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A survey of physics-based character animation synthesis methods

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Abstract

Character animation is an important research field of computer animation and virtual reality technology. In recent years, along with the animation production and the movie special effect industry vigorous development, as well as the modern medicine to the surgery simulation unceasingly thorough research. Animation for the physical reality of the increasingly demanding. Therefore, the design and production of character animation has received the attention of a large number of researchers and developed into a multidisciplinary and technical integrated field, it based on computer graphics and involves design of image processing technology, motion control principles, video technology, art, visual psychology, robotics, artificial intelligence, etc... The core of this paper is the composition method of character animation. It introduces the composition method of different character animation, how to produce the animation with high reality and accord with motion law. And make a comparison of the methods, find out the advantages and disadvantages, combined with the actual needs, the future in-depth research direction and issues.

Keywords

Computer animation, physical reality, multidisciplinary, virtual reality technology.

1. Introduction

Character animation is one of the key problems in the field of computer animation. Its research goal is to generate the corresponding motion sequence quickly and effectively according to the character's own attribute, environment, motion target and other constraints. In recent years, with the rapid development of computer animation, character animation has been widely used in medicine, education, military, entertainment and many other fields. Compared with other methods, physics-based character animation has become the focus of researchers in recent years because of its ability to generate natural motion segments.

Physics-based character animation is not nearly as popular as passive simulation of phenomena such as fluids. Simulating human and animal motion remains a challenging issue. The motion of character

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animation is a kind of non-linear motion [1], which depends on calculating the force distance between joints to control the motion of character [2]. There are few ways to perfectly simulate real life movements in a variety of ways. Humans are good at performing skills, but it can be difficult to articulate the internal strategies behind such skills, turning these skills into controllers is even more challenging [42]. But in recent years, with the rapid development of computer technology, computer animation has gradually become a multi-disciplinary and multi-technology gathering field, and various specialized technologies have emerged as the Times require, in particular, recent advances in artificial intelligence technology have brought new solutions to character animation [3, 41-42].

There are many research institutions, such as the Carnegie Mellon University, the University of Washington, the University of British Columbia, the University of Toronto, McGill University, Institute of Computing Technology, Chinese Academy of Sciences, etc. has conducted long-term research on the synthesis technology of character animation, and has made some valuable achievements, as well as some game companies, such as Ubisoft3, EPIC, Unity Technologies, etc. , some ground-breaking results have also been achieved in this regard. These results have been published in international conferences such as Pacific Graphics, ACM Siggraph, SCA and IEEE Transactions on Visualization and Computer Graphics, Computer Graphic Forum, The Visual Computer.

The main purpose of this paper is to sort out and introduce the existing physical-based character animation synthesis methods, classify and compare the synthesis methods according to different principles, and point out the advantages and disadvantages of each method, find the technical difficulties of physical character animation synthesis, put forward some feasible solutions, and predict the future development direction. In addition, this paper will introduce the intelligent learning which is widely used in the optimization of various methods in recent years, and analyze how the intelligent learning plays in the traditional methods.

2. Phsics-Based Character Animation Synthesis Method

Table 1. Phsics-Based Character Animation Synthesis

Methods			
	Principle	***Difficulty***	***Solution***
Trajectory planning	biomechanics.	Real time control computing	Fragment segmentation. Simplified model
Dynamic constrained optimization control	Optimal control	optimization model	Reference character posture Reference character movement method
Low dimensional physical model	inverted pendulum	Motion data	Motion Capture Equilibrium control Law of biomechanics
Finite state machine controller	Classical control theory	Set the controller Adjusting parameter moves like machine	SIMBICON controller Automatic switch of controller
Data driven	Physical equation of motion	Data inconsistency	Tracking motion capture data Predictive motion
Dynamic filtration	Sports database	Natural Truth.	Dynamic constraint Motion Capture
Statistical model	Low dimensional statistical model	Data is ambiguous Hard interactive control	Dimensionality reduction Statistical Models

The core of physics-based character animation is to calculate the joint force distance and drive the motion of the character. Historically, the key challenge in achieving physics-based features has been to produce a self-balancing controller that is robust, capable of producing realistic action, and

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adaptable enough, able to maintain control in all possible situations [44-45]. There is a classic scheme, the trajectory planning method, through the role of scheduled trajectory optimization to obtain the optimal scheme. In recent years, with the development of computer technology, traditional methods and new techniques have gradually merged, there are many new methods of character animation synthesis. In this paper, by comparing and classifying the commonly used animation synthesis techniques in recent years, the commonly used physics-based character animation synthesis methods are divided into 7 categories in table 1. In the tables, the principles of each method are shown roughly, difficulties and solutions will be discussed in more detail below.

2.1 Trajectory planning method

Trajectory planning method, one of the traditional computer animation synthesis methods. It can be considered as trajectory optimization or spatio-temporal optimization [46]. By building an algorithm, adding a constraint function, the animation synthesis is transformed into a simple trajectory optimization problem to generate dynamic stable, realistic character animation. But some simple algorithms are based on a process approach, which can cause the resulting motion to look unnatural in real life situations [47]. In addition to the movement is not reasonable, based on optimization-based planning [48-49] or tree-based search [50], the complexity of this algorithm and run time may be very high.

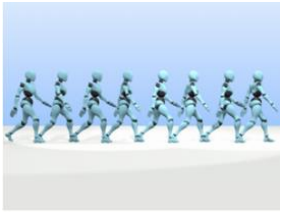

Fig. 1 Trajectory

As a rare animation production method at that time, when the problem of trajectory optimization method appears, it will promote the development of computer animation industry. Yamane et Al. [51] use motion planning algorithms to overcome the unnaturalness caused by process-based Algorithms. In order to avoid the problems of complex function, large computation and time-consuming in optimization model, the researchers try to divide the continuous motion and optimize the single motion segment, which reduces the complexity of the function [6]. In the same way, the human body model can be simplified to reduce the need to optimize the object, also plays a role in simplifying the function [7]. Some researchers [8] have proposed that collision free trajectories satisfying all these constraints can be calculated by calculating the Dynamic equilibrium and stable trajectories of discrete contact configurations, using a multi-phase optimization strategy based on decoupling planners. In recent years, a new interactive Motion Planning Algorithm [52] has been developed, which uses a three-phase optimization method to ensure a collision-free, smooth, and dynamic constrained animation for a discrete contact configuration sequence. This method can directly calculate the dynamic balance and natural-looking motion at interactive frame rate, and can keep a high rate.

In general, trajectory planning method is simple in principle, high in feasibility, compared with other methods, do not need to set too many constraints. However, after many times of optimization, there are still deficiencies in the naturalness of motion. But with the advent of new technology, this little problem is sure to be solved.

2.2 Dynamic constrained optimization control method

Fig. 2 [8] Low dimensional path editing

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The dynamic constrained optimal control method, which is based on the optimal control theory, is a character animation synthesis method. It can also be regarded as a derivative of the trajectory planning method; the problem of character animation is transformed into the problem of space-time optimization. The basic principle of constrained optimization control method is very similar to the improvement of trajectory optimization method proposed by Cohen [6], which is to try to optimize the animation of a long sequence by segments. Because of the close relationship with the trajectory planning method, the dynamic constrained optimization control method is also faced with the situation that the role model is not easy to control, so it is very difficult to solve the optimization model in real time. In addition, the constraint model has many variables and strong nonlinearity, so it is difficult to input and solve the parameters.

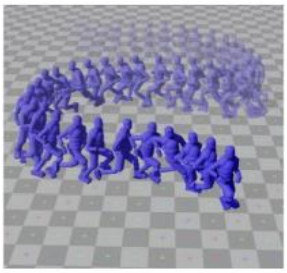

Fig. 3 [11] Keeping running

For the difficulty of the dynamic constrained optimization control method, the common solution is to set up a reference motion model and adjust the constraint conditions according to the demand. Generally, there are two kinds of motion reference model, role posture reference method and role motion reference method. When the character posture is used as the initial value of optimization, the researchers track the balance posture of the human body [9], optimize the joint force distance, and make the character feedback real-time to the outside disturbance and keep the balance. You can also choose to use momentum feedback controllers to keep the roles balanced. The reference motion of the role motion reference method is a motion capture segment. By getting the motion of the center of mass and the leg as a reference, an interactive human motion can be obtained by using the weighted optimization method [10]. Or using the motion of the trajectory tracking phase to compare with the current reference motion [11], select the most similar as the target, and generate the human motion animation. The Model Predictive Control (MPC) proposed by Daniel et Al. uses a set of hierarchical simplified models that concentrate computational resources for the near future when synthesizing [53]. Even after the reference motion is used as the initial value of the constrained optimization control method, the problem that a large number of control items and motion tracking items are included in the optimization objective function cannot be solved easily, there are often conflicting objective functions, so it if useful to classify the priority of the objective function and prioritize the higher-priority function in the operation [8].

The dynamic constraint control method can calculate the force distance of the joint in real time, adjust the position of the center of Mass and control the constraint of multiple objects, which makes it more robust than the trajectory planning method, this method solves the problem that the character animation cannot be controlled in real time and has a large amount of optimization computation.

2.3 Low dimensional physical model method

The In the first two mentioned animation compositing methods, the user needs to enter a target function, a constraint function, and a number of high-level control parameters, require the user to provide an extended set of motions [54]. It takes a lot of time and effort to build such a large data set, which is very difficult for non-computer professional art designers to use. Low-dimensional physical model method deals with these complex high-dimensional data by dimensionality reduction. This method does not simply reduce the dimension of the motion variable, but controls the movement of the whole role through the low-dimensional model. Therefore, it is very important to select a suitable low-dimensional model to synthesize animation in this method.

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Some researchers try to use the first-order inverted pendulum to describe the whole motion information of the role. The inverted pendulum system can be divided into a first-order, a second-order and a third-order inverted pendulum according to the number of pendulum rods. The first-order inverted pendulum model can reduce the dimension of the role animation, for Balance Control. Grochow etc. [15], used a variable scale hidden variable model of the GAUSS process to implement a system that could interact in real time. The system can calculate the posture of the human body which satisfies these constraints in the low-dimensional space in real time. Wang etc. [16], proposed Gaussian process dynamical model (GPDM) on the basis of gauss process hidden variable model, which can better reflect the time sequence of human motion than GPLVM [54] because of adding dynamic process in the low-dimensional space.

Through the use of low-dimensional motion model, only the role of the overall balance of motion information, for how to obtain natural and realistic human motion, but also need researchers with other methods to synthesize. The low-dimensional physical model improves the ability of role balance control, has good robustness, can easily pre-calculate control strategy, and avoid low-quality posture. The new low-dimensional model [15-16, 54] breaks through the limitation that the low-dimensional physical model method can only synthesize simple animation, and expands the scope of application.

2.4 Finite state machine controller method

The finite state machine (FSM) controller method is an optimization of the traditional controller method. After obtaining one input, the FSM will change from the current state to another state, or remain in the current state. So, FSM control can be viewed as a transition between a finite number of state machines. The periodic motion of the character animation is realized by adding a controller to the joint. Unlike other animation synthesis methods, the control unit of the FSM controller is located in each joint, so it is only responsible for each individual joint when calculating the force distance, without considering the position of the character in the whole space. In practical application, the FSM controller may be difficult to set up in the face of complex joint motion. The change of the environment variable will also bring the problem of the decrease of the controller's fidelity.

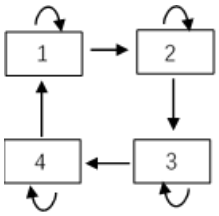

Fig. 4 FSM controller

It is difficult to design complex motion of finite state machine (FSM) controller [21-23], the main reason is that the parameters of FSM controller need to be set by experienced researchers, there are currently a number of motor skills that can be implemented by a character, but few studies have been done to combine these existing control strategies to achieve complex movements [55-56]. SIMBICON controller is one of the few compositing controllers. The generated character animation has high robustness [24, 57]. Petros et Al. [58] proposed a physics-based composite controller for character animation. They designed a framework to combine professional controllers into a convenient dynamic characteristic control system. The system can respond to external disturbances or drops in any direction, and the ability to automatically balance character animation when controlled. And the controller stores the control knowledge collected from various literatures and can give feedback on whether the target state can be achieved or not.

Most of the theoretical basis of the traditional controller method comes from the research of the robot, lack of information from the biomechanics literature, and little effort is made to realize the high-fidelity motion model. Therefore, the role of the Synthesis of animation there are mechanical action, stiffness and other problems [59]. Therefore, the finite state machine control method needs to modify the parameters of the controller [26] according to the law of biomechanics in order to obtain the human motion with high fidelity.

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The controller of finite state machine realizes the animation with high robustness by setting a controller for each shutdown. The calculation of the analytic force distance makes this method the most efficient animation synthesis method. However, due to the nature of FSM, FSM controllers can only generate periodically varying roles. In the future, the combination of controller and motion capture data will greatly improve the effect of animation synthesis.

2.5 Data-driven method

Data-driven method has always been the cornerstone of character animation composition [60], and motion capture is the most widely used data source in data-driven method, which can generate real and natural character animation. After calculating the joint force distance, the character animation tracks the motion and captures the data, which can respond to the environment change and the disturbance. When using the data-driven method, if only by accessing the motion database [26-29], the role model may not match the motion capture data in the database, but the huge amount of equipment and environmental costs involved in collecting motion data on their own keep most people away.

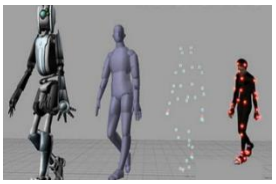

Fig. 5 [3] Motion Capture

DReCon [3], a collaboration between McGill University and UBISOFT, uses an unstructured motion capture database to synthesize human motion that follows user specified control changes in real-time, the Motion Controller finds the best animation clip to play from the features of the animation and user input, and uses reinforcement learning to find an appropriate feedback strategy. Angjoo et Al. [60] propose a data collection system based on gesture estimation and deep reinforcement learning from video, in which imperfect movements can be repaired to compensate for missing frames. This method can improve the quality of character animation. Through motion reconstruction, the animation character can simulate the action better.

The data-driven method captures the data by tracking the motion, thus improving the authenticity of the character animation. The generated animation has the characteristics of robustness and nature. The method proposed by Angjoo et Al. [60] greatly increases the flexibility of the data-driven method in generating animation, strengthens the ability of the method to deal with the environment variables, and reduces the cost to a certain extent, at the same time, the application range of data-driven method is improved.

2.6 Dynamic filtration

Kinematics filtering is a method of searching in the database based on the constraint function and the attitude of the target given by the user, synthesizing the qualified fragments to generate a character animation, different segments are connected by splicing, interpolation, etc... But the subtle differences between segments, even the most sophisticated kinetic methods cannot avoid the unnatural movements between segments, coupled with human familiarity with their own movements, the transition to kinematic filtering is often not natural enough. The size of the database will also affect the use of kinematic filtering. When the database is too large, although more symbolic fragments can be found, long-term retrieval will reduce the efficiency of animation synthesis, and when the database is too small, difficult to match the appropriate fragments, and will cause animation distortion.

Based on motion capture data, a new character [31] animation is obtained by using dynamic constraints according to the new constraints and user interaction control [32]. Motion Capture [33] data can also be used to generate the human body in the external force of the fall action, no external interference, human motion tracking database of motion segments; A motion controller is used to drive the human body as close as possible to the next selected motion segment.

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Compared with the data-driven method, the dynamic filtering method is more like an off-line computing method, searching through an existing database and generating animation. With the development of computer animation technology, the cost reduction of the data-driven method will have an impact on the dynamic filtering method.

2.7 Statistical model method

The idea of the statistical model method is very similar to that of the low-dimensional physical model method, in which the dimension of the motion model is reduced to facilitate the editing of the motion, but the statistical model method can also use the motion capture data to reconstruct the high-dimensional motion of the character through the dynamic method after the character has been edited in the low-dimensional space. The core of all dimension reduction methods is to improve the efficiency of animation by reducing the complexity of the problem, so the selection of dimension reduction model is very important.

Compared to other dimensionality reduction methods, the Gauss process is a good choice [34-36], it can simulate the character movement well, can respond to the outside interference in real time, it can also be combined with the probability model of human body motion to generate the whole-body motion.

The statistical model method can reduce the computational load of animation synthesis and improve the efficiency of animation synthesis by using the reduced dimension model. Compared with the reduced-dimensional physical model, the dynamic method can also be used to restore the high-dimensional motion of the role, which has better practicability

2.8 Methods comparison and evaluation

Table 2. Method Performance Comparison

Methods	(" ↑" stands for high,"—" stands for middle," ↓" stands for low)			
	Time efficiency	***Robustness***	***Controllability***	***Natural***
Trajectory planning	Off-line	↓	↓	—
Dynamic constrained optimization control	—	↓	↑	↓
Low dimensional physical model	↑	↓	↑	↓
Finite state machine controller	↓	↑	—	↓
Data driven	Depending on implementation	↑	↓	↑
Dynamic filtration	Off-line	↓	↑	↑
Statistical model	↓	↑	—	↑

In recent years, physics-based character animation synthesis has been a research hotspot of computer animation, and various optimization methods have emerged one after another, which brings a great choice for character animation synthesis. Users can use it according to their own purposes, select the most suitable method to complete the animation synthesis. The method of character animation is usually evaluated from four aspects: efficiency, robustness, naturalness and controllability. In view of the advantages and disadvantages of the above methods, as well as the detailed introduction, seven methods are synthesized in Table 2.

3. Summary of Research and Outlook

Physics based character animation has been at the heart of computer animation research for decades, and the goal of all researchers is to create characters that move as freely as live actors, such a role can execute the movement autonomously in any environment, and the user only needs to input the task. For Character Animation, even simple walking, climbing, need a lot of constraint functions to achieve, the role also faces the environment variables, to maintain body balance. Through the continuous

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efforts of research, the method of character animation based on physics has achieved a lot, but it is not common in industrial application because of the shortcomings of each method. In recent years, with the rapid development of artificial intelligence technology and Motion Capture, physics-based character animation has been greatly developed, and the former shortcomings are being made up, it is believed that it will play an important role in promoting the industrialization of methods.

3.1 Difficulties and solutions

Next, the article will analyze the difficulties of character animation, and summarize the current technology.

3.1.1 Controllability.

In Character animation is a nonlinear system controlled by joint force distance and environment variables. A large number of constraint functions and very large degrees of freedom of the joints, so that the role of the control is very difficult.

To control the character, the relationship between the character and the ground should be considered firstly, and the balance between the contact force on the ground and the joint force distance should be kept. There are generally three possible solutions to this problem. 1) Virtual Force model. [37] In this model, the ground contact force is transformed into the centroid coordinate system by Jacobi Matrix, and the motion balance is controlled at the same time. 2) Cullen friction cone model [38]. In this model, the ground contact force can be confined in an inverted cone. The contact force is different from the joint constraint, which is a one-way constraint. 3) Punishment law [39]. The method allows the object to be slightly punctured, and a repulsive force is applied by the spring model. This method is simple to operate, but due to its poor robustness, in the strict sense, does not have real physical properties.

The core of controlling a character is controlling the joints of the character. By adding a controller in the joint space, the joint force distance is calculated according to the initial value and the target state. However, this method only sets low-dimensional parameters such as joints, and cannot modify high-level functions accurately, so it has great limitations for users. The best way to control the interaction of high-level functions is to control the parameters in the task space. The optimal control method uses multi-objective model to calculate the joint force distance. high-level control items can be added to the function to increase the controllability of high-level parameters and facilitate interaction [10]. Such as interactive control step length, jump height, leg swing range. Or generate the character's balanced walking and standing movement based on a given footprint. But because the objective function of this method contains all kinds of control items, it is easy to have the phenomenon of mutual influence and even conflict between the objective items, so the robustness of this method is poor.

3.1.2 Equilibrium control.

Balance Control is the basic requirement of character animation, but because the character based on physics is a multi-rigid-body system, the system is very unstable, so how to keep character balance is a very important problem in animation synthesis.

For standing still character animation, the common method is to control the location of the center of mass. For character animation in motion, the automatic balancing devices currently used have greatly simplified the tedious steps that were once controlled by manually adjusting key frames, controlling the movement of the center of mass in the process of motion by error learning. Others [40] use the relative positions of the center of mass and the center of pressure as reference objects to track the motion data in space, which further maintains the robustness of the algorithm.

By comparison, these indirect control methods, such as controlling the relative position of centroid and feedback error, are not the best methods to control the role balance. A low dimensional physical model, such as a first order inverted pendulum, is the most efficient way to directly describe the change in the center of mass.

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3.1.3 Natural Fidelity

The basic requirement for Fidelity in character animation is first to conform to the biomechanics principle and the basic rules of motion, and then to be similar to the motion of real creatures.

In the early period of motion data capture technology, most of the methods will give up the quality of animation in order to satisfy the basic biomechanics. But in recent years, with the development of motion capture technology and the extensive use of motion capture databases, more and more researchers have ensured the natural fidelity of characters by making character animation similar to motion capture data, at the same time, the data drive is used to ensure the authenticity while tracking the fishing hole capture data, which increases the fidelity.

3.2 Facing problems and future development

The physics-based character animation has made great progress in the past ten years. Although the method is almost mature, the use of motion editing in game animation and special effects is still dominant, and in practical applications, compared with traditional motion editing, this method is faced with the problems of high difficulty in implementation, poor manipulation and not being able to achieve better visual effect, the physics-based character animation meets the high request in the movement authenticity, but the character animation is not the simple skeleton movement, therefore in the following has many questions to wait for this researcher to solve.

3.2.1 Simplified motion control method

Physics-based character animation has been able to control the motion state effectively, but it needs to use very complex functions when it involves high-level parameters and external interference [41], and easy to appear the phenomenon of variable conflict. And in the future the demand for interactive character animation will be more and more large, interactive response time and controllability is particularly important. So, to solve these problems, researchers first need to develop a new functional analysis scheme, optimize the control method of high-level variables, and improve the efficiency of the method, at the same time, the method of controller should be added to meet the needs of the external environment variables.

3.2.2 Multi-method fusion

Physics-based character animation synthesis is already a comprehensive field integrating multi-disciplines and multi-technologies, the existing methods have their own unique advantages and disadvantages, compared with the development of new synthetic methods, the integration of methods can bring more convenience to users in the short term. Single solution can only accomplish certain problems, in the future research, researchers should focus on the integration of the existing technology, select its essence, discard its dross, make full use of the advantages of each program. Take computer animation as the core, make full use of the advantages of technology fusion, improve the feasibility of physics-based character animation.

3.2.3 Intelligent learning

The integration of artificial intelligence and character animation will be an inevitable trend in the future, the recently introduced animation synthesis methods will almost involve the deep reinforcement learning part, the data-driven fusion is a good example. By improving the intelligent learning ability of the animation synthesis method, the method can correct the unnatural actions and segments independently in the synthesis process, greatly increasing the convenience of use, and also reducing the production cost of the animation. The researcher must aim at each method insufficiency, has the condition application artificial intelligence, through the reinforcement learning correction method unreasonable place. If the technology is mature, try to realize the animation synthesis method which creates characters that move as freely as live actors.

3.3 Summary

As an important research content in the field of computer animation, character animation has been constantly upgraded and improved. The purpose of the model being produced dictates the technique

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used to create it, with the current game animation, special effects, medicine and other fields for the animation of the continuous improvement of the authenticity of the requirements, character animation will be driven, and continue to develop. There will be more and more areas to use character animation to solve the problem, so the goal of computer animation is to produce realistic, dynamic animation.

Based on the introduction of the development of character animation in recent years, the advantages and disadvantages of each method are compared. And combined with the actual application, it puts forward some feasible development directions, and makes a guess at the problems that character animation will face, hoping that the solution of these problems can promote the development of character animation, so that the role of animation in more areas to be promoted and applied.

References

[1] Witkin A, Kass M. Spacetime constraints [J]. Computer Graphics, 1988, 22(4): 159-168

[2] Liu C, Hertzmann A, Popovic Z. Composition of complex optimal multi-character motions [C] Proc of the 2006 ACM SIGGRAPH/Eurographics Symp on Computer Animation. New York; ACM, 2006: 210-222

[3] Bergamin K, Clavet S, Holden D, Forbes J. DReCon: Data-Driven Responsive Control of Physics-Based Characters[C] Canada; ACM, 2019: 2-4

[4] KAJITA, S., MATSUMOTO, O., AND SAIGO, M. 2001. Realtime 3d walking pattern generation for a biped robot with telescopic legs. In Robotics and Automation, 2001. Proceedings 2001 ICRA. IEEE International Conference on, vol. 3, IEEE, 2299–2306.

[5] GEIJTENBEEK, T., AND PRONOST, N. 2012. Interactive character animation using simulated physics: A state-of-the-art review. In Computer Graphics Forum, vol. 31, Wiley Online Library, 2492–2515.

[6] Cohen M. Interactive spacetime control for animation [J]. Computer Graphics, 1992,26(2): 293-302

[7] Safonova A, Hodgins J, Pollard N. Synthesizing physically realistic human moton in liw-dimensional, behavior-specific spaces [J]. ACM Trans on Graphics, 2004, 23(3): 510-521

[8] Park C, Jae Sung Park, Tonneau S, Mansard N, Multon F, Pettré J, and Manocha D. 2016. Dynamically balanced and plausible trajectory planning for human-like characters. In Proceedings of the 20th ACM SIGGRAPH Symposium on Interactive 3D Graphics and Games (I3D '16). Association for Computing Machinery, New York, NY, USA, 39–48. DOI:https://doi.org/10.1145/2856400.2856405

[9] Abe Y, da silva M, Popovic J. Multi-objective control with frictional contacts [C]/ proc of the 2007 ACM SIGGRAPH/Eurographic Stmp on Computer Animation. New York: ACM, 207: 249-258

[10] de Lasa M, Mordatch I, Herzmann A. Feature-based locomotion controllers [J]. ACM Trans on Graphics, 2010, 29(4): Article No 131

[11] Wu J, Popovie Z. Terrain-adaptive bipedal locomotion control [J]. ACM Trans on Graphics, 2010, 29(4): Article No72

[12] Pan Zhigeng, Lu Pei, Xu Mingliang, etc. A review of low dimensional human motion data driven character animation generation methods [J]. Journal of computer-aided design and graphics, 2013,25(12): 1775-1785.

[13] Liu Gendai, Pan Zhigeng, Cheng Xi, et Al. Stylized human motion synthesis combining low dimensional motion model and inverse kinematics [J]. Journal of computer-aided design, 2010, 22(1): 145-151.

[14] Lv Pei, Zhang Mimgmin, Xu Mingliang, et ai, Rhythmical motion synthesis based on Gaussian process dynamical model [J]. Journal of Image and Graphics, 2011, 16(8): 1511—1515

[15] Grochow K, Martin S L, Hertzmann A. etc., Style-based inverse kinematics [J]. ACM Transactions on Graphics, 2004, 23(3): 522—53l

[16] Wang J M, Fleet D J, Hertzmann A. Gaussian process dynamical models for human motion [J]. IEEE Transactions 0n Pattern Analysis and Machine Intelligence, 2008, 30(2): 283—298

[17] Xu M, Li H, Lv P, etc., L4RW: Laziness-based realistic real-time responsive rebalance in walking[J]. Computer Graphics Forum, 2010, 29(7): 2187-2196

[18] Tsai Y, Lin W, Cheng K. etc., Real-time physics-based 3D biped character animation using an inverted pendulum model [J]. IEEE Trans on visualization and Computer Graphics 2010, 16(2): 325-337

[19] Zhu Shengren, Huang Ruiguang. Modeling application of Finite State Machine in animation character behavior. Computer Technology and development, 2007, 17(6): 130-132,182. Doi: 10.3969 J. ISSN. 1673-629x. 2007.06.039.

[20] Faloutsos P, Panne M, and Terzopoulos D. 2001. Composable controllers for physics-based character animation. In Proceedings of the 28th annual conference on Computer graphics and interactive techniques (SIGGRAPH '01). Association for Computing Machinery, New York, NY, USA, 251–260. DOI:https://doi.org/10.1145/383259.383287

[21] Raibert M, Hodgins J. Anmation of dynamic legged locomotion [J]. Computer Graphics, 1991, 25(4): 349-358

[22] Hodgins J, Wooten W, Brogan D, etc., Animationg human athletic[C]/proc of the 22nd Annual Conf on Computer Graphics and Interactive Techniques. NewYork: ACM, 1995:71-78

[23] Faloutsos P, The virtual stuntman: Dynamic characters with a repertoire of autonomous motor skills [J]. Computer & Graphics, 2011, 25(6): 933-953

[24] Yin K, Coros S, Beaudoin P, etc., Continuation methods for adapting simulated skills [J]. ACM Trans on Graphics, 2008, 27(3): Article No81

[25] Muico U, Popovic J, Popovic Z. Composite control of physically simulated charaters [J]. ACM Trans on Graphics, 2011, 30(3):Article No16

[26] Wang J, Fleet D, Hertzmann A. Optimizing walking controllers for uncertain inputs and environments[J]. ACM Trans on Graphics, 2010, 29(4): Article No73

[27] Sok K, Kim M, LEE J. Simulating biped behaviors from human motion data [J]. ACM Trans on Graphics, 2007, 26(3): Article No107

[28] da Silva M, Abe Y, Popovic J. Interactive simulation of stylized human locomotion [J]. ACM Trans on Graphics 2008, 27(3): Article No82

[29] da Silva M, Abe Y, Popovic J. Simulation of human motion data using short-horizon model-predictive control [J]. Computer Graphics Forum, 2008,27(2): Article No82

[30] Pejsa T, Pandzic I. State of the art in example-based motion synthesis for virtual characters in interactive applications [J]. computer Graphics Forum, 2010, 29(1):202-226

[31] Abe Y, Liu C, Popovic Z. Momentum-base parameterization of dynamic character motion [C] //Proc of the 2004 ACM SIGGRAPH/ Eurographics Symp on Computer Animation. NEW York: ACM 2004:191-211

[32] Abe Y, Popovic J. Interactive animation of dynamic manipulation [C]// proc of the 2006 ACM SIGGRAPH/EUROgraphics Symp on Computer Animation. New York: ACM, 2006:195-204

[33] Zordan V, Majkowska A, Chiu B. etc.., Dynamic reponse for motion capture animation [J]. ACM Trans on Graphics, 2005, 24(3): 697-701

[34] Ikemoto L, Arikan O, Forsyth D. Generallizing motion edits with Gaussian processes [J]. ACM Trans on Graphics, 2009, 28(1): Article No1

[35] Ye y, Liu C, Synthesis of responsive motion using a dynamic model [J]. Computer Graphics Forum, 2010, 29(2): 555-562

[36] Wei x, Min J, Chai J. Physically valid statistical models for human motion generation [J]. ACM TRANS on Graphics, 2011. 30(3): Article No19

[37] Drumwright E.A fast and stable penalty method for rigid body simulation [J]. IEEE Trans on Visualization and Computer Graphics, 2008, 14(1) : 231-240

[38] Wieber P. on the stability of walking systems [C]//proc of the int workshop on Humanoid and Human Friendly Robotics. Piscataway, NJ: IEEE, 2002: 226-231

[39] Coro S, Karapathy A, Jone B, etc.., Locomotion skills for simulated quadrupeds [J]. ACM Trans on Graphics, 2011, 30(4): Article No59

[40] Abe Y, Popovie J. Simulating 2D gaits with a phase-indexed tracking controller [J]. IEEE Computer Graphics and Applications, 2011, 31(4): 22-33

[41] Mazen B, EugeneF, Hertzmann A, etc.., Feedback control for rotational movements in feature space [J], Computer Graphic Forum, 2014, 33(2): 225-233

[42] Xue Bin Peng, Pieter Abbeel, Sergey Levine, and Michiel van de Panne. 2018. DeepMimic: example-guided deep reinforcement learning of physics-based character skills. ACM Trans. Graph. 37, 4, Article 143 (August 2018), 14 pages. DOI:https://doi.org/10.1145/3197517.3201311

[43] Seokpyo Hong, Daseong Han, Kyungmin Cho, Joseph S. Shin, and Junyong Noh. 2019. Physics-based full-body soccer motion control for dribbling and shooting. ACM Trans. Graph. 38, 4, Article 74 (July 2019), 12 pages. DOI:https://doi.org/10.1145/3306346.3322963

[44] Libin Liu and Jessica K. Hodgins. 2018. Learning Basketball Dribbling Skills Using Trajectory Optimization and Deep Reinforcement Learning. ACM Trans. Graph. 37, 4, Article 142 (July 2018), 14 pages. https://doi.org/10.1145/3197517.3201315

[45] Xue Bin Peng, Pieter Abbeel, Sergey Levine, and Michiel van de Panne. 2018. DeepMimic: Example-guided Deep Reinforcement Learning of Physics-based Character Skills. ACM Trans. Graph. 37, 4, Article 143 (July 2018), 14 pages. https://doi.org/10.1145/3197517.3201311

[46] GEIJTENBEEK, T., AND PRONOST, N. 2012. Interactive character animation using simulated physics: A state-of-the-art review. In Computer Graphics Forum, vol. 31, Wiley Online Library, 2492–2515.

[47] HAM ¨AL ¨AINEN ¨, P., RAJAMAKI ¨, J., AND LIU, C. K. 2015. Online control of simulated humanoids using particle belief propagation. In Proc. SIGGRAPH ’15, ACM, New York, NY, USA.

[48] PARK, C., AND MANOCHA, D. 2014. Fast and dynamically stable optimization-based planning for high-dof human-like robots. In Humanoid Robots (Humanoids), 2014 14th IEEE-RAS International Conference on, IEEE, 309–315.

[49] WAMPLER, K., POPOVIC ´, Z., AND POPOVIC ´, J. 2014. Generalizing locomotion style to new animals with inverse optimal regression. ACM Transactions on Graphics (TOG) 33, 4, 49

[50] ESCANDE, A., KHEDDAR, A., AND MIOSSEC, S. 2013. Planning contact points for humanoid robots. Robotics and Autonomous Systems 61, 5, 428–442.

[51] YAMANE, K., KUFFNER, J., AND HODGINS, J. K. 2004. Synthesizing Animations of Human Manipulation Tasks. ACM Trans.on Graphics (Proc. SIGGRAPH 2004).

[52] Chonhyon Park, Jae Sung Park, Steve Tonneau, Nicolas Mansard, Franck Multon, Julien Pettré, and Dinesh Manocha. 2016. Dynamically balanced and plausible trajectory planning for human-like characters. In Proceedings of the 20th ACM SIGGRAPH Symposium on Interactive 3D Graphics and Games (I3D '16). Association for Computing Machinery, New York, NY, USA, 39–48. DOI:https://doi.org/10.1145/2856400.2856405

[53] Daniel Zimmermann, Stelian Coros, Yuting Ye, Robert W. Sumner, and Markus Gross. 2015. Hierarchical planning and control for complex motor tasks. In Proceedings of the 14th ACM SIGGRAPH / Eurographics Symposium on Computer Animation (SCA '15). Association for Computing Machinery, New York, NY, USA, 73–81. DOI:https://doi.org/10.1145/2786784.2786795

[54] Sergey Levine, Jack M. Wang, Alexis Haraux, Zoran Popović, and Vladlen Koltun. 2012. Continuous character control with low-dimensional embeddings. ACM Trans. Graph. 31, 4, Article 28 (July 2012), 10 pages. DOI:https://doi.org/10.1145/2185520.2185524

[55] N. Badler, C. Phillips, and B. Webber. Simulating Humans: Computer Graphics, Animation, and Control. Oxford University Press, 19

[56] Tolga Capin, Igor Pandzic, Nadia Magnenat Thalmann, and Daniel Thalmann. Avatars in Networked Virtual Environments. John Wiley & Sons, 19

[57] Yin K, Loken K, vande paanne M. Simbieon: Simple biped locomotion control [J]. ACM Trans on Graphics, 2008, 27(3): Article No 105.

[58] Petros Faloutsos, Michiel van de Panne, and Demetri Terzopoulos. 2001. Composable controllers for physics-based character animation. In Proceedings of the 28th annual conference on Computer graphics and interactive techniques (SIGGRAPH '01). Association for Computing Machinery, New York, NY, USA, 251–260. DOI:https://doi.org/10.1145/383259.383287

[59] Marcus G. Pandy and Frank C. Anderson. Three-dimensional computer simulation of jumping and walking using the same model. In Proceedings of the VIIth International Symposium on Computer Simulation in Biomechanics, August 1999.

ISSN: 2414-1895 DOI: 10.6919/ICJE.202111_7(11).0075

[60] Xue Bin Peng, Angjoo Kanazawa, Jitendra Malik, Pieter Abbeel, and Sergey Levine. 2018. SFV: reinforcement learning of physical skills from videos. ACM Trans. Graph. 37, 6, Article 178 (November 2018), 14 pages. DOI:https://doi.org/10.1145/3272127.3275014.