impa INSTITUTO NACIONAL DE MATEMÁTICA PURA E APLICADA

State of the Art of Character Animation

Technical Report

Adriana Schulz

Instructor: Luiz Velho

Rio de Janeiro, May 28, 2010

Contents

Chapter 1

Introduction

By definition, to animate is to bring to life, in this case, to make a lifeless object (a graphics model) move. Realistic animation of human motion is a challenging task, firstly, because human movements can be quite complex since joints have many degrees of freedom and, secondly, because people are skilled at perceiving the subtle details of human motion. For example, people are capable of recognizing friends at a distance purely from the way they walk and can perceive personality and mood from body language. This implies that synthetic human motion needs to be very accurate in order to appear real.

1.1 Animation Techniques

The techniques for motion creation are usually divided into three basic categories: manual specification (key framing), motion capture and simulation [1].

Key framing borrows its name from traditional hand animation and is, in fact, very similar to it in the sense that, while computers reduce some of the labor by automatically interpolating between frames, the animator has to specify critical (or key) positions for the objects. This requires great training and talent, since a characters usually have many controls (e.g, each of the main characters of the movie Toy Story, which were animated in this fashion, had more than 700 controls). The advantage of this method is that the artist is able to control subtle details of the motion. Nevertheless, it is very hard to make the characters look real.

Motion Capture, is a process that transfers recorded movement to an animated object. Because of the challenges regarding realistic animation, it is the opinion of many researchers of the area that synthesis of realistic human motion can only be made possible by an approach that makes extensive use of data from the real world [2]. It this context, it has been quite appealing for animators to used methods of copying the movements of real life objects and Motion Capture technique are therefore largely used because they allow synthesizing realistic human movement in real time.

The physically based approach, uses laws of physics to generate motion through simulation and optimization. This technique is largely used, not only for human motion, but also to animate fluids, fire, explosions, face and hair. Simulation techniques supply physical realism, while MoCap allows for natural looking motion. Currently, many applications merge both techniques together in order to create models of human motion that are flexible and realistic [2].

1.2 Abstraction Levels

In addition to the different techniques to developing animations, we can also divide approaches by abstraction levels.

First, we can consider angle variations of each joint in time. This way, motion can be interpreted as several signals varying in time - one for each Degree of Freedom (DOF) of the character. From this perceptive, each DOF is modeled independently and signal processing methods can be used to create and edit motion.

The former approach is, nonetheless, very restrictive since it involves modeling each joint dependently and does not consider physical constraints. This leads to recurrent problems is the rendered motions, such physically impossible movements and other undesirable artifacts. One particularly distracting artifact is when the characters feet move when they ought to remain planted, a condition known as *footskate*. Hence, in order to control the movement of the character as a whole, we have to consider some kind of structure model approach. Many techniques use kinematic control and hierarchical modeling in order to model connectivity between body parts.

In addition to kinematics, dynamic models can be used for a more high-level control. This consists of specifying mass and force and applying laws of physics in order to generate motion. This method is very useful to simulate physical phenomenons such as gravity, inertia and collisions.

Behavior control can also be used to further consider interaction between the animated characters and the virtual world in which it is immersed. This approach consists of define rules for the way an object behaves and interacts and modeling responds to changes in the environment.

Finally, there are methods for simulating different styles. Human movements often vary according to gender, sex, age, weight, etc. In addition, motion is highly affected by mood. Therefore, in oder to generate realistic motions it is important to models the "emotional" aspects for motion, such as style and body language.

1.3 Overview

In this Technical Report, we study some of the most important topics of research related to character animation. We discuss several previous and point out new directions in the filed.

Chapter 2

Leveraging Motion Capture Data

Motion Capture (MoCap) is a technology that allows us to record human motion with sensors and to digitally map the motion to computer-generated creatures. MoCap is being largely used both by industry and academy because it guarantees natural and realistic results and is a cheap and fast (even real-time) method.

However, by itself, MoCap is nothing more than a method for reproducing acquired movements. Therefore, much effort has been, and is currently being, put into extending the applications of MoCap data.

2.1 Motion Editing

There are many reasons that make editing captured motion extremely important. Firstly, it is usually necessary to eliminate artifacts generated during acquisition. Secondly, it is important to match time and space of computer generated environments, overcome spatial constraints of capture studios and allow for the existence of motions that would be extremely hard for an actor to perform, such as the ones used in special effects. Finally, it is interesting to be able to reuse motion data in different occasions. For example, given a walking scene, it should be possible to generate a walk on an uneven terrain or steeping over an obstacle.

Because there are many degrees of freedom animation and movements can be quite complex, when developing such editing tools it is important to bear in mind not only efficiency but also simplicity. In this context, methods that make use of signal processing techniques prove to be quite interesting for motion editing. Works that have consider this approach include [3] and [4].

Another interesting work in this area is [5], which aims at making the motion more "animated" by adding effects of traditional animation (such as anticipation, follow-through, exaggeration and squash-and-stretch) by filtering the motion data with a *Cartoon Animation Filter*.

2.2 Motion Synthesize

In addition to editing, it is the interest of many researches in the field to synthesize new streams of motion from previously acquired data and, therefore, be able to create new and more complex motions. Motion synthesis strategies include constructing models of human motion [6, 7], interpolating motion to create new sequences, and reordering motion clips employing a motion graph [8].

Motions Graphs have been largely used to synthesize new motion and there are many works that discuss methods for creating motions graphs with greater conectivity [9] and selecting a good motion set with which to create an efficient motion graph [10].

Another interesing work in this area is [11], where the authors propose a method for synthesizing optimal or near optimal motions that include a variety of behaviors in a single motion. They use a discrete optimization approach and represent the desired motion as an interpolation of two time-scaled paths through a motion graph.

2.3 Database Techniques

Since Motion Capture technology is becoming evermore widespread, motion databases are now large, varied, and widely used. In this context, many reseraches have been studyng methos for organizing, processing, and navigating such databases [12].

It is in the interest of several researches to discuss efficient ways to retrieve a desired motion from a database. Several works [13, 14] use an example motion and comepare it similar motion in a datapase.

A different approach is to retrieve motion from a sall set of controls. A work that persues this idea is [15], which use a motion graph to preprocess the information and a small set of markers on a performer as control poitns.

Other important reseach topics in the area are dimensionality reduction and database compression, motion segmentation and classification, and the development of distance metrics in order to compare two different motions.

Chapter 3

Animating in Style

As mentioned before, there is more to animating characters then simply synthesizing natural and physically realistic motions. In truth, the style of a motion often conveys more meaning than the underlying motion itself. Hence many resent works in character animation involve understanding, modeling and synthesizing stylistic motion.

In this chapters we present recent efforts of several researches of the filed to incorporate style to motions. We will also discuss related topics such as modeling of body language and motion variations.

3.1 Realism and Expressiveness

As previously mentioned, since we are constantly bombarded with images of people moving about, we acquire a natural ability for recognizing and evaluating human motion. This makes creating realistic human motion a challenging task and suggests the study of methods for evaluating how realistic a given motion is.

Several of such works are refereed to in [16] include evaluating not only realism [17], emotional content [18]. These investigations often involve insights from the field of psychology that study human perception.

3.2 Motion Styles

One of the earliest works that discusses a high-level control over the style of an animation is [19]. In this paper, the authors introduce the style machine, which is a statistical model that can generate new motion sequences in different styles by adjusting a small number of parameters. Style machines are lerned from motion colections and can be used to generate new motion and transfer style form one character to another.

The idea of transferring motion to new charaters has atracted the interest of many reserches. In [20], Michal Gleicher presents a technique for adapting a motion from one character to another. This method, referred to as retargetting is specially useful to reuse an animated motion that was captured or synthesized for a character of a different hight, weight, age or gender.

In terms of stylistic retargetting, several approaches have been used including [21, 22, 23, 24]. In [21] they . In [22] the authors present a system that, with a focus on arm gestures, is capable of producing full-body gesture animation for given input text in the style of a particular performer. In [23] they introduce a system for editing animation data that is particularly well suited to making stylistic changes. In [24] they presnt a semantic deformation transfer that enables automatic transfer of new poses and animations.

Style information has also been used to add realism to movements that are synthesized from physical simulations. In [25] the authors present a control system that can reproduce a style in a new motion simulation, from a reference motion that describes it.

Finally, the work [26] present an application of motion style to inverse kinematics. They present a method for creating an inverse kinematics system based on a learned model of human poses. Since since system is data driven, it can create different styles of IK, depending of the training data.

3.3 Body Language

Another interesting subject of investigation in the context of high level characteristics of human motion is body language. Body language is not only a fundamental aspect of naturalist motion, but is also a very useful tool for communication. Hence in order for characters to communicate and interact in virtual environments it is important to model such gestures and body motions.

In [27], a method for automatically synthesizing body language from input speech signal is presented. The authors describe a method for modeling the gesture formation process that can be used in real-time rendering and develop and algorithm for creating animations from a live speech signal.

Others applications of the study of body language include character recognition. In [28] the authors show how an SVM based acoustic speaker verification system can be significantly improved in incorporating new visual features that capture the speakers body language.

3.4 Motion Variations

While style is what differentiates between examples of the same behavior, variations differentiate between examples of the same style. Varying motions can be very useful in applications where an large number of characters are being animated or when the character performs the same motion more than once.

Previous works perform motion variation by adding noise, while more recent investigations make use of previously acquired data sets and machine learning techniques. A recent work that present a method to model and synthesize variation in motion data is [29]. Given a few examples of a particular type of motion as input, they learn a generative model that is able to synthesize a family of spatial and temporal variants that are statistically similar to the input examples.

In addition, [30] presents a method to model style and variation of motion data captured from different subjects performing the same behavior.

Chapter 4

Controling and Simulating Characters

Many recent works have investigated new are more efficient ways to synthesize human motions in interactive environments in real time. Applications of this research include the control of characters in computer games, electronically mediated communications, and training simulations.

In such applications it is important to develop methods for fast and accurate character responses.

4.1 Physics-Based Control

There are several works that, taking physics into account, develop controllers to drive forward dynamic simulations.

In [31], the authors develop feedback laws based upon insights into balance and locomotion in order to controlling biped locomotion in real time. In [32] a method for precomputing robust task-based control policies is used for physically simulated characters in real time is presented. In [33] the authors describe an analytic approach for the control of standing in simulations based upon local optimization.

In [34] a constrained optimization problem is formulated at every time step in order to synthesize motion in a dynamically varying environment. In [35] a nonlinear probabilistic model of dynamic responses from very few perturbed walking sequences is learned and then used to synthesize responses and recovery motions under new perturbations.

4.2 Control from MoCap

Simulated motions have the advantage of being physically realistic, but often fail to convey stylistic, personality-rich human behaviors. Human ofter react fluidly to changes in environment. For example, we and can gracefully avoid unexpected moving obstacle while maintaining a walking speed and direction. Simulating such reaction in a high level of detail is quite difficult and therefore several approaches for real time interactive character control make use previous acquired MoCap data.

An example of this approach is [36], where the authors develop an optimization method that transforms MoCap motion into a physically-feasible, balance-maintaining simulated motion. The latter is then used to learn the character's control policy and dynamically simulate biped motion in real time.

In [37] animations are generated by blending precaptured motion clips using controllers to select the sequences of clips to achieve some goal. Near-optimal controllers are computed for a MoCap data set using a low-dimensional basis representation and used to generate a fluidly response to user control and environmental constraints in real time.

In [38] short motion fragment are also assembled in order to create motion streams in real time. Each fragment is calculated based on the previous fragment and the user's input and reinforcement learning methods are used to precalculate fragment choices.

In [39], a new method for creating compact and efficient data-driven character controllers is presented.

Chapter 5

Animating in Interactive Environments

5.1 Environment Interaction

Making characters respond to environment changes has its own challenges. Many of the works mentioned in the previous chapter approach not only the problem of guarantying user control but also the problem of responding to dynamical changes in the environment or unexpected perturbations.

Another interesting issue that is being investigated is how to make intersections with objects. In several applications, it may be important to have a character touch, hold, carry or kick or have other interactions with objects. An interesting work that approaches this problem is [40], where the authors introduce an editing tool that allows creating intersections between human motion and objects and considers complex cases that require precise synchronization, such as juggling.

5.2 Human-Computer Interaction

In many applications, such as control of characters in computer games, electronically mediated communications, and training simulations and equipment design (determining if controls can be comfortably accessed), it is important for users to be able to control motion in real time.

With this objective, researchers have not only investigated new ways of automatically synthesizing motions that respond to control specifications immediately (see Chapter 4) but also new ways for users to specify constraints.

An interesting work that addresses this problem in [15], which used MoCap data input. In this work, the authors describe a method for creating motion from only a small set of markers using a database of previously captures motion sequences and a motion graph.

In other application that do not require real time responses (such as creating animation sequences for storytelling), it is also important to create intuitive interfaces for describing motion.

A computer-user interface that is currently very popular is the sketch-based. With all the available hardware for generating sketch (iPhone, iPad, iTable, etc...) is it becoming evermore easy to use sketch as as input device. In addition sketch is much more intuitive for specifying motions than determining control points. Works that use sketch include [11] nad [41], where the user specifies the motion by sketching a path of the character through the environment in addition to other constraints.

Other works have used sketch as a way of determining keyframes. In [42] and [43] 3D articulate body animations are synthesized from 2D keyframe sketches. The idea behind such approaches is to leverage hand animators' abilities.

Chapter 6

Editing with Rythm

Several human motions, such as locomotion and dance, follow rhythmic patterns and the study of such patterns has many interesting applications.

In [44] the authors define *motion beat* as a regular rhythmic unit of time for a motion and describe a method for capturing them from a set of basic movements. With this information, they are able to synthesize new motions using a motion graph on an on-line manner, which are synchronized with an input audio signal. Another work that has proposed a different method for inducing the motions beats is [45], which uses a short-term PCA.

Other works have used audio to guide motion synthesis. In [46] the authors introduce a method for synchronizing motion to perceptual cues extracted from music using music analysis techniques. A different approach is [47], where MoCap is used to acquire dance movements that are performed on a background music and the music information is used to annotate the data.

Another interesting research topic is the inverse problem, i.e., motion-guided music composition. Some previous works, such as [48], have addressed this issue, but used only a couple of low level commands to generate simple audio results. A resent work [49] has suggested the use of a measure-synchronous motion graph to guide the composition of a full song, indicating this is an interesting topic for further investigations.

Bibliography

[1] Jessica Hodgins. Animating human motion. *Scientific American*, 278(3), March 1998.

[2] Jessica Hodgins and Zoran Popovic. *Animating Humans by Combining Simulation and Motion Capture*. SIGGRAPH'00 Course Notes 33, SIGGRAPH-ACM publication, New Orleans, Louisiana, USA, July 2000.

[3] Andrew Witkin and Zoran Popovic. Motion warping. In *SIGGRAPH '95: Proceedings of the 22nd annual conference on Computer graphics and interactive techniques*, pages 105–108, New York, NY, USA, 1995. ACM.

[4] Armin Bruderlin and Lance Williams. Motion signal processing. In *SIGGRAPH '95: Proceedings of the 22nd annual conference on Computer graphics and interactive techniques*, pages 97–104, New York, NY, USA, 1995. ACM.

[5] Jue Wang, Steven M. Drucker, Maneesh Agrawala, and Michael F. Cohen. The cartoon animation filter. In *SIGGRAPH '06: ACM SIGGRAPH 2006 Papers*, pages 1169–1173, New York, NY, USA, 2006. ACM.

[6] Yan Li, Tianshu Wang, and Heung-Yeung Shum. Motion texture: a two-level statistical model for character motion synthesis. In *SIGGRAPH '02: Proceedings of the 29th annual conference on Computer graphics and interactive techniques*, pages 465–472, New York, NY, USA, 2002. ACM.

[7] Matthew Brand and Aaron Hertzmann. Style machines. In *SIGGRAPH '00: Proceedings of the 27th annual conference on Computer graphics*

and interactive techniques, pages 183–192, New York, NY, USA, 2000. ACM Press/Addison-Wesley Publishing Co.

[8] Lucas Kovar, Michael Gleicher, and Frédéric Pighin. Motion graphs. In *SIGGRAPH '02: Proceedings of the 29th annual conference on Computer graphics and interactive techniques*, pages 473–482, New York, NY, USA, 2002. ACM.

[9] Liming Zhao and Alla Safonova. Achieving good connectivity in motion graphs. In *SCA '08: Proceedings of the 2008 ACM SIGGRAPH/Eurographics Symposium on Computer Animation*, pages 127–136, Aire-la-Ville, Switzerland, Switzerland, 2008. Eurographics Association.

[10] Liming Zhao, Aline Normoyle, Sanjeev Khanna, and Alla Safonova. Automatic construction of a minimum size motion graph. In *SCA '09: Proceedings of the 2009 ACM SIGGRAPH/Eurographics Symposium on Computer Animation*, pages 27–35, New York, NY, USA, 2009. ACM.

[11] Alla Safonova and Jessica K. Hodgins. Construction and optimal search of interpolated motion graphs. In *SIGGRAPH '07: ACM SIGGRAPH 2007 papers*, page 106, New York, NY, USA, 2007. ACM.

[12] Christos Faloutsos, Jessica Hodgins, and Nancy Pollard. Database techniques with motion capture. In *SIGGRAPH '07: ACM SIGGRAPH 2007 courses*, page 1, New York, NY, USA, 2007. ACM.

[13] Lucas Kovar and Michael Gleicher. Automated extraction and parameterization of motions in large data sets. *ACM Trans. Graph.*, 23(3):559–568, 2004.

[14] Meinard Müller, Tido Röder, and Michael Clausen. Efficient content-based retrieval of motion capture data. In *SIGGRAPH '05: ACM SIGGRAPH 2005 Papers*, pages 677–685, New York, NY, USA, 2005. ACM.

[15] Jinxiang Chai and Jessica K. Hodgins. Performance animation from low-dimensional control signals. In *SIGGRAPH '05: ACM SIGGRAPH 2005 Papers*, pages 686–696, New York, NY, USA, 2005. ACM.

[16] Aaron Hertzmann, Carol O'Sullivan, and Ken Perlin. Realistic human body movement for emotional expressiveness. In *SIGGRAPH '09: ACM*

SIGGRAPH 2009 Courses, pages 1–27, New York, NY, USA, 2009. ACM.

[17] Liu Ren, Alton Patrick, Alexei A. Efros, Jessica K. Hodgins, and James M. Rehg. A data-driven approach to quantifying natural human motion. *ACM Trans. Graph.*, 24(3):1090–1097, 2005.

[18] Rachel McDonnell, Sophie Jörg, Joanna McHugh, Fiona Newell, and Carol O'Sullivan. Evaluating the emotional content of human motions on real and virtual characters. In *APGV '08: Proceedings of the 5th symposium on Applied perception in graphics and visualization*, pages 67–74, New York, NY, USA, 2008. ACM.

[19] Matthew Brand and Aaron Hertzmann. Style machines. In *SIGGRAPH '00: Proceedings of the 27th annual conference on Computer graphics and interactive techniques*, pages 183–192, New York, NY, USA, 2000. ACM Press/Addison-Wesley Publishing Co.

[20] Michael Gleicher. Retargetting motion to new characters. In *SIGGRAPH '98: Proceedings of the 25th annual conference on Computer graphics and interactive techniques*, pages 33–42, New York, NY, USA, 1998. ACM.

[21] Eugene Hsu, Kari Pulli, and Jovan Popović. Style translation for human motion. *ACM Trans. Graph.*, 24(3):1082–1089, 2005.

[22] Michael Neff, Michael Kipp, Irene Albrecht, and Hans-Peter Seidel. Gesture modeling and animation based on a probabilistic re-creation of speaker style. *ACM Trans. Graph.*, 27(1):1–24, 2008.

[23] Michael Neff and Yejin Kim. Interactive editing of motion style using drives and correlations. In *SCA '09: Proceedings of the 2009 ACM SIGGRAPH/Eurographics Symposium on Computer Animation*, pages 103–112, New York, NY, USA, 2009. ACM.

[24] Ilya Baran, Daniel Vlasic, Eitan Grinspun, and Jovan Popovic. Semantic Deformation Transfer. *SIGGRAPH (ACM Transactions on Graphics)*, 2009.

[25] Marco da Silva, Yeuhi Abe, and Jovan Popović. Interactive simulation of stylized human locomotion. In *SIGGRAPH '08: ACM SIGGRAPH 2008 papers*, pages 1–10, New York, NY, USA, 2008. ACM.

[26] Keith Grochow, Steven L. Martin, Aaron Hertzmann, and Zoran Popović. Style-based inverse kinematics. *ACM Trans. Graph.*, 23(3):522–531, 2004.

[27] Sergey Levine, Christian Theobalt, and Vladlen Koltun. Real-time prosody-driven synthesis of body language. In *SIGGRAPH Asia '09: ACM SIGGRAPH Asia 2009 papers*, pages 1–10, New York, NY, USA, 2009. ACM.

[28] Christoph Bregler, George Williams, Sally Rosenthal, and Ian McDowall. Improving acoustic speaker verification with visual body-language features. In *Proc. IEEE ICASSP*. IEEE, 2009.

[29] Manfred Lau, Ziv Bar-Joseph, and James Kuffner. Modeling spatial and temporal variation in motion data. In *SIGGRAPH Asia '09: ACM SIGGRAPH Asia 2009 papers*, pages 1–10, New York, NY, USA, 2009. ACM.

[30] Wanli Ma, Shihong Xia, Jessica Hodgins, Xiao Yang, Chunpeng Li, and Zhaoqi Wang. Modeling style and variation in human motion. In *SCA '10: Proceedings of the 2010 ACM SIGGRAPH/Eurographics Symposium on Computer Animation*, New York, NY, USA, 2010. ACM.

[31] KangKang Yin, Kevin Loken, and Michiel van de Panne. Simbicon: Simple biped locomotion control. *ACM Trans. Graph.*, 26(3):Article 105, 2007.

[32] Stelian Coros, Philippe Beaudoin, and Michiel van de Panne. Robust task-based control policies for physics-based characters. In *SIGGRAPH Asia '09: ACM SIGGRAPH Asia 2009 papers*, pages 1–9, New York, NY, USA, 2009. ACM.

[33] Yeuhi Abe, Marco da Silva, and Jovan Popović. Multiobjective control with frictional contacts. In *SCA '07: Proceedings of the 2007 ACM SIGGRAPH/Eurographics symposium on Computer animation*, pages 249–258, Aire-la-Ville, Switzerland, Switzerland, 2007. Eurographics Association.

[34] Sumit Jain, Yuting Ye, and C. Karen Liu. Optimization-based interactive motion synthesis. *ACM Transaction on Graphics*, 28(1):1–10, 2009.

[35] Yuting Ye and C. Karen Liu. Synthesis of responsive motion using a dynamic model. In *Computer Graphics Forum (Eurographics Proceedings)*, volume 29, 2010.

[36] Kwang Won Sok, Manmyung Kim, and Jehee Lee. Simulating biped behaviors from human motion data. In *SIGGRAPH '07: ACM SIGGRAPH 2007 papers*, page 107, New York, NY, USA, 2007. ACM.

[37] Adrien Treuille, Yongjoon Lee, and Zoran Popović. Near-optimal character animation with continuous control. *ACM Trans. Graph.*, 26(3):7, 2007.

[38] James McCann and Nancy Pollard. Responsive characters from motion fragments. In *SIGGRAPH '07: ACM SIGGRAPH 2007 papers*, page 6, New York, NY, USA, 2007. ACM.

[39] Yongjoon Lee, Seong Jae Lee, and Zoran Popović. Compact character controllers. *ACM Trans. Graph.*, 28(5):1–8, 2009.

[40] Sumit Jain and C. Karen Liu. Interactive synthesis of human-object interaction. In *ACM SIGGRAPH/Eurographics Symposium on Computer Animation (SCA)*, pages 47–53, New York, NY, USA, 2009. ACM.

[41] Matthew Thorne, David Burke, and Michiel van de Panne. Motion doodles: an interface for sketching character motion. In *SIGGRAPH '04: ACM SIGGRAPH 2004 Papers*, pages 424–431, New York, NY, USA, 2004. ACM.

[42] James Davis, Maneesh Agrawala, Erika Chuang, Zoran Popović, and David Salesin. A sketching interface for articulated figure animation. In *SCA '03: Proceedings of the 2003 ACM SIGGRAPH/Eurographics symposium on Computer animation*, pages 320–328, Aire-la-Ville, Switzerland, Switzerland, 2003. Eurographics Association.

[43] Eakta Jain, Yaser Sheikh, and Jessica Hodgins. Leveraging the talent of hand animators to create three-dimensional animation. In *SCA '09: Proceedings of the 2009 ACM SIGGRAPH/Eurographics Symposium on Computer Animation*, pages 93–102, New York, NY, USA, 2009. ACM.

[44] Tae-hoon Kim, Sang Il Park, and Sung Yong Shin. Rhythmic-motion synthesis based on motion-beat analysis. *ACM Trans. Graph.*, 22(3):392–401, 2003.

[45] Jianfeng Xu, Koichi Takagi, and Akio Yoneyama. Motion beat induction based on short-term principal component analysis. In *SIGGRAPH ASIA '09: ACM SIGGRAPH ASIA 2009 Sketches*, pages 1–1, New York, NY, USA, 2009. ACM.

[46] Marc Cardle, Stephen Brooks, Loic Barthe, Mo Hassan, and Peter Robinson. Music-driven motion editing. In *SIGGRAPH '02: ACM SIGGRAPH 2002 conference abstracts and applications*, pages 222–222, New York, NY, USA, 2002. ACM.

[47] Gunwoo Kim, Yan Wang, and Hyewon Seo. Motion control of a dancing character with music. *Computer and Information Science, ACIS International Conference on*, 0:930–936, 2007.

[48] C. Dobrian and F. Bevilacqua. Gestural control of music using the vicon 8 motion capture system. In *NIME '03*, 2003.

[49] Adriana Schulz, Marcelo Cicconet, and Luiz Velho. Motion scoring. In *SIGGRAPH '10: ACM SIGGRAPH 2010 conference abstracts and applications*, New York, NY, USA, 2002. ACM.