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Survey

Computer animation: from avatars to unrestricted autonomous actors (A survey on replication and modelling mechanisms)

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Abstract

Dealing with synthetic actors who move and behave realistically in virtual environments is a task which involves different disciplines like Mechanics, Physics, Robotics, Artificial Intelligence, Artificial Life, Biology, Cognitive Sciences and so on. In this paper we use the nature of the information required for controlling actors' motion and behaviour to propose a new classification of synthetic actors. A description of the different motion and behaviour techniques is presented. A set of Internet addresses of the most relevant research groups, commercial companies and other related sites in this area is also given. © 2000 Elsevier Science Ltd. All rights reserved.

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1. Introduction

Computer animation technologies allow users to generate, control, and interact with life-like representations in virtual worlds. Such worlds may be 2D, 3D, real-time 3D, or real-time 3D shared with other participants, and the actors can be given the form of humans, animals, or animate objects.

Increases in computational power and control methods enable the creation of 3D virtual characters even for real-time interactive applications. Developments and advances in networking and virtual reality let multiple participants share virtual worlds and interact with applications or each other. Artificial intelligence techniques give computer-generated characters a life of their own and let them interact with other characters in virtual worlds.

In the more basic approach the synthetic actor can be seen as a remotely controlled puppet engaged in fictitious interactions with a simple virtual world. As synthetic actors are placed in simulated worlds of growing complexity, an obvious requirement that comes about is to make them perform in these worlds. Advances in computer animation techniques have spurred increasing levels of realism and virtual characters closely mimic physical reality and typically draw upon results from physics, biology, and the cognitive sciences. Maybe they will soon be indistinguishable from real characters.

The aims of this paper are to propose a new classification of synthetic actors and to go through the different motion and behaviour techniques used to animate them. In Section 2, we propose the classification and introduce the techniques. Section 3 deals with motion and behaviour replication, Section 4 with motion modelling, Section 5 with behaviour modelling and finally, some reflections are presented. Some Internet addresses of relevant research work groups and other interesting related links can be found in the Appendix.

2. Classifying synthetic actors

Several methods exist for classifying animation systems and synthetic actors [1–3]. In this paper we use the

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nature of the information required for controlling actors' motion and behaviour to propose a new classification of synthetic actors. Two primary mechanisms exist to specify motion and behaviour for a synthetic computer-generated character:

- Replication mechanisms that reproduce the motion or behaviour of a real actor.
- Modelling mechanisms where the motion and behaviour are based on an algorithmic approximation.

Depending on the kind of mechanism chosen, data obtaining can be carried out in real time or not. Its subsequent exploitation can likewise be carried out in real time or not depending on the type of application, independently of the obtainment method.

The replication of the motion requires the capture of data from real actors. Depending on the available equipment we may obtain a little set of key positions or a continuous stream of data. In the first case, we will use key frame techniques and in the second one the data is obtained using the technique called rotoscopy, which consists in recording input data from a virtual reality device in real time. On the other hand, motion modelling is based on different algorithmic techniques themselves based on physics, or on intelligent heuristic methods such as genetic algorithms, finite states machines, etc.

The replication of the behaviour of the character must use sensory input whereas the modelling of the behaviour provides the actors with a manner of conducting themselves based on perceived information. The actors' behavioural mechanism will determine the actions they perform. Actors may simply evolve in their environment, interact with this environment, or they can communicate interactively with other actors and real people. The techniques used have evolved from the initial perception-action schemes to artificial life complex methods.

The different techniques that can be used to replicate or to model both motion and behaviour are summarised in Table 1. According to this point of view, a strict classification falls into the next four categories:

Pure avatars or clones. Use replicated motion and behaviour. Clones must look natural and their animation is achieved by replicating movement and behaviour. For that clones are equipped with virtual sensors whose data are obtained from real actors through the rotoscopy system. Synthetic actors in live television shows could be possible examples.

Unrestricted dependant actors. Use modelled motion and replicated behaviour. Guided actors require a moving motor although their behaviour is driven by a real actor. A synthetic character in a film could be a possible example.

Autonomous actors. Use replicated motion and modelled behaviour. Typically, the virtual actor should perceive objects and other virtual actors in its environment through visual, tactile and auditory virtual sensors.

Table 1
Motion and behaviour replication and modelling techniques

Motion replication	Key-framing Motion capture or rotoscopy
Behaviour replication	Key-framing Motion capture or rotoscopy
Motion modelling	Direct/inverse kynematics Direct/inverse dynamics Genetic algorithms Sensor/actuator networks Finite-states machines

Behaviour modelling	Perception and action
	Software agents and artificial life
	  Rule-based systems
	  Fuzzy logic systems
	  Genetic algorithms
	  Expert systems
	  Neural networks
	  Action selection

For communication between virtual actors and real people, behaviour may also depend on the actor's emotional state. A synthetic character in a game could be a possible example.

Unrestricted autonomous actors. Use modelled motion and behaviour. They are similar to autonomous actors but they do not have motion restrictions imposed by nature or by practical considerations. A synthetic character in an advanced simulator could be a possible example.

3. Motion and behaviour replication

3.1. Key-framing

In the animation systems based on *keyframing* the animator specifies the system's kinematic by means of giving the parameter values in the key-frames. In-betweenings are calculated by the computer applying an interpolation law that can be linear, constrained to a mobile point [4], based on splines [5–7], or on quaternions [8–10]. In these schemes, control over animation is total. Nevertheless, if the number of parameters is considerable, motion specification becomes a tedious task (for instance, if we want to animate a human, even with a very simplified model with 22 links, more than 70 parameters — angles and references — have to be specified in each frame). Furthermore, the motion obtained can move away from real one. Most commercial animation packages make extensive use of in-betweening.

3.2. Motion capture and rotoscopy

Techniques based on live *motion capture* [11–13] or *rotoscopy* form this second group. These techniques are now being extensively used for body motions as well as for facial expressions and speech, and have given rise the development of new editing methods to treat recorded motion. They reuse and adapt captured motion and use different algorithms such as:

- multiresolution filtering to personalize motion, multi-target interpolation and smoothing techniques for motion concatenation and blending [14,15]
- displacement functions [16]
- Fourier developments on experimental data to add emotions to previously captured human motion [17]
- motion warping [18]
- contour tracking in multiple images [19], facial expressions analysis for virtual conferencing [20].

4. Motion modelling

4.1. Direct and inverse kinematics

Direct and inverse kinematics are used to develop algorithms for generating complex motion, such as human walking and different animal movements. These systems are based on biomechanical and biological studies. Instead of specifying positions, the animator specifies parameters that condense the essence of the motion and allow its individualization. In inverse kinematics, if the position of the final effector (open chains) is given, the calculation of the intermediate links is automatic [21]. The kind of equations these systems work with is highly non-linear; therefore, specific techniques have to be applied. Two different methods to solve the problem can be distinguished in inverse kinematics systems:

- the Jacobian
- non-linear programming techniques

As examples of the first group, we should mention:

- Girard and Maciejewski [22] develop a general model for legged locomotion in their PODA system.
- Boulic, Magnenat-Thalmann et al. [23] also propose a human walking model. Later, they propose a combined inverse/direct method that allows them to use pre-recorded motion as reference motion and to add user motion restrictions as a secondary task to be accomplished [24,25].
- Mas-Sansó and Thalmann [26] develop an algorithm for automatic grasping for a system that works with synthetic actors. It is based on a grasping taxonomy and both direct and inverse kinematics are used.
- Bruderlin et al. [27] characterize human walking both with locomotion parameters (forward velocity, step length and step frequency) and 15 attributes that personalize motion. This motion generator is the one used in the general-purpose system for human animation "Life Forms" [28]. They also consider the grasping problem, where inverse kinematics are very useful to position shoulder, elbow and wrist once the hand is placed.
- Mas-Sansó, Boulic and Thalmann [29,30], introduce the term *inverse kinetics* to express the combination of joint kinematics and mass distribution.

As an example of application of non-linear programming, we can mention the Jack system for animation of human figures developed in the University of Pennsylvania. The non-linear equations are solved by means of a potential function that measures the distance to the target position. Non-linear programming techniques help them to minimize the function [31].

4.2. Direct and inverse dynamics

It was the search for realism that led animation to *physically based modelling* [32], which has made possible to consider natural phenomena when applying simulation techniques. In the simulation process, objects become masses with forces and torques acting on them. Motion arises applying the laws of Classical Mechanics. Therefore, the term simulation is frequently used instead of animation. Compared to purely kinematic ones, dynamic simulations have the advantage of giving great realism and reacting automatically to the environment (collisions, inertia, etc.). On the other hand, they pose other problems such as the control of the animation and the high computational cost needed to generate them.

Mechanical simulation does not work only with articulated rigid objects but also with:

- Deformable objects [33–36]. With the apparition of systems which work with synthetic actors, the interest in human body deformations [37–39], including facial ones [40,41], and in cloth deformations [42–49] has increased.
- Particles models [50,51]. These models have been intensively used to treat certain natural phenomena such as water [52–56], smoke [57] and fire [58,59].

There are two different approaches when using dynamics:

- *Direct dynamics*, where forces and torques are known and motion is obtained with minimal control over the system. Once initial conditions are given, the system evolves "alone". It fits passive systems, without internal forces and torques.
- *Inverse dynamics*, where motion is known and forces and torques are unknown and computed. It is best suited to motor systems which convert internal energies to time-dependent forces that produce their own motion. Here, the problem is the lack of realism: arbitrary motion without physical foundation can be generated.

Different formulations have been adopted to obtain motion equations [60]: Newton–Euler [61], Lagrange

[62,63], Gibbs–Appell [64], D'Alembert [65]. Once the equations have been stated, there are two resolution schemes:

- *Systems solved by integration*. A numerical resolution system integrates the equations in each time interval moving forward in time. Systems of this kind are those of Barzel and Barr [66], Wilhelms [64,67], Raibert and Hodgins [68] and Liu et al. [69]. Isaacs and Cohen [70,65] use a mixture of direct and inverse dynamics with kinematic constraints and behaviour functions, Hodgins et al. [71–73] use the simulation to generate human motion (running, cycling, jumping or swimming) and Lamouret and Gacuel [74] use direct dynamics to simulate a trajectory constrained to a user-defined one.
- *Systems solved by non-linear optimization*. Witkin and Kass [75] introduce the *space time* concept, to refer to all the forces and to the values of all the degrees of freedom from the beginning to the end of the scene. The system automatically generates paths which have to fulfill objectives, mechanical laws (which are considered another type of constraints that tie forces and displacements) and minimize some functions (such as energy, softness, efficiency, etc.). This method is computationally expensive and non-linear optimization techniques have to be used. Systems of this type are those of Cohen [76], Cohen and Liu [77] which is an hybrid method between key-frame animation and optimization — and Liu et al. [78] that have proposed the use of a hierarchical representation using wavelets for the functions which represent the temporal evolution of the generalized degrees of freedom.

The search for a real-time response has motivated the study of different simplifications in the dynamic models. There are different approaches. The *recursive algorithms* suppose a relationship between forces and accelerations of consecutive joints, so that they do not have to simultaneously solve all the joints but will do it in a recursive manner. Some implementation examples of this type of algorithms in computer animation systems, can be found in [62,63], [79–81]. Other simplifying ideas are to consider some degrees of freedom kinematically driven through paths and leaving the others to the dynamic simulation (see [82], for example) or to develop a distributed algorithm that tries to increase the motion generation speed by means of the use of *parallelization techniques* [83].

4.3. Genetic programming algorithms

The results of these techniques [84,85] are control programs [86]. They need some starting variables and functions, a fitness function to measure individual fitting, a termination criterion and the number of individuals per generation as well as the maximum number of generations. It is a kind of artificial evolution in which only those individuals who accomplish the requirements survive [87]. Systems of this kind are those of Ngo and Marks [88,89], Auslander et al. [90] and Sims [91] who uses these techniques to obtain not only motion but also morphology of creatures.

4.4. Sensor–actuator networks (SAN)

Braitenberg [92] planned some "thought experiments" using a balanced network of different kinds of nodes in order to demonstrate the possibility of obtaining intelligent behaviour. These ideas have been used by

- Wilhelms and Skinner [93] who work with solids capable of moving through 3D space. Combining sensors, effectors, arcs and nodes with adequate connections they generate quite interesting movements with a very little input information from the animator, using a network paradigm.
- Van de Panne and Fiume [94] automatically synthesize the network. The user introduces the mechanical configuration of the system, augmented with some simple sensors and actuators. The system computes different forms of motion for each configuration. The searching process is stochastic. Van de Panne M. and Lamouret [95] in order to reduce the searching space and to obtain balanced motion apply an external *momentum* to ensure a straight position during human locomotion (later on this momentum is eliminated).

4.5. Finite-state machines

Tmovic and McGhee [96] suggested the application of automata theory of finite-state to the analysis and synthesis of engineering systems. This theory has also been applied to animation-systems:

- Zeltzer [97,98] models each joint controller as a finite-state machine. Over these machines, there are another ones (for each limb, for example) whose states are combination of the former ones. The motor program (for walking, for example) is also a finite-state machine whose states are made from local motor programs (LMPs) that have to be concurrently executed. The local motor control program accedes to the joints by changing parameter values.
- Laszlo et al. [99] use finite-state machines with PD controllers to generate an open-loop basic movement that is later disturbed to obtain stability.

5. Behaviour modelling

A clear difference between physically based modelling and behaviour-based modelling has to be made, although sometimes both techniques are complementary. Physically based modelling, as it has been stated in the previous section, emphasizes on realistic aspects like elasticity, deformation or collision, as can be sampled in hair or clothes modelling. Behaviour-based modelling covers those internal aspects, some not yet well developed, like personality, social differences, perception or reaction. Concepts like *synthetic* or *autonomous actors* and *behaviour modelling* start to crystallize by end of 1980's and beginning of the 1990's. Among the works that have started to define this point of inflexion, the following could be quoted: [97,98,100–102].

The last row of Table 1 shows behaviour modelling techniques that have been used, others which are nowadays being used and those that are starting to be used. In most cases, the final target is to obtain free synthetic actors in not predictable virtual environments. The different behaviour modelling techniques have evolved for some years now. The main changes can be summarized as follows:

- techniques are moving from animations based on scripts (like in traditional animation) to those where scripts are not needed,
- current systems are normally modular and distributed, i.e. suitable for implementation in parallel architectures,
- instead of using artificial intelligence (AI) tools, artificial life (Alife) elements are being introduced in behaviour modelling [103],
- a structure has been created where low levels of animation (motor skills), high levels of animation (behaviour skills) and even other intermediate levels can be distinguished,
- actors tend to be *autonomous*, *adaptive* and to have *learning skills*,
- a complex behaviour emerges from simple behaviour's combination.

At this step the first papers devoted to behaviour modelling appear. The work of Reynolds [104,105] is the first important step in incorporating *behaviour* and *autonomy* concepts to classical computer animation systems. He proposes a "bottom up" approach and designs a system where a global and complex behaviour emerges from a combination of several simple individual behaviours. Reynolds obtains synthetic flocks of birds, where the birds avoid crashing among them, maintain a constant velocity and remain within the flock. The animation he produces shows clearly these characteristics (see Fig. 1).

Another pioneering work in creating synthetic actors which is done by Magnenat-Thalmann and Thalmann [106], is the "Human Factory" animation system, designed to reproduce synthetic actors who play the role of famous stars already deceased, like Marilyn Monroe or Humphrey Bogart. Through their work, they provide solutions to model the skeleton and the body of the actors, and they focus on simple behaviours like grasping or expressing emotions through the face. They conclude that the key features to obtain and use synthetic actors would be:

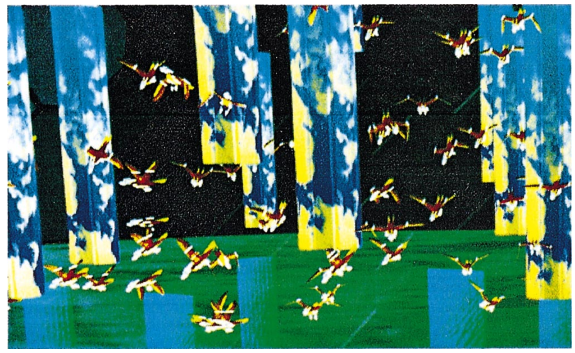

Fig. 1. A still from a preliminary version of 'Stanley and Stella in Breaking the Ice' produced around January 1987 (final version was July 1987). The simulated flock of birds was produced using the boids model by Craig W. Reynolds [104,105]. The animation was produced by a large team from Symbolics, Inc and Whitney/Demos Productions.

- To provide the actors with some knowledge about their environment.
- To control their behaviour with an adequate level of abstraction.
- To improve the quality of rendering for the animations.
- To implement quick and reliable systems to design the actors physically.

5.1. Perception and action

Lethbridge and Ware [107] present an animation system based on stimulus–responses. They state that when an animated sequence is done the actors are forced to behave as organisms responding to stimulus in their own local environment. The essence of the method is to "show" each actor how to behave within the environment and with each other. Maiocchi and Pernici [108] present their computer animation system Pinocchio, which incorporates the ability to create an animation sequence with none or very little direction from the animator. As in movie making, where the director gives general instructions to the actors who express the details of how to act in the scene by themselves, the system allows the animator to specify the global scene, the restrictions and the different objects or actors in the scene (in terms of scripts). Co-ordination issues are solved autonomously by the actors through message passing.

Wilhelms et al. [93] state that behavioural animation is a means for automatic control motion, where the objects or actors to be animated are or should be able to feel or perceive the environment and to decide their own movement following some rules. They describe a system where a network with sensors as inputs and effectors as outputs connected by arcs and other nodes is responsible for the motion of objects (see sensor–actuator networks in Section 4.4). They conclude that the future computer animation systems will have to combine low level techniques (like locomotion) and high level techniques (like interpretation or behaviour) in an intelligent fashion.

The work done by Haumann et al. [109] is also very interesting. They present a computer animation system where a complex movement is a result of the simulation of simple behaviour rules between locally related actors. Their object-oriented system is based on a message passing mechanism. They are working to provide the actors with not only physical behaviour, but also with other behaviours that may express social or personal aspects.

Zeltzer et al. [110] present an application with a perception-action approach. They describe an animation system composed of two different levels that cooperate. A *sensor-motor level*, the low level, is responsible for the locomotion of an actor (a synthetic insect) using mathematical oscillators (rhythm), reflexes (feedback from spatial restrictions) and kinematic laws (already seen in the previous section). The reflexes behave like sensors, detecting holes or obstacles, and reacting to them. The oscillators define coordinated gaits that control locomotion of the six legs of the virtual insect, offering stability in motion according to the situation. A *reactive level*, the high level, interprets the environment in order to decide the actions that the low level should carry out, like setting speed or choice of direction to move in. From that moment on, several works arise where different techniques are used to obtain actors with behaviour and autonomy. Most of them are based on artificial intelligence tools, intelligent agents theory and artificial life new paradigms.

5.2. *Software agents and artificial life-based systems*

We will now outline some of the more relevant and innovative works on behaviour modelling for computer animation based on new techniques coming from Software Agents and Artificial Life domains. More details can be found in [60,111,112]. Fig. 2 shows an example of virtual humans in a virtual environment.

5.2.1. *Intelligents agents-based systems: production rules, fuzzy logic, genetic algorithms*

Calvert et al. [113] develop a computer animation system to model behaviour, using the last advances in expert systems and knowledge engineering. Their approach uses a control structure of several agents, which interact through a reasoning process that uses an inference engine. Beardon et al. [114] propose a similar schema, using a production rule system to incorporate behaviour to computer animation. Cremer et al. [115] define a methodology, split in several steps, to create a virtual scenario or environment, and to create graphical simulations within it. When specifying the control of the actors, they propose a control schema which includes co-ordination of different agents, planning and high level behaviours.

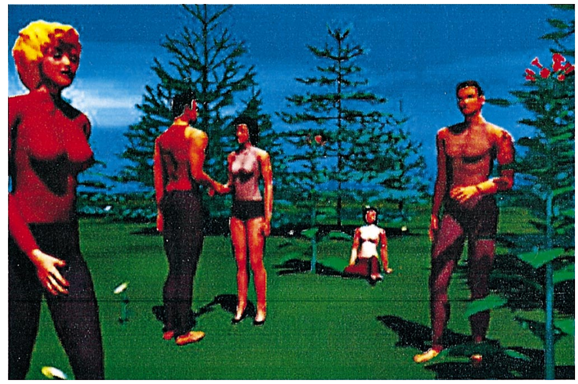

Fig. 2. "Picnic" autonomous virtual humans in a garden, M. Clavien, H. Noser, D. Thalmann, EPFL-LIG, Switzerland.

The research work developed by Pina and Serón [116,117] proposes to use classical Artificial Intelligence tools together with other techniques coming from the Artificial Life field. The goal is to design, first of all, a complex behaviour for synthetic actors, and second, changing scenarios for these actors. In order to make this possible, the actor (principal actor) is provided with decision, learning and adaptation capabilities. These characteristics are implemented using a fuzzy logic-based expert system, a neural network and a selection action algorithm. The dynamic scenario is designed through the use of different objects: static and dynamic objects and extra actors. The latter can be any object, living or not, and have associated genetic algorithms that control their evolution in the scenario.

5.2.2. *Neural networks-based systems*

Beer et al. [118–121] define the concept of *computational neuroethology*, on the basis of the fact that animals with simple nervous systems give rise to complex behaviour when they try to adapt themselves to a changing environment. They apply this principle to an artificial hexapod insect, showing a 2D graphical simulation of its behaviour and they also applied it to Robotics [122]. For the simulation, they use a set of simulated sensors, which allow it to know the state of the body (leg position), and the environment (food, other objects or energy). The possible behaviours are locomotion, turning, wall following and eating. The whole framework is based on a

Neural Network where the nodes are neurons and the connections are activatory or inhibitory, and the resulting behaviour is the imitation of an insect with a simple nervous system.

5.2.3. Action selection mechanisms

Maes et al. [123–125] present a general schema for model behaviour, which can be applied to several fields, including Robotics and Computer Animation [126,127]. Their work has been a constant reference and a source of inspiration for other behaviour modelling systems in Computer animation. The approach uses a *Perception-Action* schema as opposed to other classical approaches, which are based mostly on planning. They propose an Action Selection algorithm, based on current situation and current goals. It evaluates the environment and acts during execution (as opposed to other existing algorithms, which need to be compiled and are therefore much less versatile and do not prove to be dynamic in a changing environment during execution). The resulting system is characterized by a behaviour network in which each node represents a concrete behaviour. Inside the network a constant energy is created, and based on current goals, situations and relations among behaviours, continuous competition between these behaviour nodes is maintained, ensuring correct action selection decisions each time.

The work of Tu and Terzopoulos [128] shows a bottom-up approach, and uses a physical model to design actors (fishes) and an environment for them. The synthetic animal has a locomotion model, a sensory system and a behaviour model. At the lowest level of abstraction a fish is physically based on graphical models. The sensory system is responsible for perceiving a dynamic environment. At the highest level of abstraction, the behaviour system decides at each iteration the most adequate behaviour or action to undertake, and acts as a mediator between the perception system and a motor system. The latter is responsible for the locomotion of the artificial fish.

The work of Blumberg et al. [129,130] focuses on the design of artificial creatures and virtual environments. Although the final goal of these papers is to provide an external direction of actors in real-time computer animation systems, they present a general behaviour model, based on Perception and Action Selection for autonomous animated characters. The schema they propose defines three different levels: perception, behaviour and motor. The main idea is to satisfy a set of goals in a complex and dynamic environment, solving competition between different and/or concurrent goals, to deal with errors or incompleteness during the perception stage, and to avoid dithering between behaviours.

Thalmann et al. have been working on complex systems, which mix virtual reality, computer graphics and animation, specially with the aim to obtain a great realism and to design autonomous Synthetic Actors which imitate human behaviour [45,24,25,102,2,131]. In [132] they present a system, currently under development, which simulates the artificial life of synthetic actors. On the basis of a perception action schema, they implement virtual sensations (vision, tact and audition) and simulate actions in response to this perception like locomotion (leg motion), grasping (with the hand) or "ball in air following" using synthetic vision. The system they present is an interesting alternative in behaviour modelling. It may be a solution to providing an actor with the necessary information to find a path, avoid obstacles, play or interact with other actors and construct an internal representation of the environment, as well as learn or forget the kind of things humans usually do.

The work of Badler et al. [133,134], the creators of the "Jack" copyright, is another example of a Computer Animation system which includes a behaviour model. They propose an agent-based architecture, which presents two work levels. The lowest level is called the sensor-control-action (SCA) while the highest level presents a well defined, but still general, schema: parallel transition networks (PaT-Nets). The SCA produces local and adaptive movement. It consists of sensors, control nodes and actuators. Its basic behaviours are of the "to walk", "to go to", "to look at" type. The Pat-Nets allow the expression of more elaborate behaviour patterns than the previous basic ones. They are in fact automata, able to run in parallel and based on the current state of the environment, the current goal(s) and/or state of the system. The combination of SCA and Pat-Nets produce an adequate schema to define complex behaviour for synthetic actors.

5.2.4. Other techniques and other applications

We would like to mention another computer animation system based on *scripts* [135] which allows creation of autonomous synthetic actors. The IMPROV project is being developed at New York University's Research Media Lab and it uses classical scripts for a given actor. These scripts are divided into groups. Each group contains all the scripts (or behaviours, we might say) that are mutually exclusive, in the sense of not compatible. However, in some cases, scripts belonging to different groups may be executed at the same time (meaning that a particular behaviour may have some scripts working in parallel even if they are contradictory). Furthermore, autonomy is added to the system, by allowing the scripts to have several different conditional executions, each of which has its own probability of success. The actors can also have some special personal characteristics and preferences, establishing their own personality. These attributes allow actors to be provided with criteria to decide the adequate alternative when dealing with such conditional scripts. The overall result is that the system uses conditional scripts in which the solution chosen is based on the criteria and personality of the actors and on the given probabilities. Defining scripts, groups of scripts, personalities, criteria and probabilities, it is possible to obtain actors possessing personality and autonomy. The system is capable of producing different computer animations depending on these parameters and the interaction between scripts, i.e. actors.

Another research area on synthetic actors and virtual scenarios, is the study of theatre and the acting (art) of real actors or characters to apply these principles to the creation of believable synthetic actors. That is the case of Hayes-Roth et al. [136,137], that study the meaning of personality in a context where artificial agents behave like actors. From this point of view, they define concepts like *role*, *behaviour* or *improvisation* for synthetic actors.

Another concern in the design of synthetic actors is the fact that they should be believable, that their behaviour should seem natural and that they have to express emotions and use a natural language to communicate [138,139].

6. Reflections

The content of the present survey presents significant and important developments of computer animation and depicts a dynamic area of research where a number of impressive results have already been achieved and successfully carried over to commercial applications.

Application areas include production animation, interactive computer games, interactive digital television, multimedia products, simulations, computer-supported collaborative work, agents (personalizes information), shared virtual environments, etc.

Convergent advances in computer animation, artificial intelligence, artificial life, virtual reality, and increases in computational power and in networking give a rich variety of computer-generated characters life-like and realistic behaviours.

In this sense it is now possible to provide computer-generated characters with "manifest intelligent behaviour", that is, with the capability to interact with other characters or multiple participants in shared virtual worlds and to respond to perceived environmental situations in a meaningful and constructive way.

Current research directions in computer-generated characters include:

- Generating and controlling synthetic characters in real time.
- Creating characters with individuality and personality who react to and interact with other real or virtual characters to perform complex tasks.
- Creating characters capable of emotional responses.
- Generating population in interactive environments.
- Implementing autonomous virtual actors in virtual worlds based on perception and virtual sensors.
- Altering existing animation to produce different characteristics.
- …

We believe we have just begun to explore the potential of this material, which despite the fact that it may not be sufficient yet, will eventually engage researchers and manufacturers to include this knowledge in standard commercial applications. Consequently, users could and should come to enjoy the same levels of satisfaction as they currently do with other information technology applications.

Appendix A

A.1. Working groups web references

The following are references of research groups, who are actually working on innovative areas of Computer Animation.

MIRALab Research Laboratory in Virtual Reality, Computer Animation and Telepresence, was created in 1989 at the University of Geneva, and is directed by Prof. Nadia Magnenat-Thalmann. They are specialized on Modelling and Animation of Virtual Human Beings (Rendez–vous à Montréal).

http://miralabwww.unige.ch/

The Centre for Human Modelling and Simulation of the University of Pennsylvania directed by Norman Badler. They work on Human Motion Modelling and Animation (Jack). The overall goal of the Centre is the modelling and animation of Human Movement. That central topic guides a number of related research interests covering a broad scope from image synthesis to natural language interfaces.

http://www.cis.upenn.edu/ ~ hms/home.html

The IMPROV project, at New York University's Research Media Lab is building technologies to produce distributed responsive virtual environments in which human-directed avatars and computer-controlled agents interact in real time through a combination of procedural animation and behavioural scripting techniques.

http://www.mrl.nyu.edu/improv

The Computer Graphics Lab (LIG) at the Swiss Federal Institute of Technology (EPFL) in Lausanne was founded in July 1988 by Professor Daniel Thalmann (its director). The laboratory is mainly involved in Computer Animation and Virtual Reality. Together with MIRALab (University of Geneva), LIG is especially well known for the creation and animation of virtual actors like synthetic Marilyn Monroe. Research at the Computer Graphics Laboratory (LIG) is oriented towards the virtual worlds particularly the simulation of real-time virtual humans.

http://ligwww.epfl.ch/

The group managed by Philip D. Stroud in Los Alamos National Laboratory, Technology and Safety Assessment Division, works on the design of intelligent actors for synthetic environments.

http://sgt-york.lanl.gov/homepages/stroud/icdoc/ic1.html

http://sgt-york.lanl.gov/homepages/stroud/icdoc/ic2.html

http://sgt-york.lanl.gov/homepages/stroud/icdoc/ic3.html

The *Virtual Theatre project* aims to provide a multimedia environment in which users can interact with intelligent, automated actors, either in well-defined stories or in improvizational environments. Users themselves become actors by exercising high level control over their own intelligent agents. These agents improvize to meet the user's goals on the basis of their knowledge, personalities and moods.

http://ksl-web.stanford.edu/projects/cait/

The *Oz Project* at the University of Carnegie-Melon is developing Technology and art to help artists to create high quality interactive drama, based in part on AI technologies. In particular, this means building believable agents in dramatically interesting micro-worlds

http://www-cgi.cs.cmu.edu/afs/cs.cmu.edu/project/oz/web/

The *Software Agents Group, at MIT Media Laboratory*, works on developing agents, i.e. computational systems, which perceive, react and behave in dynamic and complex environments. One of their projects tries to create animated actors that live in 3D virtual worlds.

http://lcs.www.media.mit.edu/groups/agents/

At the *University of Georgia the Graphics, Visualisation and Usability Centre* (*GVU*), managed by Jarek Rossignac works on several Research projects involving fields such as Visualization, Computer Animation and Virtual Reality, Collaborative Design, Usability, Multimedia, Cognition, Digital Culture, Internet tools, Education and Future Computing Environments.

http://www.cc.gatech.edu/gvu

The *Graphics and Multimedia Research Lab* of the University Simon Fraser (Canada) has developed the software package LifeForms, an innovative tool for 3D human figure animation, dance choreography, movement planning, game development, Multimedia content creation and education.

http://www.cs.sfu.ca/research/groups/GMRL/projects/lifeforms.html

IMAGIS (Models, Algorithms, Geometry for Graphics and Image Synthesis) is a team of the GRAVIR/IMAG Research Lab. They work mainly in: modelling the physical behaviour of deformable objects: construction, simulation of movement, interactive manipulation, collision detection and response, simulation and control of articulated structures, particles systems

http://www-imagis.imag.fr/

The University of Toronto's *Dynamic Graphics Project* (DGP) is an interdisciplinary research laboratory within the Computer Science Department and the Computer Systems Research Institute. Research areas at DGP span a wide range of interests, including modelling (implicit models and interval methods, muscle models, representing levels of detail) and animation (physically-based simulation, control and learning, hybrid kinematic/dynamic techniques).

http://www.dgp.utoronto.ca/DGP/

The *Human Figure Animation Project* of Microsoft is working to make better and more realistic animation of humans for computer graphics. Their work involves motion capture analysis and reuse, torque-minimal transitioning of motion capture, and most recently, deriving controllable animation through interpolation of motion captured or hand-animated source environments.

http://www.research.microsoft.com/research/graphics/hfap/

The *Manchester Visualization Centre* (formerly the Computer Graphics Unit) directed by W.T. Hewitt has been working, among other things, in applying parallel computing to motion synthesis and cloth animation. Nowadays, they are working in integrating interactive computer animation into multimedia presentations, developing new interactive motion synthesis tools which help an animator describe the potential for motion.

http://www.man.ac.uk/MVC/

The *Perceptual Science Laboratory* at the University of California — Santa Cruz is engaged in a variety of experimental and theoretical inquiries in perception and cognition. A major research area concerns speech perception by ear and eye, and facial animation.

http://mambo.ucsc.edu/

A.2. Other related web references

Eptron, S.A. (Madrid, SPAIN) is a privately funded company created in 1992. Its primary goal is the development of multimedia content (mainly in CD-ROM format), oriented to the corporate promotion of companies and continuous training of their professionals.

In 1995, while keeping and increasing its presence in the training and corporate CD-ROM sector, EPTRON took the decision to adopt a new orientation, focused in the development of new products, specifically oriented to optimize the production of animated computer characters.

With this purpose in mind EPTRON has developed its own MOTION CAPTURE technology: IMPERACTOR System which was introduced to the specialized public in SIGGRAPH'95.

EPTRON present situation allows the development of advanced products and systems in areas related to REAL-time graphic edition and has just launched to the market its first system (VIRTUAL SCHOOL), that automates and integrates the overall management of on-Line teletraining environments.

http://www.eptron.com

Polhemus, founded in 1970, is a small, high-technology company, located in the town of Colchester (USA), in the beautiful Champlain Valley section of Vermont.

Polhemus specializes in measuring the position and orientation of objects in three dimensional (3D) space with sophisticated electromagnetic technology. Polhemus has led the development of electromagnetic measuring systems for two decades and owns many landmark patents.

Initially developed for military applications, Polhemus products are now extensively used in commercial applications in fields as diverse as virtual reality, computer animation, biomedical and biomechanical research, simulation and training, scientific visualization, and entertainment.

http://www.polhemus.com/

Ascension Technologies founded in 1986, is one of the premiere developers and manufacturers of motion tracking devices in the world today. Their trackers are used to measure instantly humans, instruments and object motions in animation, simulation, virtual reality (VR), medicine, biomechanics, and similar fields. Its latest tracker, MotionStar Wireless, is the world's first real-time magnetic tracker to set performers free by shedding its trailing cables.

http://www.ascension-tech.com/

X-IST Realtime Technologies GmbH (Huerth, Germany) is one of the leading edge technology development companies in the real-time animation domain.

Founded by Olaf Schirm in 1996, X-IST is regarded as a highly innovative and creative software and hardware development company in the fields of motion tracking and real-time animation. The company is based on the products that Olaf Schirm has developed and established in the market with VIERTE.

Among the main activities we develop realtime solutions in the field of computer animation, motion tracking hard and software tools and software for animation of virtual presenters.

Probably the best known X-IST products are the real-time facetracker X-IST© FACIAL EXPRESSION TRACKER and the real-time character animation software X-IST VUPPETMASTER.

http://www.x-ist.de

Blaxxun interactive, an international company with offices in San Francisco, CA (USA) and Munich (Germany) was founded in 1995. The company is market leader for Internet Multimedia Communication and addresses the markets Commerce, Communities, and Collaboration.

For these segments, blaxxun interactive develops and markets software products, such as the award-winning blaxxun Community Platform and standard applications for expert collaboration, shopping, and community operation. Moreover, blaxxun designs and delivers complete customer solutions for the above markets, for example on-line shopping, on-line banks, virtual shareholder meetings, company presentations, virtual events, on-line cities, customer clubs, communities of interest, virtual offices, virtual universities, and expert collaboration.

Finally, blaxxun, together with partners, owns and operates selected on-line communities based on blaxxun's technology. Examples include Cybertown and Colony City with others in development.

http://www.blaxxun.com/

Activeworlds.com Inc. (Newburyport, MA, USA) is a leading provider of three-dimensional (3D) virtual environment platforms for the Internet. The Company offers a complete variety of proprietary client, server and development applications, offering a totally turn-key approach to creating rich and compelling on-line 3D worlds. A number of major multinational corporations, universities and government agencies are currently using the Company's proprietary 3D platforms. Activeworlds has also developed a suite of software, clients, servers, and authoring tools that are designed to allow people to communicate, play games, and conduct business in an infinite number of shared environments on the Internet, in real time. In addition, the Company recently launched @mart, one of the first totally interactive 3D Internet shopping malls. Activeworlds has also been featured on a number of television and news broadcasts and has created the 3D interactive environments for several major motion pictures.

http://www.activeworlds.com

A Verbot is a Verbal Software Robot; — a Verbally enhanced Chatterbot — a virtual character in a computerized world with an artificial personality. They have a finite ability to understand and speak English now — other languages later — through Natural Language technology. They are the most advanced form of Cyberbot known. But Verbots are more than that, they're personalities . . . and those personalities will be less artificial with each release.

Virtual Personalities, Inc. is a company that creates and distributes Verbots like Verbot™ 3.0, the latest version of the orginal Sylvie Chatterbot.

http://www.vperson.com

Haptek Inc. Santa Cruz, CA (USA) has developed the software VirtualFriend 2.0 which allows to use fully 3-D synthetic characters that interact with the user, that can be integrated into 3D movies or into web pages. They speak spontaneously, creating original sentences, just like humans do. They can morph into animals and weird beings. They are reactive to your behaviours, they can even advise you or make predictions.

http://www.haptek.com/

Valve is an entertainment software company founded by Gabe Newell and Mike Harrington and based in Kirkland Washington (USA). Valve's debut product, *Half-Life*, released in November, 1998, has won more than 30 Game of the Year honors worldwide and has been called "a smash hit" by the Wall Street Journal. Half-Life is published by Sierra Studios.

Half-Life blends action, drama, and adventure with stunning technology to create a frighteningly realistic world where players need to think smart to survive. Throughout the game, both friends and foes behave in sophisticated and unpredictable ways, a result of Half-Life's powerful and innovative artificial intelligence

http://www.valvesoftware.com

http://halflife.net

The *Contact Consortium* (Scotts Valley, CA, USA) is the first global organization focused on inhabited virtual spaces on the Internet. These spaces are shared in real time by thousands of users and represent a new frontier in the experience of cyberspace. The non-profit Consortium supports special interest groups, holds conferences, sponsors research and papers, and serves as a catalyst for this new medium. A broad Consortium corporate, institutional and individual membership is working to ensure that this "cyberspace beyond the web document" will emerge as a powerful place to learn, play, work and interact in the 21st century.

The Contact Consortium was born out of CONTACT: Cultures of the Imagination, a 17 year old organization which has engaged anthropologists, space scientists, fiction writers and others in pioneering exercises simulating human contact between speculative cultures. The Contact Consortium was built on these foundations to become a structure for the development of human contact, community and culture in digital space. Several links to avatar virtual worlds can be found at this address.

http://www.ccon.org/

At *PF. Magic* they have developed a series of life-like computer characters called Virtual Petz. These are autonomous agents with real-time layered 3D animation and sound. Using a mouse the user moves a hand-shaped cursor to directly touch, pet, and pick up the characters, as well as use toys and objects in the virtual environments. Virtual Petz grow up over time on the user's PC computer desktop, and strive to be the user's friends and companions. They have evolving social relationships with the user and each other. In the newest version of the software, Dogz III and Catz III, Petz can breed and give birth to offspring that inherit traits of their parents, they can live and play in colourful virtual environments, and can respond to the user's voice. To implement these agents they have developed hybrid techniques that draw from cartoons, improvizational drama, AI and video games.

http://www.catz.com

http://www.dogz.com

http://www.petz.com

http://www.babyz.net

A collection of *links* by *Andrew Stern* whose interests are life-like computer characters, virtual characters, virtual pets, virtual humans artificial intelligence, artificial life, believability interactive story, interactive fiction, virtual reality.

http://pw2.netcom.com/ ~ apstern

A collection of *links* to servers which serve computer-generated animations, visualizations, movies and interactive images. This site is maintained by *Thant Nyo*, an undergraduate senior at the Towson State University, with the help of *Dr. Cohen* at the Perceptual Science Laboratory at UCSC where my documents are being hosted.

http://mambo.ucsc.edu/psl/thant/thant.html

A collection of *links* by *Humana Virtualis* Copyright © 1998 *PersonaForm* which provide information about Digitization and Acquisition, Synthesis, Behavioral Simulation, Destinations and Communities, Conferences, Events, SIGs, Publications, Articles, Papers, Esoterica and Miscellaney.

http://www.pasociety.org/hv/

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