A Comparison of Design Strategies for 3D Human Motions*

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Three-dimensional character animation and especially human animation becomes everyday more popular for simulation, multimedia applications, and games. However the specification of human motion in a computer animation system is still a tedious task for the user in most commercial systems. Based on the experience on the ESPRIT projects HUMANOID and HUMANOID-2, we compare in this paper the various strategies for describing and interacting with complex motions of the human body. We especially analyze the advantages and disadvantages of the associated interfaces. A case study of object grasping and handling is detailed within the framework of the TRACK system.

1 Introduction

In this paper we compare the design strategies for 3D human motion. We choose to concentrate on the constraints, the objectives and the methodologies adopted for the body skeleton animation thus excluding the facial animation field from our investigations. The comparison is organized according to the major trade-off between the interaction refresh rate and the desired realism of the resulting motion. Although, it is a major factor of computing cost and final realism of the human motion, we don't address in detail here the problem of the human envelope deformation, either skin or cloth. It is clear that the same trade-off also applies to that feature and we keep it in mind when comparing the different strategies. We can order the various methodologies along a scale beginning at high realism for the motion design process in a production context, then middle realism for the interactive process provided by a wide range of motion modeling systems and finally low realism for real-time applications as simulators, virtual reality and games. We review the characteristics of these various approaches by describing the strategies used to animate and interact with 3D human characters.

We first examine the design process of realistic motions for productions as films, commercials and more recently games. Then, in the second part we focus on the wide range of systems providing interactive response time basically for design purpose or for some of them dedicated to human factors evaluation. The objectives of the ESPRIT project HUMANOID 2 are recalled in that context. In this class of systems the integration of the end user interaction flow is depending on the system load. Conversely, in the simulators and the games a high input-output rate tightly constraints the system architecture as developed in the third part. We especially stress the problems which have found recent improvements and those intrinsically difficult to solve in a near future. The fifth part recalls the methodology of the TRACK system developed in the framework of the ESPRIT project HUMANOID. We focus on a case-study of complex goal-oriented grasping and handling motions. Finally, we conclude by summarizing the general trends of the field.

2 Motion Design in Film Production Context

What is required in movie productions is much more than the mere physically-based realism ; it is rather a high believability conveying the intention of the motion and the emotional state of the character. Animating a 3D human with that objective in mind makes the whole process extremely difficult as the models are still desperately simple compared to any real actor.

The animators and directors know very well that the body postures and movements express nearly as much as the face and the speech themselves [1]. This has been partly exploited in traditional 2D animation together with other observations regarding subjective interpretation of object proportions and relative motion. Such practical knowledge can now guide the 3D animators [2][3] in bringing to "life" cartoon-like or toy-like characters as recently demonstrated with the movie "Toy Story" [4].

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Apart from that masterpiece which involved an important team (110 persons at Pixar [4]), this type of work is limited to short pieces for cost reasons. At this moment, most of them are special effects, commercials and, more and more, some sophisticated games [5].
In the production context, the animators have very detailed specifications of each individual motions to design from the storyboard and artistic directives about the characters. The logical requirement on the software tools is to ask both for the highest realism and the greatest freedom of design in order to edit and improve any detail of the motion. However, as appears on Figure 1 (inspired by [6]), the techniques providing highly realistic motions, at least from the physical aspect of the problem, are the ones providing the least design freedom. We now review them and analyze why the live recording, also known as Performance Animation, is now the most popular technique is that field. In a second part we recall what still prevent performance animation systems to be more widely accepted in 3D human animation.

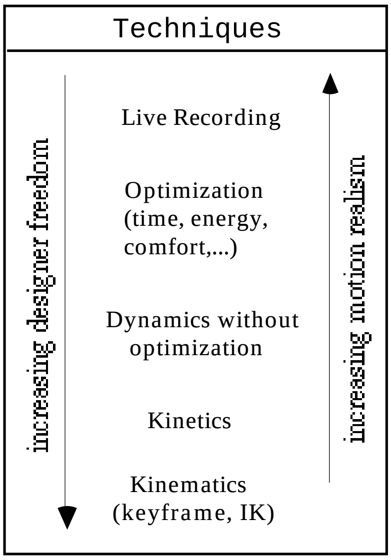

Fig. 1: designer freedom Vs motion realism

2.1 Physics alone does not bring “Life”

The major commercial systems for 3D human animation, as Alias-Wavefront-TDI and Softimage, propose various degrees of motion realism from the standard Keyframe techniques, Inverse Kinematics, Direct and Inverse Dynamics to the option of live recording. They ignore Optimization techniques and Inverse Kinetics (see details in section 3). In the film production context, the motion design is an incremental process that require the possibility for the animator to fine tune any *degree of freedom* (further noted *DOF*) of the animated structure at any point in time. This is achieved with the large set of tools manipulating keyframes [4]. Such fine control is also mandatory in cartesian space for fine positioning and orienting of end effectors (hands, feet, head, others...). This is now very common practice with Inverse Kinematics (further noted IK) [7][5]. Furthermore, the animator needs interactive specification and a fast response system to work within an efficient "look, feel and adjust" design loop. Such requirements discard language-based interfaces in this context [8][9]. Commercial systems now integrate these techniques and design requirements on standard graphic workstations, allowing to handle 3D human figures with usually around 30 DOFs.

Although impressive results have been obtained with optimization techniques [10], [11] they still face severe computation costs for such high dimension of animation space. As appears on Figure 1, the second limitation of that technique comes from the insufficient amount of animator control over the resulting motion. A recent advance in that field [6] improves these two aspects by combining the optimization with the keyframe technique:

- the animator has a greater control by specifying keyframed postures, eventually with their associated key time, as constraints. It is also possible to specify higher level constraints as velocity of the center of mass or any end effector.
- the type of in-between interpolation is fixed, so it remains only the first derivative at each DOF and the time of most keyframes to be optimized thus greatly reducing the computing cost.

Perhaps the most difficult problem faced by this approach, in term of designer control, is how to express the objective function in order to reflect the character’s intentions and mood, i.e. what makes the character looking *alive* while performing a desired motion.

This is a general problem also faced by more standard techniques (IK, Dynamics, functional models as walking, grasping, etc...). At the moment it is solved by sampling the resulting motions into keyframe motions and use the various techniques available at that bottom level of representation [12] [13]. Figure 1 has put the Live Recording technique at the top of the scale as providing the most realistic motions while, at first sight, freeing the animator from any intervention. Indeed, recording the motion from a performing actor allows to capture its natural dynamics along with the subtle attitudes and motions that are so important to convey the underlying message of the shot [5]. On the other hand, it seems that this technique transfers the responsibility of the character design from the animator to the actor. In fact, the actor usually does not match the skeleton features of the virtual creature. Even in case of ideal measurements, this technique still induces significant work of the animator after converting the motion into the standard keyframe representation. So, in short, it provides both the realism and the design freedom. This explain why the Performance Animation approach has been widely adopted in the film production context [14][5]. We now explore more technically the limitations preventing a larger acceptance.

2.2 Live recording techniques are still too “superficial”

Most of the Performance Animation systems dedicated to the recording of human body motion belong to two groups depending on the sensing technologies they rely on, either optical or magnetic. Both allow the real-time registration of the human motion, practically speaking from around 20Hz to 100Hz for magnetic, and from 50Hz to 200Hz for optical. Although the optical technology is also suited to record the hand motion, dedicated devices are proposed which are discussed in section 4. An extensive discussion about their relative merits can be found in [14]; we just recall here the major facts :

- both approaches place the sensors on the external surface of a human performer
- the magnetic technology provides the position and orientation of sensors while the optical technology provides the 3D position of reflective markers.
- real-time display is only possible with the magnetic technology ; the motion can be adjusted as a live action shot (real-time applications are discussed in section 4).
- free movements in large areas are better performed with the wire-free optical approach. The disadvantage comes from possible line-of-sight problems.

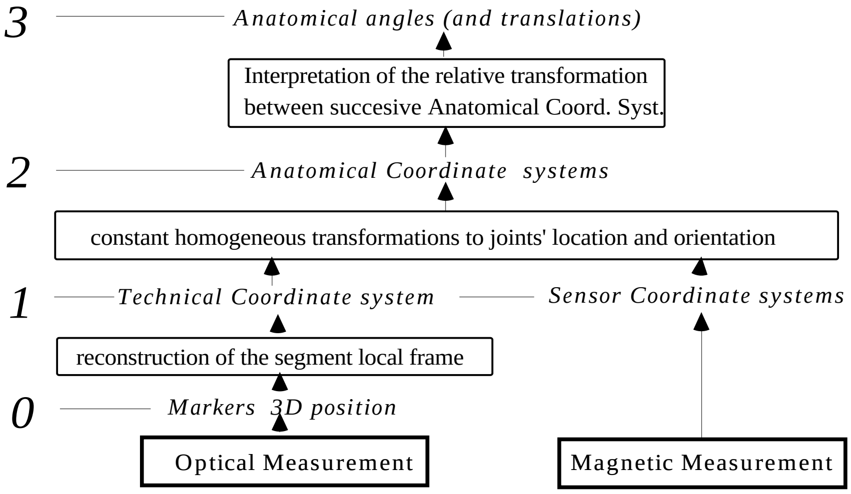

Fig. 2: The live motion recording process with Performance Animation systems

From the first point we can state that the measurement is "superficial" and this has essential consequences for its use. Figure 2 recalls the general process of translating the raw 3D trajectories into anatomical joint angles trajectories (based on the methodology of clinical motion analysis [15][16]). We can distinguish three fundamental transformations through the different levels of information :

- constructing the so-called *technical frames* associated with the body segments from the raw 3D position of at least three *markers*.
- locating the *anatomical frame* at each joint of interest by applying a rigid transformation from the *technical frame* (or magnetic *sensor frame*)
- deriving the *anatomical angles* from the relative orientation between *anatomical frames* belonging to successive segments at a given joint.

At this time, the animated character calibration seriously hamper the effective reflection of the performer's motion, generating uncertainties at the three processing levels :

- The rigid segments assumption is weak due to the deformation of muscles and the dynamics of human tissues(see [17][18] for comparative measurements).
- The performer's skeleton parameters are difficult to identify, inducing inaccurate positioning of the technical or sensor frame relative to the anatomical frame. Using bony landmarks is convenient but subject to errors (see [19] for the hip joint or [15] for the knee).
- The Biomechanics of the human joints should be reflected in the virtual character as well. It is rarely the case as real joints often exhibit complex behaviors as integrating translation DOFs, varying axis of rotation, non mutually perpendicular axis, etc... (see [16] for the knee joint).

All these factors alter the realization of the cartesian constraints effectively performed by the real actor, e.g. the animated character body may exhibit various self-collisions and external collisions (foot into floor, etc...) or, conversely, no more realize some important contacts (hand in hand, hand on face etc...). Moreover, in some cases, the imaginary character may have no real performer counterpart thus amplifying these artifacts.

As a conclusion, the animator is still left a large responsibility in the editing of motion coming from Performance Animation systems. There is also a need to improve motion editing methods in order to enforce the cartesian constraints lost in the acquisition process while retaining the initial motion dynamics [20] [12]. Recent advances in motion signal processing are also worth mentioning in that respect [21] [13]

3 The interactive simulation environment

Apart from the wide range of commercial systems providing interactive response time for the purpose of animation design, we can consider here the systems dedicated to human factors evaluation, ergonomics, human behaviors studies and autonomous agent simulations. In this paper we focus only on this second class of systems. It is more rooted in robotics as the desired result is more quantitative than in the production class of application. In that context the realism is more a matter of conformance with the situations potentially faced by populations of future users of public environment [22], working place or device [23]. Recent advances focus on extending the human model to allow a larger autonomy of the virtual human agent. In the ESPRIT project HUMANOID II, the perception faculties of vision, audition and general collision detection are basic features of the human model [24]. Modeling the perception of balance is also very useful for motion design as developed later [9] [25].

In the interactive simulation context, a large use of functional models is made to access to a higher level of specification and control of the human motion [9] [26]. Such motion modeling is usually kinematic due to its low computation cost. As such it may lack the realism requested for full believability. However, it is the price to pay for the flexibility, the higher levels of control and the longer duration of simulation. Compared to the production context where one has to pay a high price for a high quality live recording of says, a single walking motion, we have here models providing flexible and infinite duration of a walking motion at low cost. Although the resulting motion is less artistic, it remains nearly as realistic as a recorded one in term of space, time and phase characteristics [27] [28] [29]. The same remark is globally valid for other classical functional models as grasping [30] or general goal-oriented motion with IK [31] and general balance control with Inverse Kinetics [25] [7]. Regarding the evaluation of behaviors in complex environments, the language-based interface now becomes a suitable approach to structure the functional models activation resulting in a higher level plan similar to robots task planning [9].

The balance control is a fundamental problem in realistic human motion design as human subjects perform a large class of motion while standing in equilibrium on one or two feet. Inverse Kinematics is not suited to handle that problem as the mass distribution information is not integrated in the kinematic jacobian [9]. Conversely, Inverse Kinetics evaluates the exact influence of each joint on the displacement of the total center of mass [25]. An equally important property of this technique is the ability to combine it with goal-oriented motions (defined with Inverse Kinematics) in a hierarchical fashion [7]. Such tool can of course be used to design realistic postures later used as keyframes in a production context.

An important issue in that context is the management of the transition between successive actions. This is generally made with the ease-in and ease-out technique realized with simple cubic steps. Such approach is used in games where realistic prerecorded animation sequences, possibly with performance animation systems, can be combined on the fly to provide fluid behaviors [5]. Some interesting generalization of the transition management between multiple postures have be proposed to define simple behaviors that can also be used in real-time applications [32]. Basically, a set of postures is structured in a so-called Posture Transition Graph defining which posture can success to which posture with associated transition conditions. The technique has been applied to model a simple soldier behavior with postures as stand, squat, kneel on one knee, kneel on both knee, supine, crawl and prone.

Another branch of these systems focuses on the study of group and population behaviors for security assessment of public environments. This branch has begun with simple flock of birds and animal herds behaviors and now turns to simulate believable human behaviors in complex environments [22]. The theoretical background behind complex behaviors involving multiple agents are grounded in AI studies with recent applications to group behaviors of mobile robots [33]. In the human simulation context we clearly need either language-based or finite state automata structuration to represent complex behaviors emerging from the interaction of elementary behaviors. Intended applications are scenario testing in multimedia applications and games with multiple human models.

4 The real-time simulation environment

The real-time simulation environment fully integrate the end-user within the animation loop in order to drive strategic simulation parameters. In that context, only very small system lag is acceptable in response to user input. So human motion control shrinks to :

- the playback and combination of prerecorded realistic motions (Cf. section 2) according to a scenario integrating user generated events (games [5]).
- the use of Inverse Kinematics [34], functional models [35] and posture-based behavioral automata [32] (Cf. section 3)

In some highly sophisticated real-time environment the system can integrate a real-time performance animation system to either simulate a virtual character interacting with the end user (interactive TV or real-time production environment [14]), or to simulate the virtual body of the operator in the virtual environment [34], or to have bi-directional interaction between operator and virtual character in the virtual world [36]. The techniques used there are the magnetic sensor technology (Cf. section 2), the real-time image analysis [36] and various dedicated approaches to measure the hand posture with digital gloves. The use of digital glove for real-time production of character animation is called digital puppetry for two reasons :

- the interaction metaphor is close to puppetry as the movement is measured on a articulated structure (the hand) rather different from the controlled one (the character) thus requiring some adjustment on the part of the performer [14].
- only simple characters can be animated in such a way due to the limited number of measured DOFs (even if more than one puppeteer are coordinating their performance, one usually animates the body while the other one animates the face).

At the moment very few real-time simulation environments integrate the full human body representation for an operator immersed and interacting with a virtual world [34] [35]. Most VR applications limit the representation of the operator to the display of the hand posture when wearing a digital glove. Even in that limited context it can be desirable to automatically alter the displayed hand posture in order to reflect the virtual hand interaction with the virtual objects [37]. In such a way, the operator gets a feedback about the relative position of the hand-object system and is able to perform grasping with a higher efficiency.

5 The HUMANOID environment

The HUMANOID environment is dedicated to the development of multimedia, VR and CAD applications involving virtual humans [26]. This environment integrates highly heterogeneous components such as the environment model, the humanoid model and various motion generators. Among others, it supports the TRACK application providing :

- interactive manipulation of multiple humanoids on standard SGI workstations
- skin deformation of a human body, including the hands and the face
- collision detection and correction between multiple humanoid entities
- keyframing, inverse kinematics, dynamics, walking and grasping

In TRACK the motion designer can generate sequences with high level functional models as walking [27] and grasping [30] [38] and later refine or blend them at the lower keyframe level (figure 3) [12]. Inverse Kinematics is also one key component of the system especially regarding the ability to perform goal-oriented motion with grasped objects. Owned to the hierarchical nature of its solution [7], we can integrate secondary behaviors which significantly improve the realism of the resulting motion. In this paper we especially focus on two major design issues:

- integrating self-collision avoidance and gravity optimization with IK.
- combining IK and keyframe for goal-oriented motions with grasped objects.

Self-collision is difficult to avoid when the goal-oriented motion is close to the body as can be seen on figure 4a,b. With standard Inverse Kinematics the end effector usually performs a collision-free trajectory as it is directly specified by the animator (in figure 4a, the hand first grasps the sphere and then moves to the target on the left of the body). The self-collision occurs frequently with unused end effectors [39] or intermediate segments of the articulated figure (figure 4b).

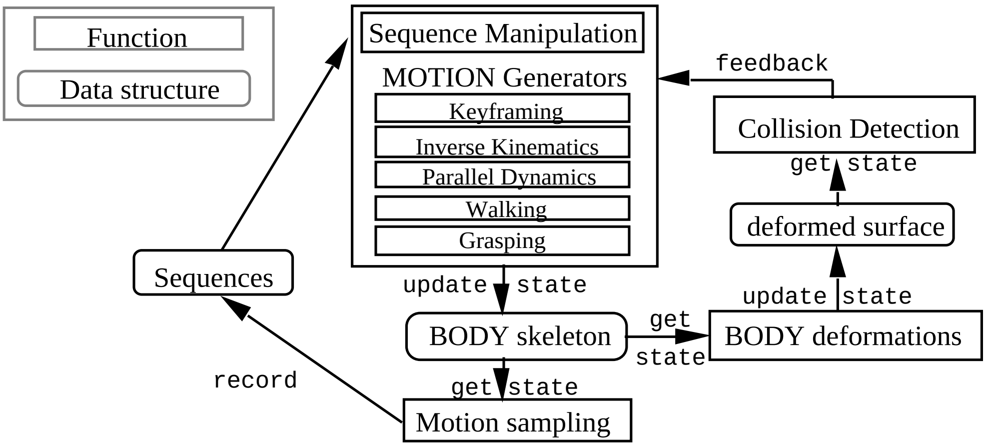

Fig. 3: The System Control Flow of TRACK

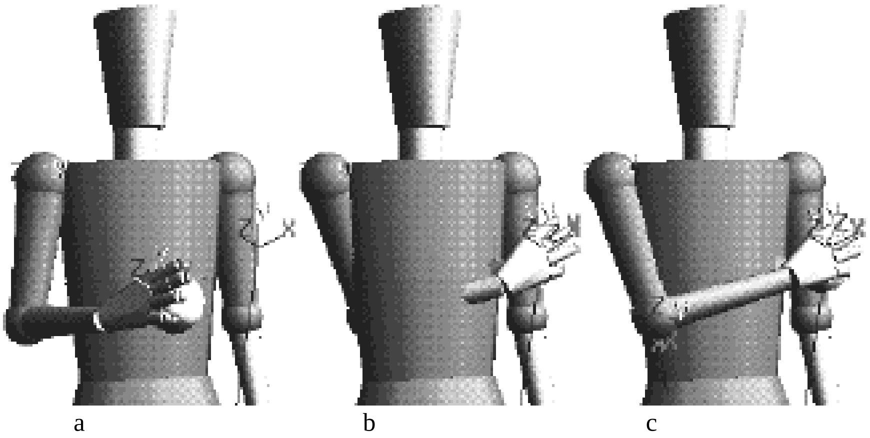
a b c

Fig. 4: moving the hand without (b) and with (c) self-collision avoidance

For that problem, we propose to generalize an approach introduced in Robotics for articulated robot arm [40] thus freeing the animator from tedious adjustments in such context. In our approach, spherical sensors are placed at strategic location of the body and they generate a correction displacement when entering into other body parts (as the elbow sensor in figure 4c). The displacement is realized as an automatic secondary behavior of the Inverse Kinematics solution [7]. It is achieved, for each step of the end effector behavior, in a two stages process :

- construction of each sensor’s kinematic jacobian which is inverted and multiplied to the correction displacement to get the correction posture variation of the character.
- the sum of the correction posture variations due to all the sensors is projected on the null space of the end effector behavior thus not disturbing its realization [7].

That correction process may have to be repeated a few iterations before converging as its priority is lower than the one of the end effector. Moreover, if there are multiple sensors the final solution is a compromise providing the smallest collision among the sensor set.

In fact, our approach is very general as it can be applied to avoid any collision, including with the environment, or to simulate the gravity as presented now. The gravity effect on a human being is to generate torques that the human being has to counter balance in order to maintain a given posture. For this reason a real human being naturally adopts the postures inducing the best comfort for a desired behavior [41]. Designing such natural postures requires a great experience from the animator.

We propose to use the same principle as for the secondary behavior of collision avoidance. In the present case, we automatically define a desired constant downward displacement for the sensors. The displacements are only partially realized as they belong to the secondary task. So the control converges to the posture realizing the main behavior with the least gravity torques (figure 5).
The gravity and collision avoidance can be added thus automatically producing realistic postures as a background behavior.

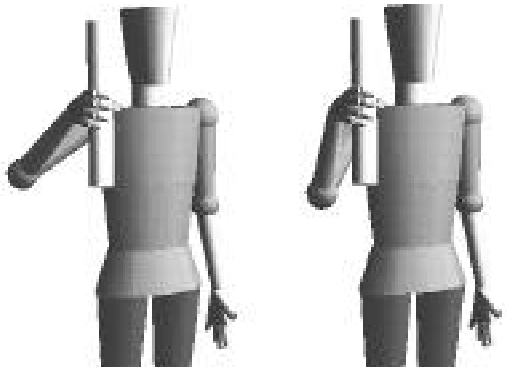

Fig. 5: applying the gravity secondary behavior

The second issue we want to highlight here is the interest of specifying the body motion from keyframed motion assigned to grasped objects. A large class of human behavior is related to the manipulation of manual tools and mechanical devices. It is often easier to specify the desired motion on these objects as they are designed to perform a specific function associated with a limited set of positions and/or orientations in space. So, we propose to set keyframes on these objects rather than on the human end effector. Combined with the Grasping function and Inverse Kinematics, we are able to obtain a coherent resulting behavior by applying the following algorithm :

- First, apply the full grasping process for the object in the initial keyframe [30], this includes the selection of the grasp, the first guidance of the hand with IK and closing of the fingers on the object [38].
- Then, for each time step of the keyframe sequence associated with the object :
  - move the object independently of the articulated figure
  - attract the hand frame to the new object location with IK
  - adjust the hand closure to the new relative position

Two examples illustrate that approach. In figure 6 two keyframes have been defined for the hammer which is used to guide the right arm motion. In figure 7 we show a two hands grasp of a turning wheel. Again the keyframes are easier to specify on the object itself.

Fig. 6: goal-oriented motion with a grasped object (hammer) with one hand

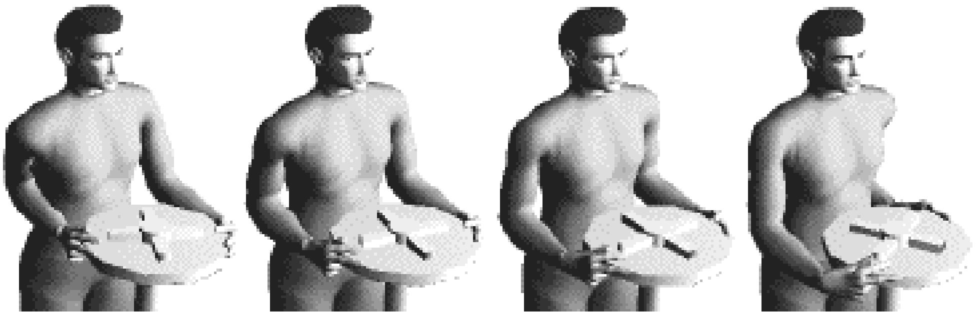

Fig. 7: turning a grasped object (wheel) with two hands

6 Conclusions

We have reviewed the various strategies used to animate 3D human characters by grossly classifying them in three classes of compromise between the requirements of motion realism and real-time interaction. When scanning these different classes of applications, the end-user profile gradually changes from the film production animator to the human behaviors analyst and finally to the Virtual Environment operator interacting with virtual humans (they all are referred as viewers in the following lines). Real-time animation of 3D human motion with convincing realism and high interaction with the viewer is far from now. The viewer has the natural skill of detecting a synthetic motion, or the synthetic mixing of recorded motions, or a synthetic display of a motion performed in real time by partners in virtual worlds . On the other hand, some class of viewers can accept the imperfection of the displayed motion, whatever the production tool, if it allows a greater interaction.

The design strategies for 3D human motions have been the object of important researches since the beginning of the 80s. Now and for the years to come, the considerable interest which has supported them is still raising as the computing power only begins to allow convenient handling of these classes of problems. However, according to productions standards, we predict a slow improvement in the direction of designing more *lively* animations out of scratch. On the other hand, more motion manipulation methods are emerging thus soon allowing a greater reusability and generalization of recorded material. Moreover, significant advances are soon to emerge in the direction of autonomous agents reacting to each other and to their environment. As a consequence these results should directly benefit to real-time simulation environments. So, if one can accept to still distinguish the real from the virtual motions and behaviors, we think that the great challenge of cooperative work between operators and virtual humans is a reasonable objective for the five years to come.

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