and Equation (6) are used in the motion frame prediction process in our method.

IV. MoCap Data Pre-processing

Data pre-processing is a vital process in our human motion synthesis system. For each MoCap sequence, it calculates the angular momentum for each joint and marks the sudden change in the motion frames. Every MoCap sequence in our database must be pre-processed before it can be used for retrieval and simulation.

Our MoCap sequences are of normal motion styles, captured at 120Hz, implying only tiny differences between adjacent frames. Using Equation (1) and (4), we compute the angular momentum of every joint once per 20 frames empirically, which turns out to work well for the retrieval in our experiments. This computation is an automatic process in which the computed results are stored in the database.

The second step in data pre-processing is to mark the sudden change in each MoCap sequence. The method for measuring the angular momentum change as described before is from a local perspective. From an overall perspective, an external force is able to affect the velocity of the center of mass. As such, we take second derivatives of the positions and, based on which, detect the sudden change in the motion frames. The detected sudden change corresponds to the time instance, or equally the motion frame, at which an external force is exerted. Then we record this frame number in an index file.

V. Motion Frame Prediction

Prediction is triggered when a perturbation occurs. Parameters of the external force are interactively determined by the user, including the exerting point, the magnitude and the exerting direction of the force, denoted as f_e, f_s and f_d, respectively.

In our prediction method, another physical principle is utilized: in any direction perpendicular to the external force direction, the body's momentum is conserved, when an external force impacts on the body for a very short period of time. It follows the impulse-momentum theorem [12], a fundamental theorem regarding momentum and collision. For this reason, we only need to make prediction about the angular momentum on the direction where the force affects, without considering other directions. Using Equation (5), we are able to compute the change of angular momentum relative to the three principal axes (as illustrated in Fig. 2).

$$\triangle \mathbf{L_j} = \begin{cases} \mathbf{r} \times \mathbf{F} \cdot \triangle t & j = J_s, \\ 0 & j \neq J_s \end{cases} \tag{7}$$

where J_s represents the index of the joint on which the external force acts. Using Equation (6), the predicted angular momentum of each joint is calculated, and a motion frame is correspondingly predicted. Iteratively running the above process, we may predict K consecutive motion frames.

VI. MoCap Data Retrieval

A. MoCap Data Organization

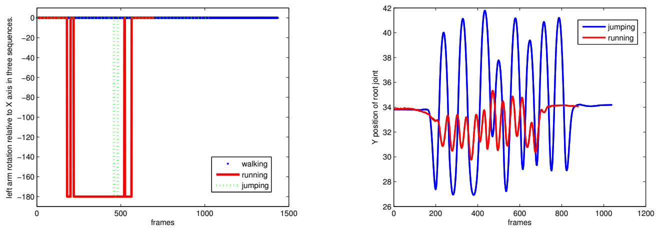
After the prediction, the system seeks for the most proper MoCap sequence that contains a consecutive sequence of frames similar to the predicted frames and synthesizes the retrieved MoCap sequence with the current one.

In order to accelerate the retrieval process, the MoCap sequences in the database are hierarchically organized. On the first level, they are divided into different motion types, *i.e.*, walking, running and jumping. On the second level, all the MoCap sequences belonging to one motion type are divided into subsets, according to their corresponding force features, *i.e.*, f_e, f_s and f_d. In our current system, we use a database with 54 subsets, 18 subsets belonging to each motion type, *i.e.*, walking, running, or jumping.

B. Subset Localization

Given a current motion sequence at an external force parameterized by f_e, f_s, and f_d, we need to first locate the subset in the database, then retrieve from the located subset for the best match.

The subset localization is performed in two steps. Firstly, the motion type is determined by analyzing the "arm rotation" and "root trajectory" characteristics of the motion sequence, which is simple and effective. As illustrated in Fig. 3(a), the range of left arm rotation for walking is much smaller than that with



(a) (b)

Fig. 3. (a) Temporal variation of the arm rotation degrees for walking, running and jumping. (b) Y-trajectory of the root joint for running and jumping.

the running or the jumping motion; as illustrated in Fig. 3(b), the running and the jumping motions have highly different Y-trajectories. Secondly, with the motion type determined, the subset is then located based on the force parameters, f_e, f_s, and f_d.

C. Retrieval in Subset

We seek for a MoCap sequence from the located subset that matches the predicted sequence the best. Specifically, we measure the similarity between the predicted sequence and each MoCap sequence in the subset and identify the MoCap sequence with the largest similarity.

The problem boils down to measuring the similarity of the predicted sequence and a MoCap sequence. We take 10 frames at an equal interval of 20 frames from the predicted frames. We also take 10 frames at an equal interval of 20 frames from the MoCap sequence starting from the frame marked with sudden change. Thereafter, we compare the thus-selected 10 predicted frames and 10 MoCap frames pair by pair. For the i-th ($i = 1, \ldots, 10$) pair, we compare them and compute a similarity value, S_i. The similarity, S, between the predicted sequence and the MoCap sequence is computed as $S = \frac{1}{10}\sum_{i=1}^{10} S_i$.

When comparing the i-th pair of frames, we compare each joint's corresponding angular momentums in the two frames. If the j-th joint has an angular momentum, L_{ij}, in the predicted frame, and an angular momentum, L'_{ij} , in the corresponding MoCap frame, assuming that L_{ij} and L'_{ij} are normalized, the similarity, S_i, between the two frames is measured with :

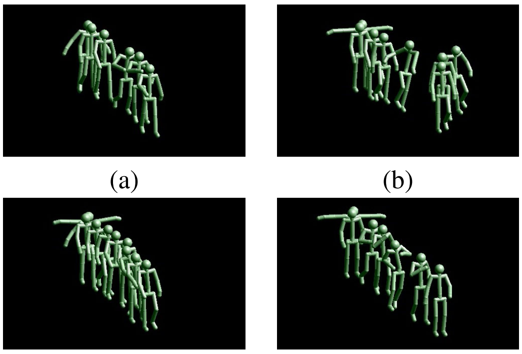
$$S_i = \sum_{j=1}^{J} \omega_j L_{ij} \cdot L'_{ij} \tag{8}$$

where J is the total number joints and ω_i is the joint weight which we determine with an Gaussian function assigning bigger (smaller) weights for joints in the high (low) level of the human body's joint hierarchy.

VII. Implementation and Results

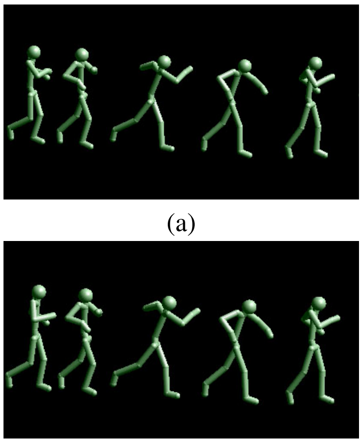
A. Experimental Setup

The skeleton model used in our experiments is from our MoCap database which has 78 degrees of freedom in total. The MoCap subject is of 178 cm in height and of 70kg in mass. The



(a) (b) (c) (d)

Fig. 4. Visual results for (a) walking with an external force on the back of a medium strength, (b) walking with an external force on the right shoulder of a strong strength, (c) walking with an external force on the left shoulder of a weak strength, and (d) running with an external force on the left shoulder of a medium strength.



(a) (b)

Fig. 5. Figure (a) shows several key frames of a MoCap sequence in which the character is perturbed by a strong force on his back while running. And figure (b) shows the corresponding key frames of a synthesized sequence when the character is influenced by a strong force on the back in running.

sequences are captured at 120HZ, using Vicon Blade MoCap system (v1.6).

We asked the subject to act various types of motions including walking, running and jumping. During each motion acting, we exert an external force of a certain level of strength (“A”, “B” or “C” in increasing order of strength) at one joint (back, waist, left shoulder, or right shoulder) and capture the subject’s real motion in response to the perturbation.

B. Experimental Results

In our experiments, a MoCap sequence is firstly used to animate a virtual human skeleton. During this process, the user may interactively specify and exert to the human body an external force at any time. Our simulation is done in real-time, owing to the data organization and subset localization techniques that we have proposed for the MoCap data retrieval.

Unlike some other methods [8] [13] that focus on walking simulation only and allow very limited user interactions, our current system successfully simulates generic walking, running and jumping motions, and allow more flexibility in user interaction. Meanwhile, The synthesized human motion sequences look realistic. As examples, Fig. 4 shows the key frames of several synthesized human motions corresponding to different configurations of motion type and external force. In addition, Fig. 5 demonstrates key frames from a synthesized human motion (bottom row) and those from an original MoCap sequence (top row). The synthesized motion is made under the same external force at the same joint as in the raw MoCap sequence. comparing with the ground truth, we see that the synthesized motion closely resembles the original.

VIII. Conclusion

We have presented a novel approach to real-time and realistic synthesis of human body motion based on angular momentum analysis and MoCap techniques. The good performance of the proposed approach mainly comes from the angular momentum analysis and the data retrieval acceleration. In the future, we would extend our system to analyze and simulate human motions of more variety and higher complexity.

Acknowledgment

This work was supported by Shandong Provincial Natural Science Foundation, China (Grant No. ZR2011FZ004), the National Natural Science Foundation of China (Grants No. U1035004 and No. 61070103), and the Program for New Century Excellent Talents in University (NCET) in China.

References

[1] S. Chung, “Animation of human walking: a survey based on artistic expression control,” *Acta Humanity and Social Research*, vol. 40, no. 2, 2010.

[2] L. Kovar and M. Gleicher, “Automated extraction and parameterization of motions in large data sets,” in *ACM Transactions on Graphics (TOG)*, vol. 23, no. 3. ACM, 2004, pp. 559–568.

[3] A. Bruderlin and L. Williams, “Motion signal processing,” in *Proceedings of the 22nd annual conference on Computer graphics and interactive techniques*. ACM, 1995, pp. 97–104.

[4] L. Kovar, M. Gleicher, and F. Pighin, “Motion graphs,” in *ACM SIGGRAPH 2008 classes*. ACM, 2008, p. 51.

[5] M. Popovic and A. Englehart, “Angular momentum primitives for human walking: biomechanics and control,” in *Intelligent Robots and Systems, 2004.(IROS 2004). Proceedings. 2004 IEEE/RSJ International Conference on*, vol. 2. IEEE, 2004, pp. 1685–1691.

[6] V. Zordan and J. Hodgins, “Motion capture-driven simulations that hit and react,” in *Proceedings of the 2002 ACM SIGGRAPH/Eurographics symposium on Computer animation*. ACM, 2002, pp. 89–96.

[7] V. Zordan, A. Majkowska, B. Chiu, and M. Fast, “Dynamic response for motion capture animation,” *ACM Transactions on Graphics (TOG)*, vol. 24, no. 3, pp. 697–701, 2005.

[8] M. Xu, H. Li, P. Lv, W. Chen, G. Liu, P. Zhu, and Z. Pan, “L4rw: Laziness-based realistic real-time responsive rebalance in walking,” in *Computer Graphics Forum*, vol. 29, no. 7. Wiley Online Library, 2010, pp. 2187–2196.

[9] X. Wei, J. Min, and J. Chai, “Physically valid statistical models for human motion generation,” *ACM Transactions on Graphics (TOG)*, vol. 30, no. 3, p. 19, 2011.

[10] A. Hof, M. Gazendam, and W. Sinke, “The condition for dynamic stability,” *Journal of biomechanics*, vol. 38, no. 1, pp. 1–8, 2005.

[11] D. Winter, “Human balance and posture control during standing and walking,” *Gait & Posture*, vol. 3, no. 4, pp. 193–214, 1995.

[12] F. Sears, M. Zemansky, and H. Young, *University physics*. Addison-Wesley, 1982.

[13] Y. Ye and C. Liu, “Optimal feedback control for character animation using an abstract model,” *ACM Transactions on Graphics (TOG)*, vol. 29, no. 4, p. 74, 2010.