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Special Focus

Recent advances on virtual human synthesis

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Virtual human is a digital representation of the geometric and behavioral property of human beings in the virtual environment generated by computer. The research goal of virtual human synthesis is to generate realistic human body models and natural human motion behavior. This paper introduces the development of the related researches on these two topics, and some progresses on example based human modeling and motion synthesis, and their applications in Chinese sign language teaching, computer-aided sports training and public safety problem studying. Finally, some hot research topics in virtual human synthesis are presented.

virtual human, human body modeling, dynamics, inverse kinematics

1 Introduction

Virtual human (or computer synthesized characters) is a digital representation of human geometric and behavioral property in computer-generated space (virtual environment)[1]. Virtual environment (or virtual reality) is a realistic computer-generated environment with full integration of vision, hearing and touch, in which users can interact with virtual objects naturally by means of some equipment or devices, and therefore get the realistic feelings and experience, for details please see ref. [2]. As a special entity, the existence of virtual human can largely enhance the immersion and reality of the virtual environment.

Factually, the study on virtual human synthesis is closely related to the actual requirements from the industry. Once these requirements are clear, many scientific institutions and organizations will conduct intensive research on them, and a lot of achievements have already been made so far, which are applied to many fields, such as human factors and ergonomics, military simulation and training, digital entertainment and so on.

(1) Human factors and ergonomics. By using virtual human, one can dynamically analyze human factors of newly designed products such as aircraft cockpit, manned spacecraft and so on, to obtain some straightforward test results before these products are put into production. For example, Boeman (from First Man to Fourth Man and Woman), a virtual human made by Boeing Co. in 1968, was used for the design evaluation of aircraft cockpit and instrument panel[3]. Another representative is JACK in ref. [4]. It enables users to embed a virtual human into a virtual environment,

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to adjust its size and position, and to manipulate it to operate on various kinds of tasks. The operation performance under a variety of working conditions can be dynamically analyzed in this way.

(2) Military simulation and training. Since the US military built a variety of military training simulation environment based on virtual reality technology in the late 1980s, many research institutions have been doing research on virtual human synthesis in order to load realistic virtual human, computer generated or an avatar of real users, into a variety of simulation environments. This environments consisting of both the real and the artificial are used for carrying out tactical drilling, hostage rescue training and so on, which provides a new effective way to improve the level of training. A typical example is DI-Guy developed by Boston Dynamics Inc. in ref. [5]. The system can embed virtual characters into the real time virtual environment, where virtual characters roam following the given route and switch motion smoothly between different behaviors. More importantly, the system is compatible with DIS and HLA, and therefore the synthesized virtual human and virtual soldiers are able to be embedded into a distributed interactive simulation environment so that it is possible to carry out large-scale military simulation and training.

(3) Digital entertainment. Games, animation, digital film are important applications of virtual human synthesis. With the development of this technology, excellent tools and software come forth in recent years from the industry, such as Half-Life. Appearance and behavior of virtual characters in this game are more realistic than that of the early games such as Doom and Quake so that it attracts a large number of players. On the other hand, Character Studio and Endorphin are representative tools in the animation production area. These tools can reuse the captured motion data to obtain high-quality character animation. Besides, the latter also supports dynamic simulation such as collision and so on. As for the digital film making, Massive demonstrates its power in large scale crowd simulation in the movie of Lord of the Rings.

The success of these applications inversely promotes further development of virtual human synthesis technology. Now this research covers many topics such as human body modeling, human motion control, crowd simulation, performance animation, human face modeling, facial animation and so on[4,6]. The techniques employed in these researches may be from computer vision, robotics, biomechanics, computer graphics, artificial intelligence and other fields. Whatever research topic and technique are, the unique goal of virtual human synthesis is to make virtual human as close as possible a real human being in appearance and behavior such that users can easily embed realistic characters into the virtual environment, through which users are able to interact with other virtual objects. This paper is dedicated to introduce the latest developments of virtual human synthesis in realistic human body modeling and natural motion behavior generation. It would be a useful reference for relevant students and researchers.

This paper is organized as follows: in section 1, the definition of virtual human and virtual environment, and research topics in virtual human synthesis and their applications in industry are introduced and summarized; in section 2, the development process of human body modeling is investigated, and an example based human body modeling method is given; in section 3, we summarize related work on human motion behavior generation, and present an example based inverse kinematics model and a multi-body dynamics model; and in section 4, several applications in Chinese sign language teaching, computer-aided sports training and public safety problem studying are highlighted; finally in section 5, we conclude this paper with some interesting topics that are still under research.

2 Research on realistic human modeling

Human body is complicated and deformable, and therefore research on human body modeling should consider not only static human shape, but also skin deformation in human movement. Up to now, human body modeling in virtual environment is still a multi-layer modeling framework. In this framework, a human model is composed of skeleton, muscle and skin layers. Additional layers are added to show hair and cloth on human body in ref. [1]. Skeleton is decided by human motion data to show poses of human during movement. Skin deformation, which is affected by muscle layer, decides appearance quality of the virtual human. Under this framework, the problems such as how to construct a realistic human model, how to reuse the model and how to drive it to show the realistic skin deformation are discussed in human modeling research community.

2.1 Human modeling related methods

Human body modeling methods include geometry based method, anatomy based method, and data capture based method. Geometry based method usually uses stick model, surface model and volume model. Stick model encodes body shape with sticks and joints; however, it is unable to deal with occlusion and to show distortion and contact. Surface model is composed of a set of polygons and a skeleton inside it. The surface modeling method is classified into polygon method, Bezier surface method and finite element method. Volume model is composed of some voxels including cylinder, ellipsoid, sphere and so on. For example, more than 300 spheres are used by Badler[7] to model the body shape. When representing human motion by volume method, the computation is very simple and the memory required is low; however, this method cannot represent local and detailed changes.

Anatomy based method[8−10] manually models human body by combining human anatomical characteristics with geometry based method. The most traditional techniques are subdivision modeling and patch modeling. Subdivision modeling is a procedure for creating smooth models while keeping the total polygon count at a low level. The sculpting process is less confusing due to small point counts. Objects are made of simple objects such as a cube, that is subdivided and deformed several times to reach the desired form. Patch modeling can be accomplished by creating points, polygons, splines, or NURBS and converting them into a polygon object.

Data capture based method is to build the human model from 3D scanners, photos, or video of real people. Hilton[11], Lee[12] and Mao[13] developed a technique that includes the extraction of body silhouettes from a number of 2D views (front, side, and back) and the subsequent deformation of a 3D template to fit the silhouettes. With the development of 3D scanning technique, researchers focus on reconstructing a realistic, and drivable human body model from scanned data. The key problems include hole filling, noise removing and skeleton extracting. Dekker[14] used a series of meaningful anatomical assumptions in order to optimize, clean, and segment data from a whole body range scanner, and skeleton was extracted by analyzing concave, convex and saddle feature points in order to drive the human body models. Wade[15] proposed a method which discretized the model, computed its discrete medial surface, and created the skeletal structure. Ma[16] described techniques to segment human body by reentrant algorithm and to detect important feature points to compute human skeleton. Gutiérrez[17] provided a semantic layer for model reconstructing, storing and reusing, and mapped the semantic layer of template to a target model. Baran[18] proposed a method to map the skeleton template to a given human body mesh in order to drive the mesh.

Interpolation based human modeling method can create a new model from a set of scanned models and an interpolation algorithm. Blanz[19] described a morphable face model for manipulating an existing model according to the changes in certain facial attributes. Some new faces were modeled by forming linear combinations of the prototypes that were collected from 200 scanned face models. Manual assignment of attributes was used to define shape and texture vectors that, when added to or subtracted from a face, would manipulate a specific attribute. Sloan[20] had used radial basis function for blending among examples of facial models and the arm. Allen[21] presented another example-based method for creating realistic skeleton-driven deformation. He made use of a template model and unorganized scanned data, and adopted a unique and compact shape description of the body geometry to handle the whole body. He briefly showed the static deformation by altering the control points of the template model. Seo[22] made use of interpolation method in his human modeling. He registered scanned human body models to a template by optimizing the distance between markers on scanned models and the template. A compact vector representation was adopted by using principal component analysis (PCA). Realistic human models could be generated by RBF method according to a number of anthropometric parameters.

Human skin deformation methods are classified in ref. [23], where the skeleton driven deformation is regarded as the most popular one. Recent research has produced more realistic models and skin deformation than before by combining the reconstruction, interpolation and deformation altogether. For example, Anguelov[24] proposed a model of reconstructing technique based on interpolation, where weights were calculated by optimizing the difference between input markers or incomplete scanned data and the models in database in order to reconstruct realistic model. Park[25] utilized the VICON devices and 350 markers and a scanned model to capture the skin deformation to reconstruct realistic body shape and deformation. Balan[26] reconstructed the human body model and the motion by analyzing the input multi-camera video sequences.

2.2 An interpolation based personalized human modeling algorithm from examples

We proposed a personalized human modeling method that involves model driving, model registering and interpolation step (see Figure 1).

In the model driving step, Morse function based on geodesic distance of human body shape is calculated, and then feature points and topological structure of the shape can be extracted automatically according to Morse theory. The shape is divided into segments based on Morse function isolines. Joints are extracted from the human body shape by analyzing the circularity of Morse function isolines. Vertices of human body shape are mapped to the skeleton and skin deformation of the shape is calculated based on the geodesic distances from the vertices to joints. For details and results please refer to ref. [27] and Figure 2.

In model registering step, template model is mapped to target model by skeleton registering and skin registering. Skeleton registering is conducted

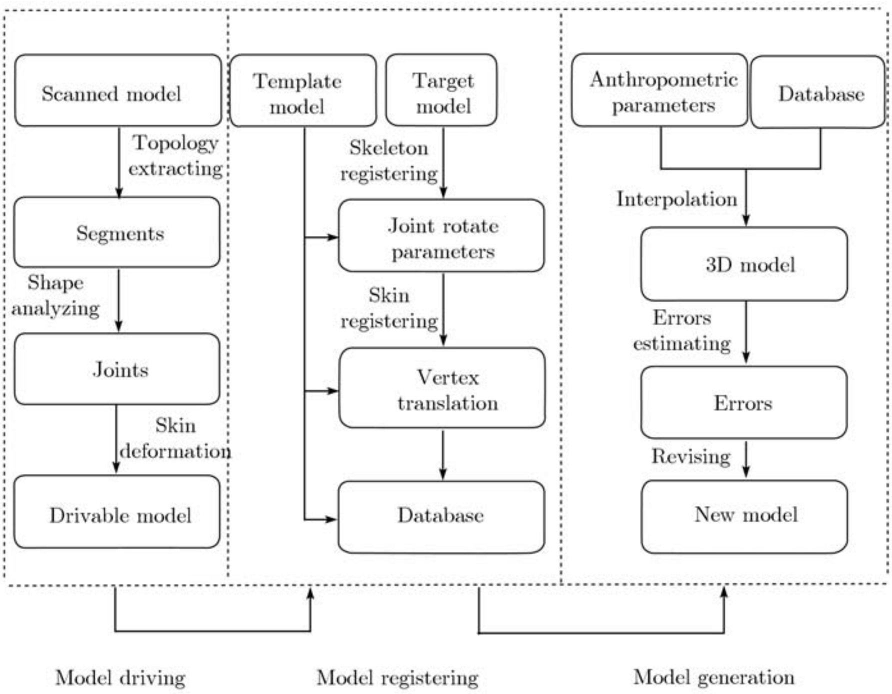

Figure 1 Framework of personalized human modeling algorithm from examples.

Figure 2 Results on automatically driving scanned human body.

by rotating the joints and driving the vertices of the template, and skin registering is to do mapping the vertexes in skeleton registered template to the nearest ones in the target model. The mass-spring model is used in error correction during skin registering.

In model interpolation step, weights are calculated by RBF network according to the input anthropometric parameters and the given ones. Bones are scaled according to the weights, so the vertices on the shape deform with the corresponding bones. Vertices are calculated by interpolating the displacement variants between examples and the template.

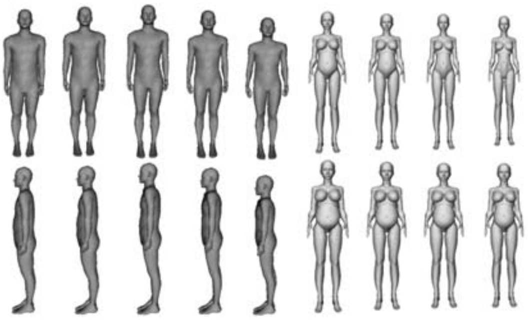

Figure 3 Synthesized personalized model.

Given a set of anthropometric parameters, personalized human model can be synthesized by this algorithm, and the model is easy to control. Models with different body sizes are shown in Figure 3. Figure 4 shows a result of a garmented virtual model.

Figure 4 A performance of a garmented virtual model.

3 Research on natural human motion behavior

Virtual human is a special entity in virtual environment, and it is difficult to simulate natural human motion behavior. That is because human beings are very complex, whose motion behavior is controlled by brain. However, the details control rule of brain is unknown, so there does not exist a general mathematic theory to model human motion. Up to now, human motion behavior has been studied by researchers from different research communities, and different abstracted human models and motion generation frameworks are presented. For example, to model the behavior of path-finding and obstacle avoidance, the human body is usually represented by a particle and accordingly the behavior is represented by a trajectory of the particle. However, in the fields such as biomechanics, robotics and character animation, the human body is represented by a system of articulated rigid bodies and the behavior is a set of trajectories of joints. The latter form is used in this section.

3.1 Human motion synthesis related methods

In traditional key-framing method, the poses of virtual human in key frames are set by the animator, and then interpolation methods are used to generate the in-betweens. Using key-framing method, animators have the complete control on the motion of virtual human, but the process of setting key posture is tedious and it is difficult to set the time of key frame too. Therefore, the visual fidelity depends on the animators' skill. Recently, some papers discussed how to adjust the key time automatically[28,29].

Kinematics based method treats human body as a linkage without mass. This kind of method includes forward kinematics and inverse kinematics. When the angles of each joint are given, it is a simple matter to compute the position and orientation of each segment, which is called forward kinematics. And the inverse kinematics problem concerns how to compute each joint angle given the end-effectors' positions. Forward kinematics manipulates the pose in angle space, but inverse kinematics is in Cartesian space which is more intuitive. There are two classes in inverse kinematics methods: analytical methods and interactive methods. The analytical methods are mainly from robotics field for controlling robot manipulators. These methods compute joint angles by solving equations, which have the advantage of high efficiency. But they cannot deal with the problem for complicated models whose degree of freedom is more than the number of constraints. Iterative methods are more general, which can deal with any model. These methods can also be divided into three subclasses further, namely cyclic coordinate descent (CCD) method, Jacobian matrix based method and optimization based method.

CCD method is a heuristic iterative method, which optimizes only one joint in every single step to minimize the distance between the end-effector's position and the target. The idea of CCD method is to convert the complicated optimization problem for whole body into a simple one for each joint. The latter problem can be solved analytically because of its simplicity. Johnson[30] first proposed quaternion-based CCD method, in which joint rotations are represented in quaternions. Li[31] improved this method by converting the problem into an absolute orientation problem, which can deal with multi-constraints.

The key idea of Jacobian based methods is to linearize the original inverse kinematics problem. A set of linear equations is used to describe the relationship between the subtle joint angles and the end-effectors' positions. The fundamental work, Jacobian-inverse method, is presented by Whitney[32]. Wampler[33] proposed Damped Least Squares method, which introduces a disturbance near the singularity to overcome the drawback of Jacobian-inverse method. Along with widespread use of motion capture device, traditional Jaociban methods are extended with the utilization of motion capture data. Komura[34] introduced a weighting matrix in compute the inverse of Jacobian, which can improve the result. However, this method degenerates to traditional Jacobian inverse method when it is an identity matrix. In order to get a reasonable weighting matrix, the author also proposed a method to extract it from motion capture data. Komura's method improves the visual fidelity of result but it is still time-consuming because of inverting matrix. Li[35] used a self organizing map to learning the inverse of Jacobian directly from motion capture data, which can solve the inverse kinematics problem in real time.

Optimization based methods solve the inverse kinematics problem by using nonlinear optimization techniques. Zhao's work in ref. [21] gave one of the most general methods. They defined different goals such as position goals, direction goals, position-direction goals, line goals, plane goals, half-space goals as the objective function, and the joint angles as the variables. Then, modified BFGS is used to solve the minimization problem. This approach is also an iterative method, but it is applicable to any tree structured system and can be involved with other kinds of constraints easily. Tak[37] proposed a new method for combining the optimization techniques and motion capture data. The objective function of this method consists of not only the distance between the end-effectors and targets, but also the distance from examples in database, which can improve the visual fidelity of the synthesized pose.

Dynamics based method also regards humans as an articulated joint system or a multi-rigid-body system, but in which each segment has a mass. This method can be classified as forward dynamics based method, the trajectory optimization method or controller based method. The dynamic equations of multi-rigid-body system are the basis for forward dynamics based method and the trajectory optimization method.

There are several types of the dynamic equations of multi-rigid-body system. According to the type of deduction, these methods can be classified into two classes. One is Newton-Euler equations and the other is Lagrange equations[38]. The Newton-Euler equations are deduced by the method of Newton-Euler. By Plucker vector, Featherstone[39] proposed a new form of Newton-Euler equations where the translation and rotation can be dealt with congruously. The efficiency of this method is good and has been applied in research of robotics and human motion simulation[40,41]. In order to avoid the singularity in Euler angles, Nikravesh[42] proposed a matrix form equation of dynamics by expressing the rotation of rigid body with unit quaternion. Lagrange equations are deduced by the Lagrange method. In theory, Lagrange equations are more compact than Newton-Euler equations. However, the length of Lagrange equations is increased exponentially with the number of the rigid bodies when we expand them in numerical computation. In order to solve the problem of combinatorial explosion, Liu[43] proposed a new method by using the technique of reduction of common expression. In this method, the length of Lagrange equations is increased polynomially with the number of the rigid bodies. Guenter[44] further improved the effect of reduction by the greedy algorithms. Hollerbach[45] and Popovic[46] pointed out the recursive structure of Lagrange equations and proposed a recursive form of Lagrange equations. This method solves the problem of combinatorial explosion of Lagrange equations thoroughly.

The method based on forward dynamics originates from the computation mechanics and the biomechanics. The mass and inertial tensor are decided by the experiential equations in biomechanics or manually. The principle of forward dynamic is that the character moves by the torque acting on joints of character. The motion of character is realistic because the motion is calculated by dynamics. In this method, it is difficult to decide the accurate torque acting on joints of character directly, see refs. [47, 48]. In order to solve this problem, Isaacs[49] proposed two methods. In the first method, the torque acting in joints of character is calculated by inverse dynamics and users revise the torques to generate the new motion by forward dynamics. In the second method, the torque is an indirect ratio to the difference between current pose of human and the target pose of human so that the pose of human can approach to target pose. Armstrong[50] and McKenna[51] also proposed similar methods. The difference between two methods is that in the second method, the relation between the torque and the pose's difference is an exponential type.

Compared to the method based on forward dynamics, trajectory optimization method in ref. [52] can be seen as a process of inverse computation. The core of this method is as follows: firstly, the complete motion is divided into several segments and the constraints on the time, displacement, velocity and acceleration at the ends of each segment are set. These constraints describe the characteristic of motion and can be thought of as an indirect description of this motion; secondly, by the equation of multi-rigid-body system, the relation between the pose and torque is built. According to these constraints and the principle of human motion that during motion the energy consumed should be minimal, the optimization model can be built and the optimal motion can be solved by sequential quadratic programming (SQP). In order to deal with the drawback of optimization model, such as the complexity and the difficulty in numerical computation, some researchers aim to find reasonable objective function and reduce the model's computation scale. Witkin[52] and Liu[53] proposed a type of objective function that measures the energy consumed during human movement. Popovic[46] pointed out that the wobble may emerge in the simulated human motion when using energy consumed function and he proposed a new type of objective function for calculating the integral of the second derivative of torque to time. He called this function torques smooth function. Yang[54] proposed an objective function as the ratio between torques and the limit of torques. In order to make the generated motion similar to the original motion, Gleicher[55] and Sulejmanpasic[56] defined an objective function as difference between generated motion and the original motion. Fang[57] simplified the dynamics equation of human and took the weighted acceleration of joint motion as the objective function. Cohen[58] segmented whole motion into several clips, and dealt with them one by one. Popvic[59] reduced the model of human by the symmetric property of special motion. But this method can be only applied to motion with symmetry. Safonova[41] used the PCA to analyze the relation between joint's motions and optimized the human motion in the reduced space. Liu[60] reduced the number of variable in optimization model by the method of block coordinate descent. In the method of block coordinate descent, the variables optimized are divided into two classes. The variables in the first class are called active and the variables in the second class are called inactive. In each iterative, the active variables are optimized and the elements in two classes are interchanged by some rules. Smith[61] pointed out that what causes the difficulty in trajectory optimization method is the fact that it is difficult to make the constraints of dynamics satisfied. He took torques as the variables so that the constraint equations of dynamics are transformed from the second ordinary different equation into a simple equation without the derivative term. However, this method transforms simple equation of pose's constraints into complicated integral equation so that the nonlinear of trajectory optimization model is the same as before.

As for the controller based method, the proportional-derivative (PD) controller is used in ref. [62], and a finite state automation is built to describe the whole movement. In each joint, the PD controller generates the torque to drive human moving. By this method, Hodgins[63−65] simulated several types of human motion, such as walking, running, diving, bike and jumping over. The computation of coefficient of PD controller, the analysis of motion's stabilization and reuse of controller are hot topics in recent researches. When the coefficient of PD controller of human A is known, Hodgins[66] computed the initial coefficient of PD controller of human B by the ratio between the inertial parameters of human A and human B. The initial coefficient of PD controller of human B is refined by simulated annealing technique. Liu[67] proposed a method by which the coefficient of PD controller can be learnt from the motion captured data. The basis of this method is the equivalence between inverse dynamics and the method based on controller. However, this method is very sensitive to the initial value of coefficient of PD controller and the property of convergence of optimization is not good. Laszlo[68] pointed out that there is a limit cycle in unit normal vector of the section of the waist when humans walk and can be used to stabilize human walking. Firstly, this method determines whether human motion departs from the limit cycles. If the difference between human motion and the limit cycles exceeds a given threshold, the extra torque is applied on waist so that the balance of human walking can be resumed. Different from Laszlo's method, Sok[69] decided whether human motion turned unstable by computing the minimal distance between the current sequential poses and poses in motion database. When an unstable motion is detected, the method finds an example motion in database such that these two motions are as similar as possible. The displacement mapping is applied to two motions and the translation from unstable motion to selected motion can be generated. In this way, the stability of motion can be resumed. Faloutsos[70] proposed a method to assemble controllers. Firstly, the pre-conditions and the post-conditions are defined for each controller and all controllers form a pool of controllers. Secondly, a controller is selected according to the input target motion and the current environment. When a controller arrives at its end, a new controller is selected according to the current state of human. This process of controller's selection continues until a human pose is close to the target pose given by users.

As for motion synthesis based on motion capture data, hot topics include how to reuse motion data to generate new motion that fits new human model, new environment and new constraints; how to organize lots of motion capture data in database and how to search motion data in database quickly for the purpose of synthesizing a new motion; how to depict the character of motion by the parameterized model and how to synthesize a new motion meeting given constraints. The methods can be divided into three classes: motion edition, methods based on analysis of motion database and methods based on special model. Motion edition includes motion blending, motion stitching, motion retargeting, motion warping, displacement mapping and so on. The core of the methods based on analysis of motion database is as follows. We capture lots of motion data and search the desired data from database according to the given condition. Motion graph is most representative among these methods. In the methods based on special model, human motion is regarded as an input signal and the parameterized motion can be obtained by the technique of hierarchy spline, Fourier transformation, the hidden Markov model and the system of linear time invariant. Some other methods reduce the high dimensional space into a low dimensional space by machine learning or dimension reduction techniques and analyze the projected motion in the low dimensional space. These methods include principle component analysis, self organizing map, manifold based learning methods and so on. Because of the limited space, we will not give a detailed description of these methods.

3.2 A physics based human motion synthesis algorithm from examples

There are some drawbacks in trajectory optimization method. 1) Witkin and Kass[52] built the dynamic equations of human motion by symbolic computation. The length of dynamic equations increases exponentially with the degrees of human model. This is the so-called problem of combinatorial explosion. 2) The optimization model in this method is complex and is difficult to solve. 3) The timing is not optimized in this method so that user must set the exact timing; however, so doing is very difficult. So we propose a method to build the dynamic equations of human motion, where the singularity in Euler angles is avoided. And we build a robust optimization model for simulating the realistic human motion in flight. The timing of pose's constraints can be adjusted automatically.

The equation of dynamics is the basis of synthesizing the realistic human motion. In theory, all types of equations of dynamics are equivalent. But in view of computation, these equations are not equivalent. Especially, there exists the singularity in Euler angles when expressing the human motion by Euler angles in traditional methods (see ref. [71] for details). That is because there exists a discontinuity in Euler angle sequences (Figure 5). In order to solve this problem, we extend the method in ref. [39] and propose a new Newton-Euler equation encoded by quaternions and Euler angles for system with tree structure in ref. [72]. By this equation, we can not only avoid the singularity in Euler angles but also reduce the computation complexity. This equation is fit for the analysis of biomechanics of human motion and the trajectory optimization method.

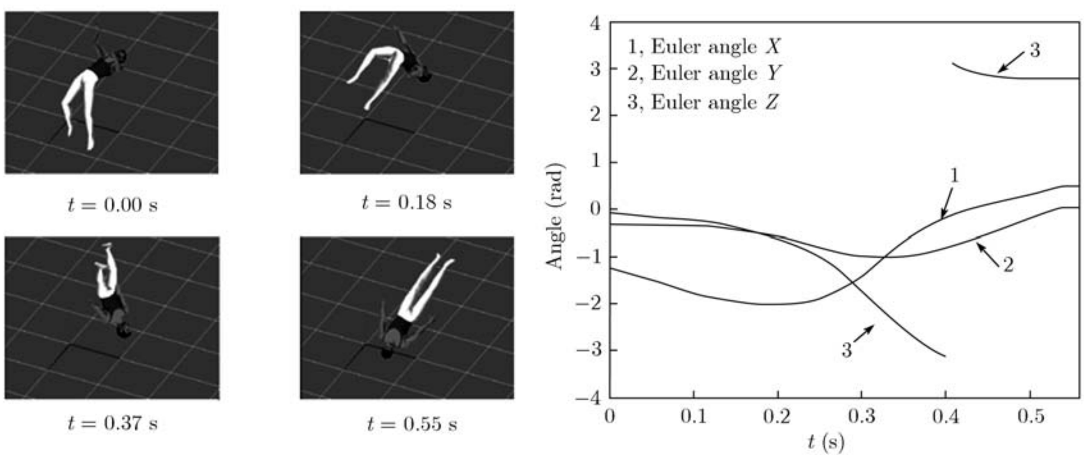

Figure 5 An example of singularity in Euler angles.

In traditional trajectory optimization models, the constraint of balance of force is regarded as the direct constraint condition and the effect of these methods relies on the good initial values. If the initial values are not good, it is difficult to find the optimal solution. The reasons come from three aspects: the strong nonlinearity of Newton's law, the error of mass parameters of human body, the error of the given timing and the fact that the current optimization methods can only find local minimizers. The optimization of traditional trajectory optimization models often fail because the constraint of balance of force cannot be satisfied. A feasible method to solve this problem is to slack the constraints of balance of force. But Wei[73] pointed out that the magnitude of slack depends on the type of simulated motion, the initial value of optimized variables, and so on. The relation between the magnitude of slack and these factors cannot be quantified. Based on the analysis above, Wei[73] proposed the following optimization model (1) of human motion in flight.

$$\begin{aligned}
&\min_{p(t),q(t),T_{\text{key}}} T^{-1}\int_0^T \sum_{i=1}^{6} F_i^2(p(t),q(t))dt\\
\text{s.t.}\quad &|p(t_i)-\bar{p}(t_i)| \leqslant e_1,\\
&|q_k(t_i)-\bar{q}_k(t_i)| \leqslant e_2,\\
&t_i < t_{i+1},\quad q_k \in q(t),\\
&t_i, t_{i+1} \in T_{\text{key}}, i = 1\ldots n-1,
\end{aligned}\tag{1}$$

where, $F_1,\cdots,F_6$ are six aggregated generalized forces acting on root of human body, $q(t) = \{q_1(t),\cdots,q_n(t)\}$ describes the motion of n rotation joints, $p(t)$ expresses the movement of root in human body, $\bar{p}(t_i),\bar{q}(t_i)$ are the values of pose's constraints at timing of key frames; e_1, e_2 are tolerant error of pose at timing of key frames; T_{key} is the set of timing of key frames; T is the time of motion.

In this model, by converting the constraint of balance of force into the objective function, the feasible area of model is extended. By adding the optimization of given timing, the quality of optimal motion can be independent of the error of given timing. By using the Newton-Euler equation encoded by quaternions and Euler angles, the capability of this model on simulating the complex human motion in flight increases remarkably. Figure 6 shows three simulated motions on trampoline.

In model (1), the trajectory of motion and timing of key frames are optimized simultaneously so that the size of model (1) and the time for computation are large. Model (2) is proposed by combining the key framing and the physics-based optimization in ref. [74]. In this model, the timing of key frames can be computed quickly.

$$\begin{aligned}
&\min_{T_{\text{key}}} \quad T^{-1}\int_0^T \sum_{i=1}^{6} F_i^2(p(t),q(t))dt\\
\text{s.t.}\quad &t_i < t_{i+1},\quad q_k \in q(t).\\
&t_i, t_{i+1} \in T_{\text{key}}, i = 1\ldots n-1.
\end{aligned}\tag{2}$$

Take synthesizing a motion "1 and 3/4 front somersaults with 1/2 twist" as an example. There are 12 key frames (including the processes of taking off, somersaulting, twisting and landing). At taking off, the velocity of centroid is (0, 7.8, 0.015 m/s). The hang time is 1.6 s so that there is enough time to do this motion for humans. Because the true values of timing of key frames are not known, the initial value of timing of key frames are distributed between 0 and 1.6 averagely. Figure 7 shows the difference between the initial timing and the optimized one. Figure 8 shows the difference of synthesized motion from the initial and optimized timing. The rationality of the result is analyzed by the following two points of view:

1) According to Newton's Law, relative to the centroid of humans, the angular momentum is equal to the product of the rotational inertia and the angular speed. By the angular momentum conservation law, the angular speed depends on the rotational inertia when humans are in flight. The rotational inertia when a body is crouching is less than that when a body is stretching so that the angular speed when the body is crouching is more than that when body is stretching. In Figure 7, the body crouches between the third frame and the eighth frame so that the time between these frames is shortened observably. Contrarily, the time between the first frame and the third frame and the time between the eighth frame and twelfth the twe-

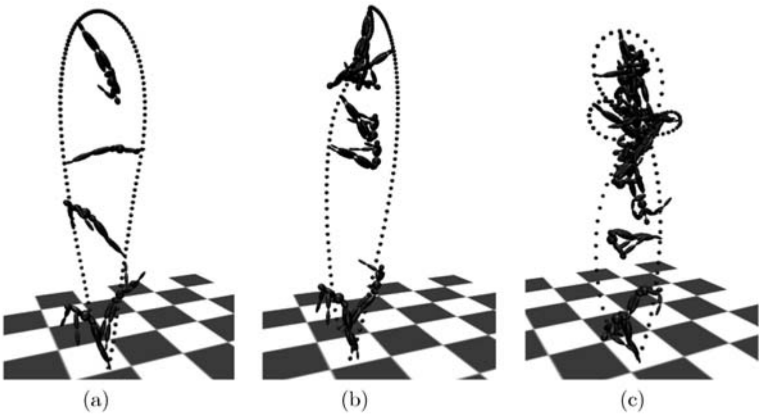

Figure 6 Three simulated motion on trampoline. (a) Back somersault (straight); (b) back somersault (tucked); (c) double front somersaults with 1 and 1/2 twist.

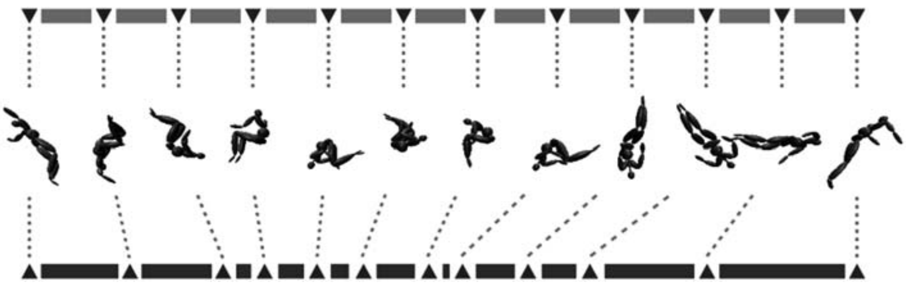

Figure 7 The contrast of initial timing and optimized one. Upside down triangle: the initial value of timing; triangle: optimized timing.

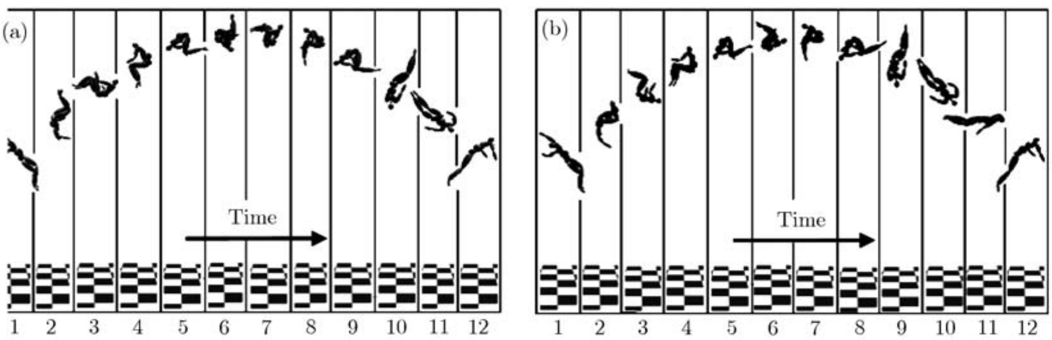

Figure 8 The contrast of synthesized motion. (a) Synthesized motion from initial timing; (b) synthesized motion from optimized timing.

lfth frame are extended observably. The phenomenon shows that the motion synthesized by the timing after optimization observes the angular momentum conservation law.

2) When humans perform the complex somersault, the most part of somersault should be done before the peak of trajectory so that there is enough time to do the landing. Otherwise, it is likely to hit the ground. In Figure 8(b), the pose between the fifth and the eighth lying at the peak and the most part of somersault has been done after passing the peak. The body is transformed from crouching into stretching for state of landing. This phenomenon observes the fact. In Figure 8(a), the ninth pose passing the peak is crouching and the angular speed relative to the centroid of human is still fast. This phenomenon conflicts with the fact.

3.3 An inverse kinematics based human motion synthesis algorithm from examples

Traditional jacobian inverse method for inverse kinematics problem (see Table 1) is valid only if the Jacobian matrix is square and reversible. For a redundant model, when the degree of freedom is more than the number of constraints, the Jacobian matrix is not reversible, meaning that there are infinite offsets of posture Δq satisfying the movement of end-effectors Δg. Under this situation, the inverse of Jacobian matrix is replaced with the general inverse J^+ . However, the result computed with J^+ is only one solution in the solution space with some properties. For example, the solution obtained using Moore-Penrose inverse is the minimum norm solution. This kind of solution is good from the view of mathematics, but it may not suit for human posture synthesis.

One possible way is to obtain the inverse of the jacobian matrix from motion capture data and then use them to synthesized new postures satisfied constraints. We proposed a new method based on learning jacobian inverse from motion capture data in ref. [35]. It consists of two phases: learning and synthesis.

In the learning phase, a low-dimensional and discrete representation of the space of natural poses is constructed by using a self organizing map (SOM), as shown in Figure 9. Note that the Jacobian matrix is a continuous function over a space of poses. Base on this fact, we can assume that the poses belonging to the same cluster share the same Jacobian matrix and its inverse. This assumption can be represented as a minimization problem (3), which can draw the Jaocibna inverse for each cluster directly.

Table 1 Jacobian inverse based inverse kinematics

1. $n = 0$; //Initialize the counter
2. $q_n = 0$; //Initialize the posture
3. $g_n = f(q_n)$; //Compute the position of end-effector
4. while (g_n is too far from g) //Decide if the constraint is satisfied or not
5. {
6. $J =$ Jacobian (q_n); //Compute the jacobian matrix of current poseture
7. $J^{-1} =$ inverse (J); //Compute the inverse of the jacobian matrix
8. $\Delta g_n = g - g_n$; //Move a step toward the target
9. $\Delta q = \alpha J^{-1} \Delta g_n$; //Compute the increment of posture
10. $q_{n+1} = q_n + \Delta q$; //Update the posture
11. $n = n + 1$; //Update the counter
12. $g_n = f(q_n)$; //Compute the new position of end-effector
13. }

$$J^+ = \arg\min \sum ||\Delta q - J^+ \Delta g||^2, \qquad (3)$$

where Δq means the difference between the central pose of a cluster and a pose belonging to it, and Δg denotes the displacement of the end-effector's position between them. Theoretically, if all the postures in the same cluster are identical, that means Δg equals zero for any two poses. In this situation, eq. (3) is degenerated, so there exists no proper J^+. But in practice, these situations rarely occur. When the learning phase is finished, two kinds of parameters are learnt: the reference poses and the Jacobian inverse matrices for all the clusters.

In synthesis phase, there are two steps to solve a given inverse kinematics problem. Firstly, initialize the configuration by searching all the reference poses, whose end-effector's position is the closest to the desired position. Secondly, refine the pose to satisfy the constraints precisely using the Jacobian inverse learned above. See ref. [35] for details.

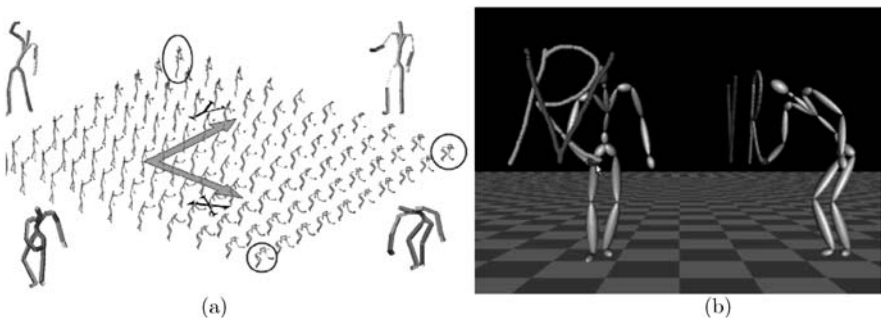

Figure 9 Pose synthesis based on learned Jacboian inverse. (a) SOM output of 'bend over' motion; (b) synthesized motion.

4 Applications

4.1 Chinese sign language teaching

Sign language expresses meaning by the motion of hand, which is mainly used by the deaf. Synthesis of sign language is to automatically translate the sentences of natural language into sign language, and display them vividly with virtual human generated by computer in ref. [75]. It is not only convenient for the deaf to make use of various kinds of computer information, but also helps them take part in normal activities (such as watching TV) and communicate with people without difficulty.

We implemented a synthesis system of Chinese deaf sign language based on virtual human synthesis technology in ref. [75]; it can convert described content into Chinese deaf sign language, and display it on the computer in a way of three-dimensional virtual human animation (see Figure 10). The system can use standard VRML virtual human model, and the synthesized sign language is rich, including all 5500 words in the book of Chinese Sign Language, which collect lots of sign words for daily life and teaching. The accurate, natural, vivid and high intelligible virtual human motion can be widely used in teaching television, internet and other mass media, which could help the deaf participate in activities as normal people.

4.2 Computer aided sports training

Existing sports training methods based on high-tech can be broadly divided into two categories: one is based on virtual reality, where trainees interact with virtual environment by means of devices with the purpose of learning and improving skills; the other is based on video analysis, where comparative analysis and advice of improving skill are given by comparing trainees with excellent athletes. In order to aid sports training, we have developed a three-dimensional simulation of human motion and video analysis system for sports training system based on virtual human synthesis technology (see refs. [76,78] for details).

This system not only supports video based data collection and analysis in ref. [77], but also reconstructs 3D athlete's performance from the motion capture data by VICON device[79,80]. And then we implement kinematic analysis and dynamic analysis of human motion based on the domain knowledge from biomechanics and the human dynamics motion equations in ref. [72]. We further arrange virtual athlete's performance based on motion editing and motion transition into a long sequence and design a new motion from given constraints using the physics-based simulation technology in ref. [73]. Finally, comparative analysis result could be presented by comparing the designed new motion with that of the real athlete on the same video screen in ref. [81]. Figure 11 shows a snapshot of sports training system. The system can be used for assisting coaches with an immediate information feedback in training, aiding coaches to design new motion for a specific athlete and so on.

4.3 Computer aided public safety studying

In public safety research community, what researches are interested in is how to simulate crowd behavior in complex building and especially how to visualize the simulated result in three-dimensional space with normal PC. Up to now, we have achieved some results: a hierarchical obstacle avoidance based crowd simulation method, a point based large-scale crowd rendering method, and a system, CrowdViewer, which can populate thirty thousands virtual human.

As for crowd behavior simulation, traditional methods have some drawbacks such as the presence of collision and robot like motion behavior. To avoid these limits, we put forward a hierarchical obstacle avoidance model for crowd simulation and a constraint directed steering method for path execution in ref. [82], where hierarchical obstacle avoidance model focuses on a three-level obstacle avoidance method which contains two-level obstacle avoidance behavior and an intersection elimina-

Figure 10 A synthesis result of sign language "hello".

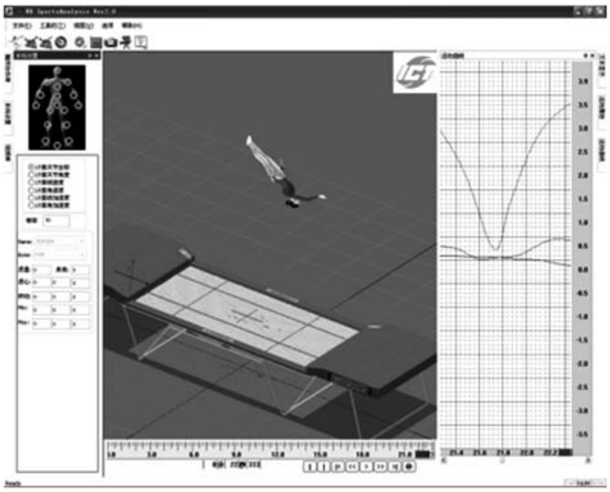

Figure 11 A snapshot of sports training system.

Figure 12 Two snapshots of CrowdViewer.

tion level. The two-level obstacle avoidance behavior is used for avoiding collision during the behavior planning and execution while the intersection elimination level is employed to adjust overlapping after coarse renewed positions are calculated for agents. The two-level obstacle avoidance behavior, including static obstacle avoidance and dynamic obstacle avoidance, extremely reduces the complexity of the situation to be considered in the planning and execution of agent's behavior by dividing the objects into two kinds: static obstacles and dynamic obstacles according to their attributions and making use of separate obstacle avoidance method to avoid collision. The intersection elimination level, based on agent's variable bounding box and its previous position, eliminates intersection artifacts absolutely in every update period without space restrictions and visually artifacts. And by generating recognizable environments and enactments of individual behavior(collision avoidance, social custom and unit attribute, etc.), the constraint directed steering method can generate motion trails closer to movement of natural creatures in a flexible way.

As for 3D rendering of large-scale crowd, we adopt a point-based policy, in which traditional triangles that produce good image quality are combined into an octree structure with samples which are good at representing simplified modes with very fast rendering speed. We not only improve, but also add item decomposition and reusing, effective data management to the original algorithm, and finally realize a real-time rendered scene of 30000 individually animated virtual human models. For details please refer to ref. [83].

As for the behavioral reconstruction and playback of crowd simulation result, we applied personalized model generation technique, database based motion synthesis and crowd rendering technique integrally, and finally implemented a 3D crowd behavior browse system CrowdViewer in ref. [84], which can realize real-time rebuilding and browsing of tens of thousands of virtual characters. Figure 12 shows two snapshots of the system.

5 Conclusion

There are more and more research topics in virtual human synthesis, which now include human body modeling, motion control, motion simulation, facial animation and so on. Whatever the specific topic is, the goal of virtual human synthesis is to make the virtual human close to real human being as much as possible both in appearance and motion behavior. Following this idea, this paper surveys the development of virtual human synthesis and its application in industry from two aspects of human body modeling and natural human motion behavior generation. Particularly, according to the work from the authors and their colleagues, this paper gives recent research progress and applications in Chinese sign language teaching, computer aided sports training and public safety studying. In natural human motion behavior, this paper focuses on the classical kinematics and dynamics model. And therefore, related works discussed in this paper are limited.

To conclude, we try to list the following interesting topics in virtual human synthesis for interested readers.

1) How to conveniently reconstruct highly realistic human model from video sequences.

2) How to flexibly control the performance of virtual human by some devices such as game controller.

3) How to effectively organize and display the large-scale database of human motion data.

4) How to avoid the behavior clone phenomena in crow animation.

5) How to combine mesh based human animation and skeleton based human animation in order to reuse mutual research methods.

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