Research Problems for Creating Digital Actors

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Research Problems for Creating Digital Actors

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Abstract

An interesting challenge for the computer graphics community is to use computer graphics technology to simulate digital actors *that seem so real that people cannot tell whether they are animated or real. Our group is engaged in an ongoing project to develop and integrate the techniques required for creating digital actors. In particular, our research has been focused on components such as facial animation, hair animation, clothing animation, and body animation, which are crucial to the successful realization of digital actors. This article summarizes the results of our research on those topics, reviews other approaches that have been taken in digital actor research, and outlines the challenges that must be overcome in this area.*

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1. Introduction

In the 21st century, an interesting challenge for the computer graphics community is to create *digital actors*, actors created by computer graphics technology that are so real that people cannot tell whether they are animated or captured from the real world.

Animal characters such as those in "Stuart Little" [3] are generally not considered to be digital actors. Compared to the simulation of animal characters, creating visually convincing human actors is more difficult because viewers are surprisingly skilled at perceiving the subtlties of human movement and expression. In addition, the human boy Andy in "Toy Story" [2] is not classified as a digital actor because the character was not created to convince people that it is a real human. In "Titanic"[4], on the other hand, thousands of characters were created by computer graphics technology; these characters are true digital actors because they were created to convince viewers that they are real humans.

The generation of digital actors is a challenging problem that encompasses almost every aspect of the field of computer graphics. Although the potential of digital actor technology has been demonstrated in movies such as "Titanic", the technology is not yet sufficiently sophisticated to allow digital actors to replace real actors in lead or support roles.

To make the problem of generating digital actors tractable, we need to restrict the scope of the task. First, we do not require that the character should have (artificial) intelligence or be capable of generating autonomous life-like behavior, nor do we require that the whole process of creating the final visual should run at an interactive speed. In addition, animators will be allowed to control the process provided the amount of manual work is not overwhelming. Thus, the emphasis of digital actor research will be placed on the realism of the appearance and motion of the simulated character.

We have an ongoing interest in the development and integration of the techniques required for creating digital actors. In particular, our research has focused on components such as facial animation, hair animation, clothing animation, and body animation techniques, which are crucial for realizing digital actors. This article summarizes the results of our research on those topics, reviews other approaches used in digital actor research, and outlines the challenges confronting workers in this area.

2. Facial Animation

Realistic simulation of the human face is one of the most challenging areas of digital actor technology. Although the face occupies only a small portion of the body, it is the principal source of information on the internal state of a character. Everybody is expert at recognizing facial expressions, including those of synthetic characters. Therefore, the face of a digital actor must be modeled, rendered, and animated with a greater level of accuracy and realism than is necessary for other parts of the body.

We developed a method for separating expression capture data into linear combinations of a deformation basis [16].

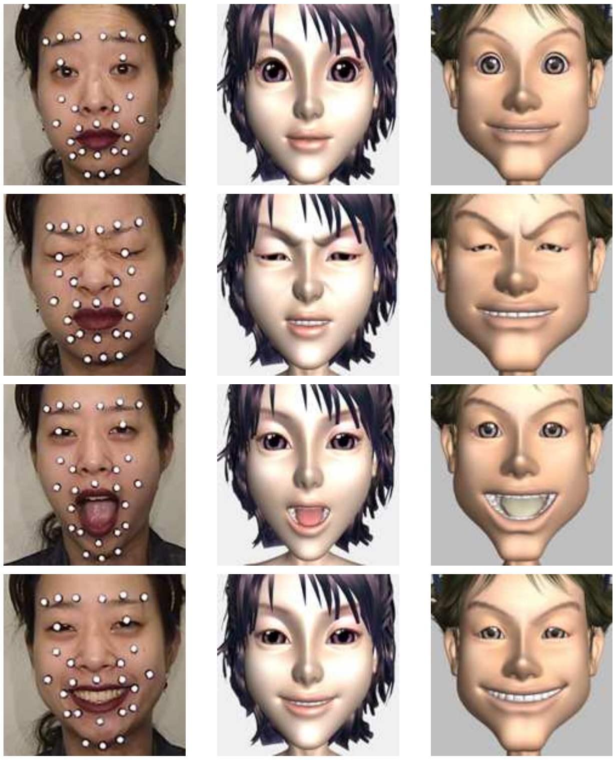

Figure 1: *Original expressions (left column) and expressions retargeted to other computer models (middle and right columns).*

In modeling the deformation basis, we included the artists' modeling capability as an integral part of the method. We had the artists manually sculpt a set of facial expressions called the *muscle actuation basis*. Each element of the actuation basis corresponds to the facial shape when a single expression muscle is fully actuated and the other muscles are relaxed. Once the basis is generated, it is possible to (1) reproduce the performance by finding the weights of the basis elements, (2) modify the original expression by interactively changing the weight values, and (3) retarget the expressions by applying the analyzed weights to other computer models with equivalent deformation bases. Figure 1 shows the result of expression retargeting using our system.

To achieve the goal of generating lifelike human faces, the following problems must be solved:

1. Accurate modeling of face geometry (including eyes and teeth),
2. Rendering of facial surface showing the correct reflectance properties of skin,
3. Animation of the full range of human expressions with realistic skin deformation.

2.1. Modeling the 3D Geometry

3D scanners have been widely used to obtain the geometries of individual faces. Because 3D scanners usually generate dense data, a simplified mesh needs to be generated for use in subsequent processing steps such as animation. Terzopoulos *et al.* [77, 50] constructed the facial model of a human subject by adjusting the vertices of a generic model to fit the laser-scanned range data. Blanz and Vetter [8] reconstructed 3D faces from only one or two photographs utilizing a database of 3D face shapes and textures obtained by laser scanning. As an alternative to using scanners, Pighin *et al.* [65] presented an image-based modeling technique. They reconstructed the geometry and texture of an individual face from five photographs of the subject. To date, however, the eyes, teeth, and tongue of digital characters have been modeled manually.

2.2. Rendering

Current rendering techniques often generate glossy faces that resemble plastic. Recently, a number of face rendering algorithms with elaborate skin reflectance models have been developed that come closer to photo-realistic rendering of faces. Pighin *et al.* [65] extracted high-quality textures from photographs, which turned out quite effective to show detailed wrinkles and creases. However, their method could not correctly render the face under different light conditions. To render faces illuminated by arbitrary light sources, Marschner *et al.* [57] used a Bidirectional Reflectance Distribution Function (BRDF) model with an albedo map (diffuse component) for each individual face. Noting that human skin has complicated subsurface scattering, Jensen *et al.* [38] measured the subsurface scattering component in human skin and rendered the face using a Bidirectional Surface Scattering Distribution Function (BSSRDF) model. Rendering with the BSSRDF model successfully reproduced the soft appearance of real skin and natural skin properties such as color bleeding. To capture the skin reflectance of an individual subject, Debevec *et al.* [21] first collected images of a subject's face under different illumination conditions and viewing directions, and then used those images to compose an image-based reflectance function. Using this function, they could render the face realistically under arbitrary illumination and viewing directions.

2.3. Animation

Many facial animation techniques have been developed since the seminal work of Parke [62]. A review of all previous work in this area is beyond the scope of this paper; here we restrict our discussion to only a few prominent methods that have been recently developed. We urge interested readers to see the excellent survey by Parke and Waters [63].

Physically Based Animation Waters [86] developed an anatomy-based method for synthesizing facial expressions using a linear vector muscle model. Terzopoulos *et al.* [77, 50] simulated the deformation of the skin surface due to muscle actuation using a layered skin model based on a mass-spring system. As input for their system, they estimated the muscle contraction values from video-recorded expressions using so-called snakes [78]. Essa *et al.* [22, 23] modeled the skin surface using a Finite Element Method (FEM), and estimated the muscle actuation corresponding to the skin deformation using feedback control theory. Kähler *et al.* [39] proposed an anatomy-based face model that reconstructed the face starting from the skull layer. They then used a dynamic muscle model to produce facial animations.

Performance-Driven Animation Driving the motion of the entire set of vertices from a small set of feature points has been widely used for performance-driven facial animation since Williams [87] first introduced this technique. Guenter *et al.* [31] produced life-like facial expressions showing complicated skin deformation by performing accurate 3D tracking of a large number of points. Noh and Neumann [61] reconstructed facial expressions from a small set of feature points tracked with an optical motion capture device, and presented an expression retargeting technique that could transfer the motion vectors to other face models with different topologies.

Shape-Blending Techniques One of the most widely used techniques in animation production houses is shape blending, a technique by which previously modeled key shapes are interpolated to give a new shape. Pighin *et al.* [65] modeled several key shapes corresponding to major expressions, then generated facial animations by blending them. By allowing the blending operation to apply to selective regions, the method could generate a variety of expressions from a small number of key shapes. Lewis *et al.* [52] pointed out that use of linear combinations of key shapes can lead to unwanted motion of the vertices, and suggested using a standard expression space in which the coordinate values can be interpreted as the blending weights. Instead of manually forming the expression space, Kalberer and Van Gool [41] determined the deformation basis automatically using Principal Component Analysis (PCA).

Figure 2: *Animation of Hair within a wind field*

Voice-Driven Animation People are highly sensitive to the mutual interaction of voice and facial expression. Therefore, we need to develop a method that properly synchronizes the motions of the lips and tongue, as well as other parts of the face, to the speech. Bregler *et al.* [10] and Ezzat *et al.* [25] presented voice-driven video-realistic facial animation techniques that synthesize the mouth region in 2D image space according to the input voice signal. Brand [9] presented a system that synthesizes the motion of the entire face based on the expression information in an audio track. Despite the progress made in this area, in most animation studios the majority of the task of lip-synching remains in the realm of manual processing by animators. While expression control is regarded as creative, lip-synching is regarded as tedious and unrewarding. Therefore developing a technique that automatically generates realistic lip-synching would be a valuable step toward realizing digital actors.

Animation of Eye Movements Eye movement is a crucial aspect of facial expression. Recently, Lee *et al.* [49] proposed an eye movement model based on empirical models of saccadic eye movements [discontinuous (subconscious) eye movements] and statistical models of eye-tracking data. Given the importance of eye movements, surprisingly few studies have considered the problem of how to accurately simulate such movements. Artifacts in eye movement are quite conspicuous. In animations produced to date, even high quality feature movies, the eye movements of human characters look unnatural. Thus, if digital actors are to be made completely life-like, new approaches that produce natural eye movement will need to be developed.

3. Hair Animation

Realistic hair is essential if a digital character is to appear human. Several algorithms for animating and rendering hair have been proposed; however, they are seldom employed in commercial animation production because they currently require a disproportionate amount of computation and manual processing in comparison to other body parts. The problems associated with animating human hair arise from the fact that humans have an extremely large number of very thin hair strands [69].

We proposed a physics-based technique for modeling various human hairstyles and animating hair movement according to the head motion and external forces [46]. The proposed technique models hair strands as serial chains of rigid links and formulates the dynamic equations that account for the effects of gravity, wind, air resistance, and hair-to-head and hair-to-hair frictional forces. Figure 2 shows a snapshot taken from an experiment on the movement of hair within a wind field.

Real hair movement cannot be easily captured using currently available techniques. Procedural approaches based on physical simulation seem the most reasonable approach to hair animation. Anjyo *et al.* [6], Deldegan *et al.* [20], and Lee *et al.* [46] proposed methods that compute the movement of the numerous individual hair strands by numerically solving simplified dynamics equations. Due to the simplifications, however, these methods produce implausible artifacts when there are complex hair–hair or hair–environment interactions. One of the most time-consuming steps in these physical simulations is collision handling. Lee *et al.* [46] proposed a layered hull technique to efficiently detect head-to-hair and hair-to-hair collisions. Chang *et al.* [15] simulated mutual hair interactions efficiently by solving the interaction between some key hair strands. Hadap and Magnenat-Thalmann solved the mutual interactions and internal dynamics within a unified continuum mechanics framework.

Hair must be rendered correctly for a synthetic face to look real. Since the introduction of Kajiya and Kay's hair rendering model [40], many rendering techniques have been developed [64, 45, 84, 30, 13]. Recently, Marschner *et al.* [58] measured the scattering from individual hair fibers, and found that the real scattering differed significantly from that which had been assumed since Kajiya and Kay's work. Based on the scattering measurements, they proposed a practical shading model for rendering the complicated scattering effects observed in real hair. Because the thickness of each strand is usually smaller than a pixel in the final image, integrating the hair rendering result into the final scene should be done carefully. Lee *et al.*[46] and Kim *et al.*[43] proposed methods for solving this aliasing problem, and Lokovic *et al.*[55] and Kim *et al.*[43] generated a self-shadowing effect among hair strands.

Another important issue is hair modeling or styling. Watanabe and Suenaga [85] introduced the concept of using wisps, where each wisp is a group of hair strands interpolated from three key hairs. Xu and Yang [90] presented an interactive hair modeling system based on generalized cylinders. Kim *et al.* [43] developed a hair modeling system based on a multi-resolution technique that can generate various kinds of hair styles through user-interaction.

The research problems confronting efforts to create realistic hair can be summarized as follows: (1) developing techniques that allow modeling of realistic hairstyles in the presence of a gravitational field with proper treatment of collisions; (2) accurate simulation of hair movement that considers all the dynamic elements including gravity, inertia, air-drag, and collision responses; and (3) photo-realistic rendering of hair strands.

4. Clothing Simulation

The realistic simulation and animation of the clothing worn by digital characters is crucial to making them appear human. Nevertheless, in most animation productions carried out to date clothing has either been omitted or simplified due to the lack of an adequate clothing simulation technique.

Figure 3: *Snapshots from a Clothing Simulation*

We have carried out considerable work on physically based techniques for creating more realistic cloth movement, achieving faster run-times, and constructing and simulating more complex garments [18]. Figure 3 shows snapshots taken from one of our clothing simulations.

4.1. Physical Model and Simulation

In engineering applications, the accuracy and validity of the physical model of a cloth are of utmost importance. However, in computer graphics applications, the speed with which the algorithm runs is more important than the accuracy or validity of the underlying model. Numerical instabilities have proved the main obstacle hindering the implementation of fast simulators. The numerical instability problem emerging from the stiff set of differential equations was addressed by Baraff and Witkin [7]. They developed a semi-implicit scheme for numerical integration that increased the numerical stability and produced visually pleasing cloth animations while using much less computation than had been required using previous methods. Subsequent to this work, many studies have been undertaken to analyze, improve, and simplify Baraff and Witkin's technique for use in clothing simulations [80, 81, 59, 24, 32, 42].

In addition to the numerical instability, which is well treated by the implicit method, there remains another kind of instability, referred to as the buckling instability. The buckling instability occurs whenever a cloth is about to form a wrinkle. Because this instability is an inherent physical property of thin materials, it cannot be avoided by adjusting the numerical method. Choi and Ko [18] proposed the *immediate buckling model* in order to avoid the buckling instability. This model is based on the assumption that application of a compressive force on cloth immediately initiates buckling rather than compression followed by buckling. The model developed under this assumption is defined such that it inherently lacks the buckling instability. Simulations incorporating the immediate buckling assumption produced realistic, responsive wrinkles without suffering from the buckling instability.

Several aspects of cloth modeling that could potentially increase the realism of cloth movement have not yet been explored. One key area worthy of further study is the problem of accurately modeling the nonlinearity and hysteresis inherent in the movements of cloths. Although some effort has been made to incorporate these effects into cloth models, most commonly through particle or mass-spring models, methods based on a continuum model warrant further investigation.

4.2. Collision Resolution

Collision resolution is another important issue in cloth simulation. In simulations of complex garments, the procedure for resolving collisions occupies more than 70 percent of the computation. If a collision goes undetected, it is difficult to subsequently recover the valid state because the cloth surface has no outside/inside distinction as far as collision detection is concerned. Therefore, it is of the utmost importance that the collision detection algorithm detects all collisions.

Volino and Thalmann [82] proposed a technique that increases the speed of self-collision detection by efficiently pruning the comparison pairs based on an analysis of the surface curvature coherency. Provot also presented a surface curvature heuristic [68]. Two other approaches widely used for collision pruning are hierarchical bounding volumes[83, 11, 60] and uniform spatial subdivision[34, 18]. For robust detection of collisions among moving triangles, Provot[68] and Bridson *et al.*[11] assumed the vertices undergo linear motion; this assumption allowed collision resolution to be reduced to problem of solving a cubic polynomial equation. To achieve the same goal, Huh et al.[35] used the swept volume approach.

Volino and Thalmann[83] used a geometric correction method as the basis for a collision response model. The resulting model, which is capable of robustly resolving multiple collisions, uses barycentric coordinates to distribute collision responses among vertices so as to generate continuous collision responses among triangles. Provot[68] addressed the multiple collision problem by introducing the concept of a *zone of impact*. In this approach, the particles involved in the collisions within a local zone are treated as a rigid object. Huh *et al.*[35] also proposed a method for resolving multiple collisions based on the concept of a zone of impact. They divided the particles in an impact zone into collision clusters and then, to avoid possible subsequent collisions, they simultaneously resolved the collisions of those clusters by solving a linear system. The collision response in their method conserved momentum, in contrast to the method of Volino and Thalmann[83]. Bridson *et al.*[11] proposed a robust and accurate collision handling technique that combined the repulsive force, geometric correction, and the concept of impact zones. They also proposed a collision-aware subdivision scheme as a post-processing step to increase visual realism.

4.3. Constructing Complex Garments

One aspect of clothing simulation that to date has been largely neglected is garment construction. The basic problem confronting garment designers is the nonintuitive task of clothing a 3D character with a garment constructed from 2D patterns. In clothing simulation, the generation of garments that both have the required design and fit the animated character is a time-consuming preprocess that most animators dislike. Although numerous pattern CAD packages are available, they are targeted at pattern makers and the nonexpert will find few of them to be user-friendly. The necessity of engaging an expert pattern maker to create interesting garments is one of the factors hindering rich clothing animation. Thus, the development of more intuitive garment design techniques suitable for use by nonexperts is an important challenge in cloth simulation.

5. Body Animation

For animating the gross body motion of a digital actor, 3D motion capture is a valuable source of information because it provides high-quality motion data in which the details of the original motion are preserved. However, in most cases the motion data needs to be edited to account for different anthropometric scales or actor-to-environment interactions. This need to adapt motion data has heightened interest in methods for modifying or retargeting a captured motion to different characters.

In the past few years, we have developed an online motion retargeting algorithm [17] based on per-frame inverse kinematics that avoids discontinuities by using motion similarity as a secondary task. In addition, we have developed a motion balance filtering algorithm [73] that modifies a kinematically generated motion such that the resulting motion is dynamically balanced. More recently, we have developed an interactive dynamic constraints solving technique [74] that handles both the kinematic and dynamic constraints in a scalable fashion. In contrast to previous optimization-based methods, our algorithm works as a *filter* that sequentially scans the input

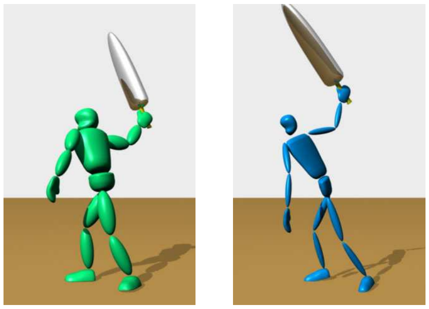
(a) (b)

Figure 4: *Sword swing: (a) original, (b) retargeted to a lean character.*

motion to produce a stream of output motion frames at a stable interactive rate. Figures 4, 5, and 6 show some representative results obtained using our approach. In Figure 4, we retarget an original sword swing motion to a very lean character. In the resulting motion, the upper-body of the character makes a big movement to counterbalance the heavy sword. In Figure 5, we retarget the motion of a ballet dancer to a short and heavy character. In the resulting motion, the leg of the character cannot lift as high as that of the ballet dancer, and the character's upper body sways to compensate for the momentum of the heavy swinging leg. Figure 6 shows limbo motions retargeted from a normal walking motion. The first character can clear the limbo bar; however the second, heavier character cannot bend his waist sufficiently to clear the bar due to his heavy torso.

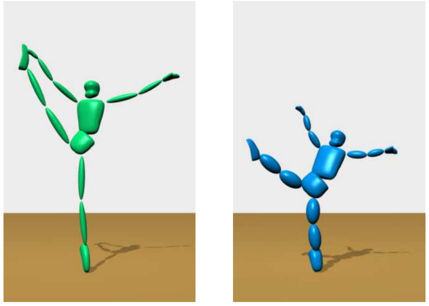
(a) (b)

Figure 5: *Ballet dancer: (a) original, (b) retargeted to a short, heavy character.*

Motion editing has been studied by numerous animation researchers. Early studies on motion editing were mainly related to motion signal processing. Bruderlin and Williams [12] applied a number of signal processing techniques to motion data, Unuma *et al.* [79] used the Fourier series expansion in their motion data manipulation, Witkin and Popović [89] introduced a motion warping technique, and Lee and Shin [48] proposed a multi-resolution analysis method guaranteeing coordinate invariance.

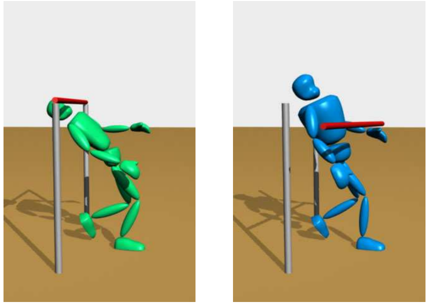
(a) (b)

Figure 6: *Limbo Walk: (a) with a normal torso, (b) with a heavier torso.*

To date, various constraint-based motion editing methods have been proposed. Gleicher [28, 29] formulated the kinematic motion editing problem as a spacetime optimization over the entire motion. Lee and Shin [47] divided the problem into per-frame inverse kinematics and curve fitting for global smoothness. Shin *et al.* [72] proposed an on-line retargeting algorithm based on the notion of dynamic importance of end-effectors. These kinematic motion editing techniques have shown acceptable results in many cases. However, when the dynamic context differs significantly between the source and target motions, it is necessary to consider physical properties such as segment weights and joint strengths.

Many researchers have explored physically based motion editing techniques. Pollard *et al.* [66] proposed a fast motion transformation method based on a simple force-scaling technique. Komura *et al.* [44] used a musculoskeletal model to tackle the retargeting problem. Yamane and Nakamura [91] proposed a filtering technique that transforms a given motion into a physically consistent one, and Popović and Witkin [67] addressed the physically based motion transformation problem using spacetime optimization.

There are two other important approaches to motion synthesis that do not exploit the captured motion: the spacetime constraints method and dynamic simulation. The spacetime constraints approach was first proposed by Witkin and Kass [88], and several groups [19, 54, 70, 53] have improved the original spacetime constraints algorithm and extended its applicability. Another approach to the generation of physically based animations is dynamic simulation. Several interesting techniques such as the controller-scaling technique [33], automatic controller composition [27], and motion-capture driven simulation [92] have been proposed.

Body deformation is essential to the realism of digital actors. The most common technique for deforming articulated characters is to bind the surface geometry to an underlying skeletal structure or to a set of control parameters. The free-form deformation (FFD) technique introduced by Sederberg and Parry[71] is a common choice for supporting human body deformation in commercial animation packages. FFD embeds a surface geometry in a domain that can be more easily parameterized than the object itself. MacCracken and Joy improved the applicability of FFD by allowing lattices of arbitrary topology[56], and Faloutsos *et al.*[26] introduced dynamic free-form deformation to apply FFD to animation.

In recent years, example-based approaches have been proposed to obtain more realistic deformation. Lewis *et al.*[51] introduced a pose space deformation technique that formulates deformation as scattered data interpolation based on radial basis functions. To obtain more realistic results, Allen *et al.*[5] exploited range scan data captured from real humans and used k-nearest neighbor interpolation.

Physically based dynamic simulation, which was pioneered by Terzopoulos *et al.* [75, 76], is another popular approach to animating deformations [36]. Algorithms for obtaining the deformation of a skeletal structure from joint angle input data have been proposed by Capell *et al.*[14], and James and Pai[37].

Despite the progress made to date, none of the approaches outlined above can produce body deformation of digital actors with a satisfactory level of realism. Thus, the challenge remains to develop techniques for acquiring an accurate geometric model of a human body and then to make that model exhibit both dynamic deformation behaviors (e.g., vibration) and kinematic deformation behaviors (e.g., muscle stretching and bulging).

6. Conclusion

In this paper we have considered the problems facing efforts to create digital actors, and have identified the component technologies that will need to be perfected to achieve this aim.

Digital actors have already been included in various movies either for practical or experimental purposes. The feature animation "Final Fantasy"[1] was a pioneering attempt to create digital actors. However, due to the technical immaturity of the field, the project involved enormous amounts of manual work by animators. Digital actor technology has many potential commercial applications, including the creation of *digital clones* of celebrities. In fact, several movie projects are cautiously attempting to revive old movie stars such as Bruce Lee.

The impact of digital actors will be enormous; the movie industry will dramatically change, and human culture will be significantly affected. To promote advances in digital actor technology, we propose that a worldwide competition called the *Turing Digital Actor Contest* be set up, in which submitted animations are judged on the basis of the realism of the motion and appearance of their human characters.

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