Investigation of an Emotional Virtual Human Modelling Method

A thesis submitted to Brunel University in fulfilment of the requirement for the degree of Doctor of Philosophy

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Brunel
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To my parents

Lianxi Zhao and Qin Xue

To my twin brother

Chao Zhao

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Abstract

In order to simulate virtual humans more realistically and enable them life-like behaviours, several exploration research on emotion calculation, synthetic perception, and decision making process have been discussed. A series of sub-modules have been designed and simulation results have been presented with discussion.

A visual based synthetic perception system has been proposed in this thesis, which allows virtual humans to detect the surrounding virtual environment through a collision-based synthetic vision system. It enables autonomous virtual humans to change their emotion states according to stimuli in real time. The synthetic perception system also allows virtual humans to remember limited information within their own First-in-first-out short-term virtual memory.

The new emotion generation method includes a novel hierarchical emotion structure and a group of emotion calculation equations, which enables virtual humans to perform emotionally in real-time according to their internal and external factors. Emotion calculation equations used in this research were derived from psychologic emotion measurements. Virtual humans can utilise the information in virtual memory and emotion calculation equations to generate their own numerical emotion states within the hierarchical emotion structure. Those emotion states are important internal references for virtual humans to adopt appropriate behaviours and also key cues for their decision making.

The work introduces a dynamic emotional motion database structure for virtual human modelling. When developing realistic virtual human behaviours, lots of subjects were motion-captured whilst performing emotional motions with or without intent. The captured motions were endowed to virtual characters and implemented in different virtual scenarios to help evoke and verify design ideas, possible consequences of simulation (such as fire evacuation).

This work also introduced simple heuristics theory into decision making process in order to make the virtual human's decision making more like real human. Emotion values are proposed as a group of the key cues for decision making under the simple heuristic structures. A data interface which connects the emotion calculation and the decision making structure together has also been designed for the simulation system.

List of publications and Awards

Journal publications

1. "Synthetic Vision and Emotion Calculation in Intelligent Virtual Human Modelling", Yue Zhao, Jinsheng Kang, David K. Wright. Biomedical Sciences Instrumentation, vol. 43, 2007. ISSN 0067-8856

2. "Emotion-Affected Decision Making in Human Simulation", Yue Zhao, Jinsheng Kang, David K. Wright. Biomedical Sciences Instrumentation, vol. 42, 2006. pp. 482-387, ISSN 0067-8856

3. "Human Motion Modelling and Simulation By Anatomical Approach", Jinsheng Kang, Basil Badi, Yue Zhao, David K. Wright. WSEAS TRANSACTIONS ON COMPUTERS, Issue 6, Vol. 5, June 2006, pp. 1325-1332, ISSN: 1109-2750.

4. "Modelling human behaviours and reactions under dangerous environment", Jinsheng Kang, David K. Wright, Shengfeng Qin, and Yue Zhao. Biomedical Sciences Instrumentation, vol. 41, pp. 265-270, 2005. ISSN 0067-8856

5. "Fluctuating asymmetry and preferences for sex-typical bodily characteristics", William M. Brown, Michael Price, Jinsheng Kang, Nicholas Pound, Yue Zhao, Hui Yu. Proceedings of the National Academy of Sciences of the United States of America (PNAS), vol.105, no.35. September 2, 2008.

Conference publications

6. "Emotional Virtual Human Modelling", Yue Zhao, Jinsheng Kang, David K. Wright. SED Conference 2008 (ReSCon 2008), Brunel University, West London, UK, 25th-26th June, 2008

7. "Synthetic Vision and Emotion Calculation in Intelligent Virtual Human Modelling" (Conference Poster), Yue Zhao, Dr. Jinsheng Kang, Prof. David Wright. 44th Annual Rockey Mountain Bioengineering Symposium, Denver, Colorado, USA, 12th -14th April 2007

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Chapter 1
Introduction

1.1 Virtual humans

With the development of virtual reality technology during the last two decades, the application of virtual humans has also been extended. Rather than trying to describe an inaccessible building or structure using words, sketches, or pictures, virtual reality techniques have introduced a wide range of new methods of interaction between virtual humans and their virtual environments. Virtual environment technology offers a number of tools which can reconstruct the entire virtual scene in three dimensions. The virtual scene is allowed to be reviewed from different view points. Virtual environments are also composed of static and dynamic virtual entities which are decorated with 3D graphic objects, sounds, images, and videos. However, these static 3D architectural models can only be manipulated in real-time, in a passive way and offer few function for actual exploration, interaction and participation.

In these virtual environments, virtual humans are the key technology to produce virtual presenters, virtual guiders, and virtual actors. These technologies can also be used to show how humans act in various situations. Between virtual humans and virtual environments, there are many complex problems that researchers have been trying to solve for several years. With the development of interactive multimedia products, there is also a need for systems to provide designers with the ability to embed real-time simulated virtual humans into games, multimedia and films.

A virtual human is a software entity that looks and performs like a real person but lives in a virtual environment. It is expected to act appropriately and automatically with flexible body parts that can be controlled in real time. The motion of a virtual human is realised through either kinematic methods or dynamic methods. The simulation of virtual humans includes groups of autonomous virtual agents and dynamic 3D virtual environments with which virtual humans can interact. The idea behaviour of virtual humans should be guided by their needs, such as hunger, tiredness, etc. In the past decade, virtual humans have been developed for specific application and carried on presenting unpredictable behaviours. This distinguishes virtual humans' behaviour strategies from those pre-determined behaviour strategies in traditional artificial intelligence. Virtual humans need to have their own motivations and perceptions, which allow them to act in accordance with their surrounding environment, to be able to react to its changes, to the other agents and also to the actions of real humans interacting with the virtual world individually. Therefore, virtual humans can not only simulate human behaviour in some dangerous scenarios, but also present a wide range of behaviour with some personality features. Behaviour models of virtual humans have been developed not only to execute a group of virtual agents' behaviour, but also to provide diverse behaviours. Their action selection mechanism can determine suitable actions to take in real time (**Figure 1-1**). The development of these technologies, virtual humans will be indistinguishable from real humans. "Ours may be the last generation that sees and readily knows the difference between real and virtual things" (Badler 2001).

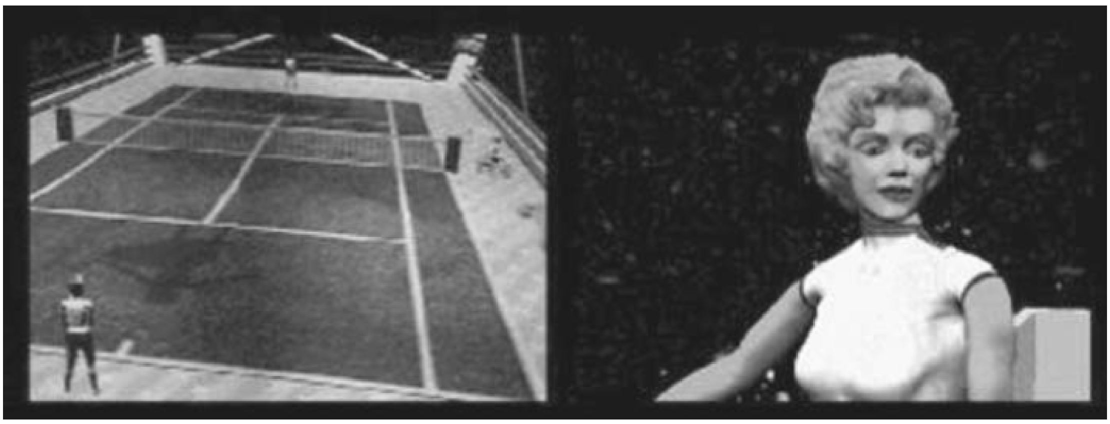


Figure 1-1 Real-time virtual Marilyn as referee in a virtual tennis match (Magnenat-Thalmann 2004)

Next section will focus on the development of existing virtual human models which include simple stick figures and real-time interaction models with complex synthetic perceptions.

1.2 The history of virtual humans

1.2.1 Stick figure models

The earliest application of a virtual human and its motion in computer graphics was in the field of ergonomic analysis. One common feature of the early virtual humans is the implementation of link-based stick figures, which were initially used for creating animation. The stick figures of the human form or other animals used for special effects in films display the outcome of a scene and save money, time and effort that a completed shot would require.

William Fetter's Landing Signal Officer (LSO) developed for Boeing in 1949 (Fetter 1982) was a link-based figure, also known as "First Man", with seven joints. It was used for studying the instrument panel of a Boeing 747, enabling many pilot actions to be displayed by articulating the figure's pelvis, neck, shoulders, and elbows. The articulation of "First Man" was then improved and led to "Second Man" which incorporated a greater number of joints and increased anthropometric accuracy. With an addition of 12 extra joints, this "Second Man" was used to generate a set of animation film sequences based on a series of photographs (Muybridge 1955). Fetter then developed the third virtual human model at Southern Illinois University at Carbondale's Department of Design. It was actually a hierarchical figure series with successive figures which are differentiated by an order of magnitude in complexity. For example, one of his figures had 10 joint points, a single line represented an entire limb, head, or torso. As the number of point increased, a more complex figure was displayed with lines to represent the contours of the body. The most complex figure in this series had 1000 points. These figures were used for general ergonomic studies. In 1977, Fetter and his colleagues produced another virtual human model, "Fourth Man", based on data from biostereometric tapes (Fetter 1978). They also developed a program that contained options for selecting contours, selecting desired numbers of points along the contours, and dividing the points evenly along each contour. Therefore it was possible to display virtual human figures with different levels of detail. These figures could be displayed as a series of coloured polygons on contour-based devices.

Blakeley's Cyberman is a link-based figure with 14 joints. It was developed for modelling human activity in and around a car (Blakeley 1980). Evans's Combiman using a 34 internal-link skeletal system, was specifically designed to test how easily a human can reach objects in a cockpit (Evans 1976). Boeman designed in 1969 by the Boeing Corporation was built as a 23-joint figure with variable link lengths. The system can detect collisions and identify visual interferences during Boeman's tasks (Dooley 1982): Boeman can reach virtual objects among a pre-defined mathematical description of the virtual object with pre-determined reaching behaviour. In the UK, Sammie (System for Aiding Man Machine Interaction Evaluation) was designed in 1972 at the University of Nottingham for general ergonomic design and analysis. It is based on a model with 21 rigid links and 17 joints. Sammie can also manipulate complex objects with a vision system. The human model was based on a measurement survey of a general population group. It was one of the best link-based virtual human models and presented a choice of physical types: slim, fat, muscled, etc. (Bonney 1972; Kingsley 1981).

1.2.2 Surface models

The early link-based models were enhanced by the addition of surfaces 'attached' to the sticks of the basic models. Surface models normally contain a skeleton surrounded by surfaces composed of planar or curved patches, simulating the skin. Several models have been developed since the 1960s. Fetter's surface model of a man was composed of only seven segments (Fetter 1982). He also introduced a more fully articulated man known as the "second man" in 1969. Then he updated his surface model to create the "Third man" in 1981. Dooley summarized some other surface models based on anthropometric data. She presented the result of a review for available and technologically useful anthropometric modelling programs. However, she did not provide sufficient discussion and comparison of program capabilities (Dooley 1982). The Jack™ software package developed by Badler *et al*. (Phillips 1988) at the Center for Human Modelling and Simulation at the University of Pennsylvania, was made commercially available through Transom Technologies Inc. It was one of the earliest virtual human models with a scalable link-based body figure. The Jack™ package enables users to study and improve the ergonomics of product design and workplace tasks through the positioning of biomechanically accurate digital humans of various sizes in virtual environments.

Figure 1-2 Jack's MOOse Lodge, an example of surface models (Shi 1999)

1.2.3 Volume models

The volume models approximate the structure and the shape of the body with a collection of primitive volumes (Nedel 1998), such as cylinders (Potter 1975; Evans 1976), ellipsoids (Herbison-Evans 1974), or spheres (Badler 1977). A few cylinders or ellipsoids can capture the surface and longitudinal axis properties of many body parts, although the similarities are quite stylized, like cartoons. Those models were developed at an early stage of human animation when graphic systems had very limited capabilities. Even having some advantages in other aspects, volume models cannot produce better looks than surface models. Volume models also suffer from inadequate control mechanism of large set primitives during the animation.

A recent and interesting example of human representation by the use of volume primitives was presented by Yoshimoto (Yoshimito 1992). He proposed the application of metaballs, by considering the volume as a potential function. This technique produces good and natural results to create very realistic ballerinas. About 400 metaballs and some ellipsoids were used to design the ballerina's body and costume (**Figure 1-3**).

Figure 1-3 Ballerina made of metaballs (Yoshimito 1992)

1.2.4 Multi-layered models

Multi-layered models were developed to represent human figures in the 1990s. A layer can be defined as a conceptual simulation model which maps higher level input parameters into lower level outputs. In this approach, a skeleton is normally used to support intermediate layers that simulate the body volume (which includes bones, muscles, fat, tissues, and so on) and the skin layer. Sometimes a clothing layer can be also considered. Various constraint relationships between the layers are specified by the designers and the global motion can be controlled from a higher level.

A good example of layered construction and animation of deformable characters are presented by Chadwick et al (Chadwick 1989). In their approach, the geometric skin is not simply fitted to an articulated skeleton. It captures the fluid squash and stretch behaviour of the surface geometry by providing volumetric muscle bulging, dynamic fatty tissue response, and creasing at the joint. A four layered model from high to low levels was designed: ①the motion specification, referred to as the behaviour layer in the system; ②the motion foundation, represented by an articulated skeleton layer; ③ the shape transition, squash and stretch, corresponding to the muscles and fatty tissues layer; and ④the surface description, surface appearance and geometry, corresponding to the skin and clothing layer.

Figure 1-4 Bragger Bones, a character in the Critter system (Chadwick 1989)

The skeleton layer provides the foundation for controlling the motion of the character and is composed of a tree structure hierarchy of robotics manipulators, robotics joint-link parameters, joint angle constraints, and physical attributes. The muscle layer is added on top of and attached to the skeleton hierarchy. The foundation for the muscle and fat is based on Free Form Deformations (FFDs) (Sederberg 1986). The control points of the deformations are constrained by the positioning (joint angles) and forces (joint torques) applied to and by the underlying skeleton. These deformations then act as glue and deform the geometric skin to the underlying skeleton. The skin layer represents the actual visible surface geometry to be rendered. **Figure 1-4** shows an example of a human character generated using this layered approach.

1.2.5 Motion and behaviour models

There are two distinct classes of technologies for the animation of virtual human models in the field of virtual human research: Kinematic methods and Dynamic methods.

Both kinematics and inverse kinematics as important problems in the manipulation of virtual humans have been extensively studied, first in robotics and later in computer graphics. Kinematics deals with the geometry of motion regardless of its physical realisation. It is more concerned with the position, velocity and acceleration of the moving bodies than with its natural attribute, such as, torque, mass, strength, etc. Using kinematic manipulation techniques to realise the body control of a link-based virtual human is similar to the manipulation of a doll. The model can be regarded as a mechanism controlled by adjusting the joint angles. The pose and motion control of the model is so called the direct kinematics problem, which determines the gesture of a link-based figure model based on a group of joint parameter settings. The solution to the kinematic animation problem is a set of angles, which is visualised as a pose of the figure. However, by considering the constraints which are caused by the limitation on the range of body movement, it is difficult to adjust the joints to get the desired gesture. For example, multiple joint angle constraints have to be considered when modelling the shoulder, elbow and wrist joints. With these constraints, only allowed pose can be generated. In order to create motion with a given target, it is necessary to solve an indeterminate set of joint angles. The process of determining joint angles of a jointed flexible object is called inverse kinematics. Theoretically, the solution to the inverse kinematics problem is infinite. Because there are infinite possible gestures can be used to reach the same target. Restricting algorithms have to be used to reduce the number of solutions.

Different from the kinematic method, a great deal of work has been done on the dynamics of link-based figure models, or articulated bodies (Huston 1990). Dynamics is based on Newton's laws of motion and is more concerned with the causes of motion through the acceleration of a body, such as forces. Many efficient direct dynamics algorithms which include a few structures with many degrees of freedom have been developed in robotics (Featherstone 1986). These algorithms have been applied to the dynamic simulation of virtual human in computer animation as well (Kenna 1996). Some software packages are available now to handle a wide range of simulations; for example, McGuan introduced a digital human modelling tool called *Figure Human Modeller*, which is a plug-in to ADAMS (McGuan 2001). Some other existing commercial system is Natural Motion (Natural Motion 2006); also the DANCE system from University of Toronto (Shapiro 2005). There are other reactive dynamics software tools such as MADYMO for crash simulation (Berlioz 2005). Basically, dynamics algorithms can calculate the motion of a complex link-based body based on the laws of rigid body dynamics with a given a set of external forces (e.g. gravity or wind) and internal forces (physical constraints or joint torques). Impressive animations such as falling bodies on stairs can be generated in this way. However, the dynamics approach can also turn itself into a tedious task as the animation can only be indirectly controlled during the simulation and sometime the internal forces may not be known.

Behaviour should be presented as a result of a multi-agent system, sharing a virtual environment. For example, no model unit for group behaviour is available in a scenario where a crowd of virtual humans are trying to escape from a building on fire. Each virtual human reacts differently depending on different variables. The variable can be his/her level of anxiety, ability to move, etc. The individual entity (virtual human) modelling has lots of different possible behaviours as a result of the interaction of common individual behaviours. The behaviour of different virtual individuals should not be explicitly pre-programmed. This idea is accepted by more and more researchers (Maes 1991; Kang 2005; Sevin 2005). Magnenat-Thalmann's perspective on virtual human research was to realise “the simulations of virtual worlds inhabited by a virtual human society, where Virtual Humans will co-operate, negotiate, make friends, communicate, group and break up, depending on their likes, moods, emotions, goals, fears, etc. But such interaction and corresponding groups should not be programmed.” (Magnenat-Thalmann 2004)

1.2.6 Perception, interaction and intelligence models

In order to improve the autonomy and reality of reactions, virtual sensors need to be added on board virtual humans. Before the mid 1990s, there was no real virtual sensor for virtual human modelling. Virtual humans were designed to retrieve the location of each virtual object directly from the virtual environment. This is of course the fastest solution and was extensively used in video-games. However, as inhabiting in a dynamic and unpredictable virtual world, virtual humans should be able to have autonomous behaviour, which means they must have a manner of conducting themselves. To be autonomous, they must be able to perceive their environment and decide what to do to reach their goals. Typically, virtual humans perceive the objects and the other virtual humans in the environment through virtual sensors (Thalmann 1995; Noser 1995(2); Pursel 2004).

Many virtual sensors, such as visual, tactile and auditory sensors, have been developed for virtual humans since the 1990s. Generating complex behaviours through realistic virtual perception is considered as one of the main challenges for virtual human modelling (Thalmann 1997; Kuffner 1999; Peters 2002; Pursel 2004). Virtual sensor, also known as synthetic perception, was developed as a relative independent branch in virtual human research. The perception models are responsible for connecting a virtual agent with its virtual environment. These virtual sensors are actually information channels to connect the virtual human with the inhabited world. Based on the perceived information, the virtual human will determine which motions can and will be performed through a behavioural mechanism.

Noser first defined the difference between synthetic vision and artificial vision (Hansrudi Noser 1995(1)). Synthetic vision is the simulated vision for a digital actor. The computer either renders from the virtual character's point of view the virtual environment in a window corresponding to the actor's vision image, or 'perceives' the visibility information of objects in the virtual environment through virtual sense organs by simulating faculties of human eyes.

The term artificial vision is used to define a process that recognises the image of the real environment captured by a camera. It is an important research topic in robotics and artificial intelligence. However the problems of 3D recognition and interpretation are still not yet solved properly. In robotics, for example, the robot gets information from its sensors. A visual sensor for robot is normally a camera. The information extracting process of a robot is actually an image processing or video processing. Even now, it is still a difficult task to extract all the semantic information of the world from images.

In synthetic vision, it is not necessary to address these problems in image processing, such as pattern recognition and interpretation of 2D images to 3D entities. When an object is within the FOV volume, it is assumed that virtual humans can see it and recognise its semantic information directly. This saves the process of image processing and helps to speed up the system.

Synthetic vision modelling in this work is concerned with:

- Simulating the biological / optical abilities and limitations of the human vision.
- Interpreting sensory data by simulating the results of visual information within the virtual memory and decision making unit of human beings.

Furthermore, in order to realise realistic virtual human behaviour, it is not sufficient to equip them only with detecting sensors. It is also necessary to provide virtual humans with memory of what has been discovered in a certain time span. At least, the time should be long enough to allow virtual humans to understand and analyse the information for decision-making. Therefore, the conception of virtual memory is also one of the relative research topics in virtual human modelling.

Figure 1-5 Virtual characters and objects mixed with real decor in LIFEPLUS Project (MIRALab 2004)

In the 1990s, with improved appearance, the emphasis of virtual human research shifted to real-time animation and interaction in virtual worlds. With the aim of creating believable behaviour, Thalmann launched the Virtual Reality Lab at Lausanne in 1988. His work mainly involved with the modelling and animation of Three-Dimensional Inhabited Virtual Worlds (VRLab 1988). The laboratory is also known for the modelling of real-time virtual humans and in the area of multimodal interaction, immersive virtual environments, and augmented reality. One year later at Geneva, Switzerland, Magnenat-Thalmann founded MIRALab which has a focus on interdisciplinary group work in the field of Computer Graphics, Computer Animation and Virtual Worlds (MIRALab 1989; Thalmann 1990; Thalmann 1996(1)). She mainly conducts research on the simulation of human functionality and physics-based deformable models such as clothing and hair. Both laboratories have extended the research of virtual humans into diverse branches. Their work also introduced the areas of gesture-based commands, interactive physical deformations, and shared Virtual Environments (Magnenat-Thalmann 1987; Noser 1993; Noser 1995(1); Noser

1995(2); Thalmann 1997).

With the development of artificial intelligence, the intelligence of virtual human models has also been improved. Attempts have been made to integrate artificial intelligence research achievements with virtual human models. For example, research on parallel distributed processing (PDP) in computer sciences. The attempts of PDP application through the neural networks on other fields had never stopped. John Hopfield (Hopfield 1982) analysed the storage and optimisation features of neural networks in physical systems through statistical approach. In psychology, Rumelhart and Hinton started working on modelling human cognition with neural network (Rumelhart 1986). Many work had been done afterward. Neural network modelling is considered as an important approach which can be utilized to simulate the learning and decision-making processing of human brain in machine. However, only recently, some work begin to attempt the PDP on real-time virtual human modelling (Chevallier 2005).

1.2.7 Summary

After the first glance of virtual humans' history, it is able to summarize some features of virtual humans. Virtual human models in virtual environment require at least the following four main elements:

1. Graphics, which present the realistic aspects including skin, hair, and clothes of virtual humans. (Mentioned in **Section 1.2.2, 1.2.3**)
2. Advanced behaviours, which indicate virtual human's intelligent decision-making, motivation, and social behaviours. (Mentioned in **Section 1.2.4**)
3. Motion control, which is responsible for flexible motion control and management. (Mentioned in **Section 1.2.5**)
4. Synthetic perceptions which can help to improve the autonomous and intelligent of virtual humans. A synthetic perception model can be virtual sensor model (for Virtual

Worlds) and real sensor (for Real Worlds). (Mentioned in **Section 1.2.6**)

1.3 The applications of the virtual humans

The applications of virtual humans are mainly focused on two areas: ergonomics and computer sciences.

1.3.1 Virtual human models for ergonomic analysis

The virtual humans in ergonomic analysis are substituting for people performing tasks under difficult or dangerous conditions, such as selecting tools and sequencing reactions. The focus of virtual human research in ergonomics is on modelling equivalent digital models of humans for physics and kinematics simulation, includes crash simulation (car occupant injury), environmental injury (falls/slips), orthopaedics (joint and tissue mechanics), task simulation (virtual factory) and sport-performance simulation.

Norman Badler, who has been creating virtual humans for years, summarised previous knowledge of computer graphics on virtual human modelling with related work in human figure modelling and human-centred design (Badler 1993). He also investigated state of arts for the interactive control and motion specification of articulated human figures. Now, he has put his virtual humans to maintain complex physical systems, including military aircraft, by simulating assembly, repair, and maintenance functions in a 3D virtual environment. Jokes abound, Badler et al. write, concerning unintelligible instructions. If the instructions given to the virtual humans are incorrect or the design is flawed, the system reports failures. A procedure is valid if no failures occur across a sufficiently large range of anthropometric body sizes (Rosenbloom 2002).

The Santos system, created at the University of Iowa, governs virtual characters' motion based on human performance measures that act as objective functions in an optimisation problem. It is one of the main targets of the Virtual Soldier Research (VSR) program (Abdel-Malek 2006). The aim of the project is to develop a new generation of digital humans comprising of realistic human models including anatomy, biomechanics, physiology, and intelligence in real-time.

The principal features of virtual human models for ergonomics analysis, such as the Jack™ system, include a detailed human model, realistic behavioural controls, anthropometric scaling, task animation and evaluation systems, view analysis, automatic reach and grasp, and collision detection and avoidance. However, the movement of the virtual human figure in ergonomic analysis normally needs to be predefined. For example, the Jack™ system does not support virtual characters the capability to select reactions based on real-time decision making but only provides limited motion patterns. Although some models have considered the effects of body types in ergonomic analysis, such as the Sammie project, the appearance of the virtual character's behaviour is still far from realistic. More abundant motion pattern databases need to be created and imported from other motion modelling techniques by considering individual differences.

Similar to Jack™ and Sammie, Cyberman is a virtual human system which was created by Blakeley in the early 1980s. The simple wire frame model was developed for the automobile industry in order to define and analyse limb and body locations within a virtual environment. It is used specifically to analyse virtual drivers and pedestrians and their activities in and around a vehicle (Blakeley 1980).

The AMRL (Aerospace Medical Research Laboratory) in the US designed a virtual model: Combiman, which was modelled in order to determine human reach capability and was applied for aircraft cockpit-configuration design and evaluation (Bapu 1980). The main idea of these computerised human models was to simulate a very simple articulated structure for studying problems related to ergonomics. Ergonomic analysis also provides some of the earliest applications in computer graphics for modelling a human figure and its motion.

Human Solutions Company, which is based in Kaiserslautern, Germany, has been developing and selling hardware and software solutions for the measurement and simulation of human beings and then integrating them into product development and manufacturing processes since 1986 (Human Solutions 1986). The company's Solution products, such as RAMSIS, eBTD, ANTHROSCAN, are proving successful in more than 300 companies worldwide.

SAFEWORK® technology Inc (Canada) permits designers to execute human factors analysis effectively during the entire product design process. It has been integrated with CATIA, created by Dassault Group, a French group of companies to combine the superior human modelling capabilities with CATIA product design tools to undertake advanced Human Factors analysis. The main product, SAFEWORK® Pro™, enables designers to adopt a 'user-centered' approach to design, from initial concepts through to final acceptance testing for application areas in domains, such as aerospace, automotive, fabrication, assembly and consumer goods.

ManneQuin series of human modelling programs that started in 1990 was the world's first PC based human modelling solution (NexGen Ergonomics Inc 1990). It has been superseded by HumanCAD and is no longer available for sale. HumanCAD is a human modelling solution that creates digital humans in a three-dimensional environment in which a variety of ergonomic and human factor analyses can be performed. HumanCAD's human factor tools support users with the product and workplaces design by determining what humans of different sizes can reach, see, feel and fit in.

Marek was using ADAMS for human gait analysis (Wojtyra 2000). He recommended ADAMS as a powerful tool, which enables the use of the direct dynamic approach to human gait analysis. The approach can predict system behaviour without measuring ground reaction forces and extrapolate gait patterns without time constraint.

SIMM is another flexible CAD tool that helps researchers to create and analyse virtual human models. The software suite is produced by MusculoGraphics, Inc., a division of Motion Analysis. Besides create virtual human models, SIMM can also provide musculoskeletal structure of virtual humans, an intuitive graphical interface for creating anatomically correct models and for analyzing their functional properties, such as muscle strength and joint torque. SIMM has been used by researchers and clinicians to help understand the musculoskeletal system and diagnose and treat people with musculoskeletal deficiencies (Herrmann 1999; Delp 2000; Arnold 2001; Piazza 2001; Hicks 2007). It is noticed that SIMM is not the only musculoskeletal modelling software to solve design problems on ergonomics. AnyBody Modelling System™, created by Aalborg University at Denmark, can also simulate the mechanics of a live human body in concert with its environment. It can provide results on individual muscle forces, joint forces and moments, metabolism, elastic energy in tendons, antagonistic muscle actions, etc. (Rasmussen 2000; Lindsay 2001)

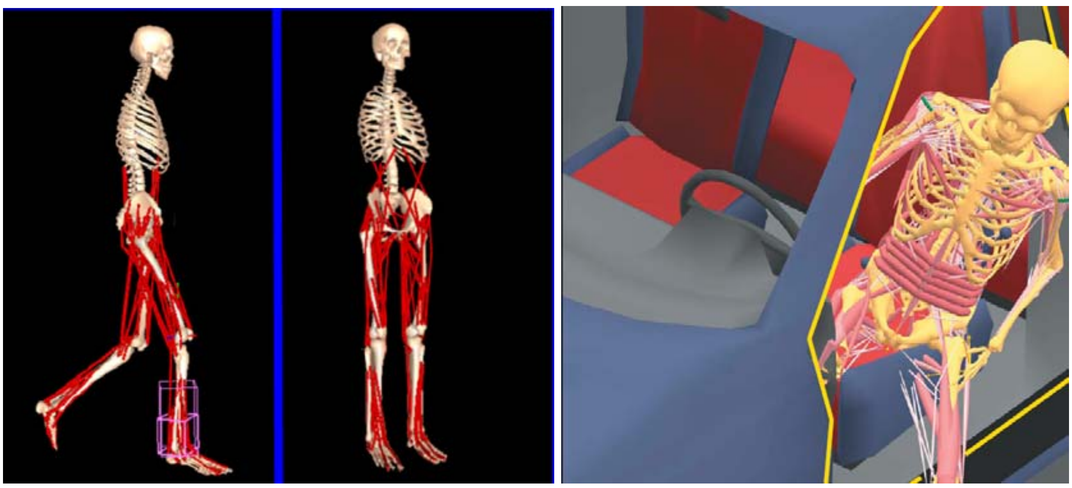


Figure 1-6 SIMM package (Hicks 2007) and AnyBody system (Rasmussen 2008)

1.3.2 Virtual human models for computer science

Along with research which is focused on ergonomic analysis, virtual humans are also widely studied in computer science. Nowadays, the construction of a virtual human model is a complex, time consuming and multidisciplinary work. Virtual human modelling combines several computer science areas with issues from other research areas, such as ethnology, social science, artificial intelligence, computer graphics, geometric modelling, psychology and anthropology.

In computer science, quite similar structures have been followed when creating virtual humans in virtual environments. Wray declared that three main segments need to be considered: modelling the geometry of the human, recreating behaviours and organization of the behaviours (Wray 1999). The idea has been extended and substantiated by considering modelling at three levels: appearance modelling; realistic, smooth, and flexible motion in any situation; and realistic high-level behaviour (Thalmann 2005).

Virtual humans have already been applied in a wide range of fields, such as education and training, therapy, manufacturing and entertainment (Gratch 2002). In addition, they can also be applied in many other areas, such as artificial intelligence, behaviour simulation (gait simulation / rehabilitation), medical research (virtual treatment and pathological simulation), virtual cultural heritage, virtual mannequins for clothing, virtual characters for computer-generated movies and video games. Furthermore, there are some areas which can be potential fields of virtual human application. For example, the development of the future multimedia with systems, there is an intention to allow participants to share professional and private experiences, meetings, games, and parties within a virtual environment. Virtual humans have a key role to play in these shared virtual environments. Realistic interaction with virtual humans is still a great challenge. Although a lot of research has been going on in the field of networked virtual environments, most of the existing systems still use simple embodiments for the representation of participants in these environments. More advanced virtual human models need to be develop in order to increase the natural interaction within the environment. Autonomous virtual humans with more natural behaviours and interactions can increase the sense of being together for a real human, and thus the overall sense of shared presence in the environment.

Many areas can be identified where virtual humans can be applied. The three main application areas, where virtual humans are involved, are listed here:

- Virtual humans for inhabited virtual environments. It is interesting and important to simulate virtual environments with many people, such as virtual airports or even virtual cities. Virtual humans are also expected to replace real humans when undertaking some dangerous simulation. For example, simulating escape from a building on fire. In the next few years, virtual humans will be seen in many applications within inhabited virtual environment. These virtual humans will be more autonomous and also more like real humans in all aspects.

- Virtual substitutes. A virtual substitute is an intelligent computer-generated agent able to act instead of the real person and on behalf of this person on the network. It has the voice appearance of a real person. The virtual substitute will appear on the screen of the workstation/TV, communicate with people, and have pre-defined behaviours planned by the owner to answer the requests of other people.

- Virtual medical assistance. Nowadays, there is still no effective solution for chronic care without remote care of patients at home by a kind of virtual medical doctor. The modelling of a virtual patient correspondent to medical images is also a key issue and a basis for tele-surgery (Cavazza 2003; Dickerson 2005). The application of virtual human in virtual medical assistance is not relevant to the work in this thesis.

The following figure summarizes the requirements of virtual human modelling (VHM) in different applications **Table 1-1**. It is necessary to point out that the application of virtual humans in virtual medical assistance is a fast developing research topic in the past two decades. However, this is not the area where this work is going to explore substantially, because the topic is beyond my concerning of virtual human modelling.

Table 1-1 Requirement of VHM in different applications (Badler 1998)

Application	Appearance	Function	Time	Autonomy	Individuality
Cartoons	*High*	*Low*	*High*	*Low*	*High*
Games	*High*	*Low*	*Low*	*Medium*	*Medium*
Special Effects	*High*	*Low*	*High*	*Low*	*Medium*
Medicine	*High*	*High*	*Medium*	*Medium*	*Medium*
Ergonomics	*Medium*	*High*	*Medium*	*Medium*	*Low*
Education	*Medium*	*Low*	*Low*	*Medium*	*Medium*
Tutoring	*Medium*	*Low*	*Medium*	*High*	*Low*
Military	*Medium*	*Medium*	*Low*	*Medium*	*Low*

1.4 Organization of thesis

This thesis proposes an emotion generation model and investigates how the model could affect and integrate with virtual humans' decision-making and behavioural animation mechanism.

The thesis topic and its main objectives are presented. The main terms and concepts that are used in the context are defined. A brief history of virtual human modelling is presented. The techniques used for implementing existing virtual human models are also described. Then, the limitations of virtual human modelling are clarified in **Chapter 2**. Based on the investigation of existing virtual human modelling methods, some proposals are also presented in the chapter.

Chapter 3 presents a review of the knowledge from different domains which are related to this virtual human modelling. These related works also help to justify the feasibility of this work. The chapter also reviews the literature about modelling virtual humans with emotional features.

As this work combines techniques from computer graphics to emotion simulation, the conceptual architecture of this work is organised into two main groups: External

Modelling and Internal Modelling as shown in **Figure 1-8**. It is classified by whether the processes correspond to the changes of external states or internal states.

Chapter 4 describes methods used to test a new virtual human system. Based on some improvements of a basic virtual human model, some updated models have been integrated with the virtual human step by step in order to extend the basic model's capability. The design of an individualised emotional motion database is also introduced in this chapter. In **Chapter 5**, a synthetic perception-memory module is investigated for the external modelling. The internal modelling for this virtual human with an emotion generation module and decision-making module is presented in **Chapter 6** and **Chapter 7**.

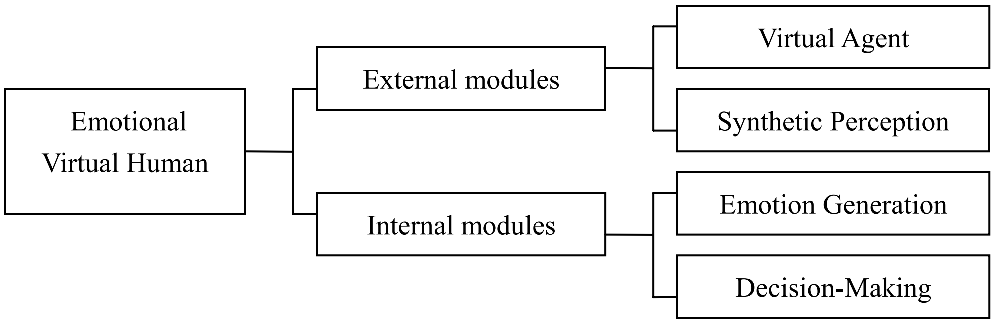


Figure 1-8 Conceptual architecture of virtual human with emotions

A complete visualisation platform is presented in **Chapter 8**, which is designed to integrate these element modules in association with an adaptable virtual environment toolkit. Examples and test results of this platform are also discussed in this chapter.

Finally, **Chapter 9** discusses the case studies of the emotion generation and emotional decision-making modules in the real-time virtual human modelling. How can a virtual human live in a virtual world based on their internal emotions and external factors. It also presents the limitations and possible future work.

Chapter 2
Limitations of Existing Virtual human Models and Proposals

In **Chapter 1**, the concept of virtual human modelling is introduced. A brief history of virtual human modelling and some possible applications are also presented. The concept of virtual human had only been proposed and accepted for less than two decades. There are still many limitations within the existing virtual human models.

In this chapter, limitations of the existing virtual human models are reviewed (**Section 2.1**). Some possible directions of virtual human research are inspired from these limitations (**Section 2.2**)

2.1 The limitations of existing virtual human models

In ergonomic analysis, originally, virtual human models and virtual training systems involved the operation of strictly technological entities (aircrafts, nuclear power stations, complex hardware devices, etc). Even if it had been equipped with powerful artificial intelligent drives, the behaviour of the virtual human was still not very convincing. This was partly because only limited motion patterns are set for the simulation. Virtual humans can only perform very limited standard motion patterns no matter how complex the inhabited environment can be.

In computer sciences, existing graphics technology allows the creation of cartoon films with vivid, realistic looks, such as in Final Fantasy VII: Advent Children. However, the behaviour of computer controlled virtual characters often leads to a shallow and unconvincing interactive experience, such as the non player characters in computer games (Namee 2001).

These limitations actually show the difference of virtual human modelling in a general way and for a certain application. Badler (Badler 1999) discussed the difficulty of modelling a virtual human in a general way. "Why are real-time virtual humans so difficult to construct? After all, anyone who can watch a movie can see marvellous synthetic animals, characters, and people. But they are typically created for a single scene or movie and are neither autonomous nor meant to engage in interactive communication with real people. What makes a believable virtual human is not just a well-executed exterior design, but movements, reactions, self-motivated decision making, and interactions that appear 'natural', appropriate, and contextually sensitive."

Inspired by the computer games industry, an advanced virtual human modelling requires a virtual human to reach a higher level of believability which can extend its applications into other domains, such as emergency situations. One important point in the simulation is the believability of the individual virtual humans. Virtual human needs to be more like a real human by enduing with some human capabilities, such as perception, diverse and goal-driven behaviour, reactivity to the environment, memory, personalities, interpersonal interactions and possibly others. One of the problems is how to improve virtual human behaviours under emergency situations, such as escaping from fire. Not only does it need to be considered by the ergonomists, but also by computer scientists and computer games industry.

2.2 Proposals for virtual human modelling

2.2.1 Reality of motions

After the review of the existing virtual human models, some limitations can be recognised. A person's flight in panic is likely to be different to the person's normal gait. In general, human body gestures and reactions with emotion are different to their motions when they are calm. The range and rhythm of one's motions with emotion can be very different to rational movements (Zarboutis 2005; Garcia-Rojas 2006).

One's reactions under emotion are less rational and usually have strong individual differences. "There is no particular 'form of behaviour' which satisfies an emotion and so can in that way become so closely associated with it as to be said to be characteristic of it." (Lyons 1978). In this situation, the virtual human is not only expected to react with reasonable decision making but also needs to react with accurate emotional motion styles.

Emotional motion is a person's movements under a certain emotion state. It is one's gesture and reaction with emotion, which includes some features different from one's gesture under normal situation without a certain emotion. It is an important aspect that needs to be considered when introducing emotion into virtual human modelling. Emotion provides intuitionistic difference and makes the reaction of virtual humans more convincing. It had also been realised that "the believability of an actor is made possible by the emergence of emotions clearly expressed at the right moment" (Bates 1994). The apparent emotions of an actor and the way it reacts are what give it the appearance of a living being with needs and desires. Without it, an actor would just look like a robot.

Another problem in animating digital virtual humans is the adaptation of various emotional motions into different characters, known as motion retargeting and composing. It is a classic animation issue to create 'life-like' creatures. If their proportions differ, it is not straightforward to adapt one animation to another virtual figure. Adapting one's animation to another virtual figure is a topic in motion conversion and composing. The motion conversion and composing is not included in the target of this work. All emotional motions used in this virtual human modelling are captured and organised individually from different subjects.

The first proposal for this work is to develop an emotional motion selection mechanism for virtual human design, to help virtual humans organise and execute their emotional motions when reacting and making decisions in a virtual environment.

2.2.2 High-level behaviour

The advanced behaviour of virtual humans actually distinguishes the 'emotion' feature of a virtual human from other attributes of virtual humans, such as advanced skills used in video games. Before the use of emotions in virtual humans, artificial intelligence approaches created diversity of virtual human reactions by pre-programmed virtual human's attributes individually. The emotion capability of virtual humans can provide unpredictable but reasonable reactions rather than simply pre-defining some possible reactions for them. The emotional virtual humans can provide virtual behaviours with emotion features as much as the virtual humans which adopted traditional AI approaches (such as Neural Networks). The difference between AI approaches and the approaches with emotion capability is that the later provides the same diversity and even more unpredictable result without rule-based programming and any data training algorithms which make it suitable for real-time simulation. The contributions of emotions compared to the traditional AI architectures are summarized by Cañamero (Cañamero 1997) in **Table 2-1**.

Meanwhile, it is interesting to notice that emotions have become commonly recognised as an important issue nowadays in the entertainment industry, specifically in video games. While the quality of animation has improved during the last few years, realistic reaction is still a major bottleneck in animation. It is especially true in video games where the system has to be very responsive while simulating complex behaviours of autonomous agents (Gratch 2001; Young 2001; Laird 2002). Therefore, research assigning virtual humans with emotional capabilities is expecting to lead virtual human modelling into another level. It is also expected to inspire new thoughts for computer–aided design.

One of the main interests for virtual human research is to design a standard for virtual humans that can be used for all applications with believable and coherent behaviours (Sevin 2006). Some other researchers also suggested that the 'virtual humans' interaction should not be fully pre-programmed, as behaviour should emerge as a result of a multi-agent system sharing a common environment. If a distinctive entity modelled, there will be groups of different behaviours (not programmed explicitly) as a result of the interaction of common distinctive behaviours… behaviour models should be simple enough to allow real-time execution of a group of agents, yet still sufficiently complex to provide interesting behaviours (Magnenat-Thalmann 2004). This actually requires modelling of more fundamental elements which can guide virtual humans to make their own decisions rather than simply tell virtual humans what to do with pre-programmed codes. Ideally, these decisions should be depending on the real-time updates from their virtual environments.

Table 2-1 Contributions to AI: the emotions and the motivations (Cañamero 1997)

Problems with reactive and motivated architectures	Contributions of emotions
Rigidity of behaviours (S / R)	More flexible and varied behaviour as a function of internal state (e.g. predator: attack or flee)
Insufficient autonomous (reactions, drives)	Modulation / change of motivational state and behaviour
Repetitive and inefficient behaviours (Loops)	Self-monitoring, interruption of inefficient behaviour
Inefficient treatment of urgency situations, “goal forgetfulness”	Faster responses, anticipation (emotional memory) Re-equilibration of internal milieu, back to goal
“Atomic” behaviour	Behavioural chains (e.g. fear, escape, anger, attack, relief)

In order to create more interesting behaviour, psychology and communication theories are considered to appropriately convey nonverbal behaviour (Bower 1982; Salovey 1990; Frijda 1995; Goleman 1995). Individuality of virtual human is also considered

(Clapworthy 1998; Egges 2002). Sevin concluded that individuality is important to obtain believable virtual humans as they can interact with each other in a virtual community and have their own goals, emotions, and personalities (Sevin 2006).

In this work, virtual humans are expected to act and react differently to each other. It is proposed that virtual humans' behaviours should be based on their own internal and external states. Internal states correspond to the virtual humans' perception, memory, emotions, and decision-makings. External states are the changes of their virtual environment, about the other virtual humans and also about the interaction from real humans.

2.2.3 Cognitive sciences

Before 1990, there was insufficient effort to simulate the psychology of virtual humans, such as emotional reactions. Until recent years, there has been an interest in the role of emotion in the design of virtual humans (Egges 2003; Freitas 2005; Muramatsu 2005). Psychological research has also suggested that emotion plays important roles in behaviour and decision-making (Lyons 1978; Goleman 1995; Ketelaar 1998; Henninger 2003). Emotions are central to human motivation: they are both the precondition and result of many tasks, and feature prominently in the relationships we have, the way we talk, and the decisions we make. One's emotional reactions under certain scenarios can be very different to reactions within common scenarios. For example, a crowd of people running away from a fire building with sentiments such as panic, fear and impatience. Such issues are traditionally dealt by the crowd and social psychology literature (Quarantelli 1981; Paulsen 1984; Brown 1985; Sime 1985) described how these emotional states influence the individual behaviour in the crowd, and vice versa. In computer science, emotion modelling is featuring emotion generation as well as emotion expression in computer. In order to socially connect the user to virtual agents, emotions also need to be reasonably integrated into virtual agent architecture. However, compared with the fast development of artificial intelligence, little progress has been made to create working and experimental models of emotion (Elliott 1992). There is a need of more emotional virtual humans to populate the virtual worlds (Davis 2003; Freitas 2005; Muramatsu 2005).

There are many reasons for insufficiency of research in emotion modelling: Firstly, there is no acknowledged definition of emotion. Everyone can have their own understanding of what an emotion is, but few can define emotion in general. Some work has been done in both psychology and computer sciences (Frijda 1986; Lazarus 1991). However, different understandings of emotion still exist. For example: Ortony has argued that shock should not be considered as prospect-based emotions (Ortony 1988). This also shows how the different understanding of language can lead to misunderstanding when talking about emotions. In this chapter, all conception related to emotions are consistent with the Ortony's theory. Secondly, emotions have little to do with fact and largely with interpretations. People exhibit 'emotion-directed' behaviours which are traditionally characterised as irrational and computational models of intelligence usually ignore this.

Considered as evolutionary adaptations (Darwin 1872), emotions actually are groups of reflection that enhance an organism's ability to experience and evaluate its environment and thus increase its likelihood to survive and reproduce. Emotions can be defined as experiencing the attitude of whether entities meet human needs. The entity means the object of existence or a sensible environment factor. As a kind of subjective consciousness, emotions must have their corresponding entities. The key point of building an emotion model is whether those entities can be identified. From this definition, the problem of "whether entities meet human needs" is actually a typical evaluation problem. Whether "human's needs are met" is the standard for this evaluation. Maslow's theory of a hierarchy of needs (Maslow 1943) proved that human's needs actually exist objectively. 'Attitude' and 'experience' are ways for humans to understand and reflect these needs. Therefore, emotion can be understood as evaluation of some special existence. This actually supports the feasibility of modelling emotion for virtual humans.

The advantage of emotion modelling in virtual human research is that the integration of emotions and decision-making based on these dynamic emotion states, which are affected by virtual perceptual sensors, can make virtual humans seem more convincing and intelligent (Kang 2005; Zhao 2006; Zhao 2007). Virtual Humans should be capable of responding emotionally to their situation as well as acting physically within virtual environments. Virtual humans will be equipped with a simple computational model of emotional behaviour, to which emotionally related behaviour such as facial expressions and posture can be coupled and used to influence their actions. Apart from making virtual humans more realistic, visible emotions on virtual humans can provide a direct way of affecting the user's own emotional state.

It is believed that general methodology, which is close to human physiology and psychology to feature emotion capabilities for virtual humans, is necessary to provide more convincing virtual characters. Due to the limitations of knowledge in physiology and psychology, this thesis is not attempting to investigate emotion as a psychological concept or provide a new structure for emotion simulation. It is rather to find the appropriate model with only exoterically inspired by psychology for some virtual human problem in computer sciences.

Finally, it is also necessary to distinguish differences between emotion and expression. Emotion in this chapter is intended to be explained as a cognitive process (Ortony 1988), but not expression. Based on this understanding, one's expression will not always equal to one's emotion state. One could hide his/her real feeling and pretend to use different expressions. For example, an upset pleader could pretend that they are calm or even using an opposite expression, smile. But inside he is actually very angry.

2.2.4 Decision-making

As mentioned in the previous section, much work has been done on external modelling of the virtual human modelling. External modelling can be understood as those visible aspects of virtual human modelling, such as the appearance of a virtual character's hair and clothes, skin deformation, motion deformation, facial deformation, etc (Nedel 1998; Badler 2001; Abdel-Malek 2006). However, not as much research has been done for virtual human on internal modelling, such as decision-making, behavioural animation. Some concept and algorithms have been introduced from related field, normally from Artificial Intelligence. As criticised by Badler, these conceptions and algorithms, which had successfully applied and improved the reality of virtual humans in some cases, were not quite suitable for simulating virtual humans in a general way. This is because these problem solving mechanisms, normally rule-based, were not really following the same ways as real humans solve their problems. For example, the algorithms that are used in path-finding need to go through all possible options and make decisions. No one really go through all possible options every time and make decisions after fully analysing all possible situations without the consideration of time limit.

Emotion affects one's decision-making (Frank 1988; Ketelaar 1997; Ketelaar 1998; Lopez 2004; Haselton 2009). The effect is normally observed and represented through one's behaviour and reactions. It happens in everyone's daily life. Those emotional behaviours and reactions can be a fatal factor in certain circumstance and can lead to totally different consequences. In dangerous situations, irrational reactions are adopted by individuals, especially in crowded environments (Zarboutis 2005). For example, in some situations, human beings may switch to hopeful thinking and make their decisions. Real human decision making is based on emotions (Bower 1982), so is the case of virtual human decision making.

Traditional decision-making and problem solving mechanisms based on optimal strategy search are not able to tell the difference. It has been suggested that analysis of the decision-making process is a possible way out (Naqvi 2006). The decision making with emotion features should be considered as a key factor in virtual human design, as it gives virtual characters emotional intentions when making judgement.

2.2.5 Emotion Calculation

Last but not least, an emotional decision-making virtual human needs an emotion generator, known as an emotion calculation module. A suitable interface needs to be created as well in order to integrate the module into the virtual human's decision making system. Due to the shortage of support in psychological research, "the emotion theories to be employed in computational systems are scarcely discussed and very few comparisons are made between projects. There are still many open questions emotion-based projects might face to field developments" (Freitas 2005). Some pioneers did some work on emotion calculation with the motivation of improving the reality of the virtual characters based on artificial intelligence methods (Velásquez 1998; Bazzan 2001; Henninger 2001; Scheutz 2004). They have successfully showed a few emotion features during the virtual human's decision-making and behaviours. However, there is no systematic research on how to integrate emotion theory into computers.

Emotion issues were treated as irrational processing, but now recognised as an important element in a human's decision making and a key issue for the next generation of artificial intelligence (Freitas 2005; Muramatsu 2005). In order to introduce emotion modelling to computer sciences, two problems need to be addressed: well-proportioned emotion measurements for emotion generation and the relations between different emotions.

Virtual human modelling with emotion capabilities is not a pure artificial intelligence problem. Some multidisciplinary research is also involved, such as emotion structure and how it interacts with traditional AI units.

Therefore, in order to improve the emotion generation and emotional decision-making capabilities in computers, it is necessary to propose an appropriate architecture for emotion calculation.

2.3 Summary

In this chapter, main existing virtual human models have been summarized. Five proposals have been offered for this virtual human modelling. These proposals are related to emotional motions and emotional decision making in virtual humans. A brief justification for each proposal is also presented. It is believed that the reality of virtual humans can be improved through adding emotion features. From the next chapter, literatures which relate to adding emotion features into virtual human modelling will be reviewed and clarified deeply.

Chapter 3 Background Research

In **Chapter 2**, the limitations of the existing virtual human models have been reviewed. Five proposals have also been discussed. From this chapter, these proposals are studied with the consideration of related background knowledge from different domains. It is believed that the background knowledge can be applied to virtual human modelling potentially. Some background knowledge also helps to narrow down the topic of this work, and justifies the validity of the chosen method in this work.

3.1 Emotion Models

In order to justify the proposals and exploit the possibility of implementing emotion functions within a computational system, it is necessary to find approaches to implement these functions effectively. Existing computational approaches typically adopt one of two approaches. Communication-driven approaches deliberately select an emotional display purely for its communicative or manipulative effect. Simulation-based approaches, in contrast, attempt to simulate aspects of emotion processes, essentially giving the agents true emotions. Although this distinction is blurred in humans, computational systems can, and typically have, adopted just one of these perspectives. The virtual human modelling in this work is not communication-based. The initial intentions were to simulate aspects of emotion processes based on analysing and modelling human's cognitive structure of emotion.

Based on the review of the history of virtual human models, one can conclude that, in computer science, previous research has attempted to improve the reality of virtual human based on predetermined empirical data and optimisation functions. The emotion issues have not been fully considered in the simulation of an intelligent virtual human system, even though it incontestably affects a person's behaviour in daily life. Some researchers had realised how different the situation could be if emotional reactions had been adopted (Breazeal 2003; Sevin 2006). However, there is still no convincible emotion generation model for virtual human modelling. The role of emotions in virtual human modelling is not matched by the status of emotion in real human's decision-making and behaviour. This is because the application of virtual humans in ergonomics is more likely to focus on using the virtual human models as an immersed information sensor for its virtual environment. Emotion issues are not the main interests of ergonomic analysis. Virtual human models are normally developed for specific applications in ergonomic analysis. Even though many effort has been made on how to improve the reality of interaction between a virtual agent and its surrounding virtual environment, the virtual human models for ergonomic analysis are normally equipped with relatively simple behaviour strategies. This is mainly due to the limitation of application as in each individual case, such as, predefining tasks for virtual agents and recording interactive data from the virtual agents during the simulation. Some of these applications have pre-programmed some attribution to make the virtual human appear to react emotionally.

The study of emotion reaches back well over a century (Darwin 1872) and has produced a wide range of theories: identifying emotions with outward expressions, physiological responses, distinct behaviours, or cognitive processes, among others.

Damasio gives the definition of emotion as “the combination of a mental evaluative process, simple and complex, with dispositional responses to that process, mostly toward the body proper, resulting in an emotional body state, but also toward the brain itself (neurotransmitter nuclei in brain stem), result in additional mental changes.” (Damasio 1994) Emotional states also greatly influence perception, attention, promote selective memory and learning (Bower 1982).

Sevin summarised five advantages of emotions in real human's life: 1. emotions take control in an emergency, 2. re-equilibration of internal milieu, 3. management of social interactions, 4. emotions in mood and general state influence, and 5. make behaviours more realistic, autonomous, coherent and adaptive. In emergency, such as evacuation from fire, emotions take control of decision-making. “Motivations are in charge of driving behaviours under normal circumstances; emotions affect behaviours and change goal priorities in situations requiring an urgent response” (Cañamero 1997). Emotion is also related to moods and temperaments. A mood can be explained as a (low) tonic level of arousal of emotion, whereas emotions affect more sudden activities within a relatively short duration. Temperaments can be explained as “predetermined” threshold levels that make the activation of a particular emotion more likely. Last but not least, emotions and their expression are crucial in communication for autonomous agents situated in complex social environments. They give a lot of information about the current state of virtual agents and increase believability. Therefore, emotions seem to have a central position in autonomy and adaptation in biological systems to build “life-like” virtual characters with better interaction capabilities, with more flexible behaviour, showing human-like style of “errors”, etc. (Sevin 2006)

In the past decade, as well as in neuroscience and psychology (Plutchik 1980; Frijda 1993; Ledoux 1996; Antonio 2001), emotion has attracted the attention of researchers in computer sciences and artificial intelligence areas (Frijda 1995; Custodio 1999; Petta 2001; Mera 2003). The idea that emotion associates with irrationality idea and non-logical behaviour in human beings was oppugned (Goleman 1995; McCauley 1998; Bryson 2001; Gratch 2004). This virtual human modelling is especially interested in scientific beliefs that emotions play an essential role in human cognitive processes and about its importance for problem solving competence and decision-making.

Emotion models are computational approaches which are based on some descriptions or theories (Malatesta 2007 (1)). The approaches are often combinations of more than one type of description from psychology and computer sciences. Emotion models expect to validate these descriptions / theories and also extend them. They allow the simulation of behaviour and aid in recognizing and understanding human emotions as well as generating synthetic emotional responses.

Simon claimed that an explanatory account of human rationality must identify the significance of emotions for a choosing behaviour (Simon 1983). The importance of his opinion has been recognised and appreciated more recently. Cañamero pointed out that "motivations states are drives that constitute urges to actions based on internal bodily needs related to self-sufficiently and survival, whereas emotions are the second-order modifiers or amplifiers of motivations and behaviours. Emotions enhance autonomy, adaptation, and social interactions in artificial and mixed-agent societies" (Cañamero 2001).

A number of computational models addressing emotion have been developed in cognitive science and Artificial Intelligence. One of the earliest affective theory points out the intensity and density characteristic of emotions (Tomkins 1984). According to Tomkins, optimal mental health requires the maximization of positive affect and the minimization of negative affect. Malatesta divides emotion models into two categories. "Some are named 'deep models'. These models take into account the situations that initiate the emotions and how they are construed by the testing subjects and focus on the predicted emotion. The others are called 'shallow models'. These models deal with the 'results' of an emotional episode, for example, facial expression, voice, conversational virtual human etc (Malatesta 2007(2)). However, in recent work, the boundary of these two categories is already blurred and intends to integrate 'deep models' into systems in order to improve the 'results' of so called 'shallow models'.

One thing that can be used to differentiate the emotion modelling approaches is the level of abstraction. The level of abstraction can be used as a key criterion in the selection of the appropriate models. In this section, the existing emotion models are classified into three types based on their different levels of abstraction:

- The first group of emotion models is called mechanism-level emotion models. These models have a lower level of abstraction, which attempt to emulate some specific aspect of affective processing (Frijda 1987).

- The second group of emotion models is called task-level models of emotion. These models have an intermediate level of abstraction, which focus on addressing a single task, such as natural language understanding or specific problem solving (Raouzaiou 2005; Ioannou 2005; Malatesta 2007(1)). Ekman proposed models for facial expression. His emotion model indicates six basic emotions: fear, anger, sadness, happiness, disgust, surprise. These six expressions are understood universally (across cultures), but there is also a much larger number of possible expressions and these are not a combinatorial "basis" for the others. The model is proposed as a model to be applicable universally across cultures (Ekman 1992). Ren et al proposed an emotion measurement system (Ren 2003) based on the multifactor-analytic emotion theory (Plutchik 1960). They also proposed an algorithm for the prototype system which is based on natural language processing. It is supposed to simulate how an audience understands the intention of the speaker by recognizing key words in context and generates corresponding emotion based on the key words. However, it cannot handle those situations when the context cannot be realised.

- The third group is called architecture-level models. These models have a higher level of abstraction, which embody emotion processing. As opposed to deliberately conveyed emotion as in communication-driven models, these simulation-based emotion modelling models, which embody emotion processing, attempt to simulate 'true' emotion. Rather than triggering emotional displays explicitly because of their communicative function, emotion displays are tied to the agent's simulated emotional state (Ortony 1988; Scherer 1993; Velasquez 1997; Canamero 1998; Paiva 2000; Breazeal 2003; Fiorella 2003). Ortony et al investigated a cognitive model of emotion based on OCC theory (Ortony 1988).

Gratch et al applied a computational framework of appraisal and coping to model emotion as a core aspect of virtual human's behaviours (Gratch 2004). Pribram proposed an emotional mechanism as complementary roles. While motivation is concerned with the operations of appetitive processes that try to activate action as a response to deprivation, emotion is derived from processes that try to stop ongoing behaviour (Pribram 1984).

These architecture-level models range from individual processes to integrated architectures, and explore several of the emotion theories outlined above. Since an emotional system is complex and connected to many other behavioural and cognitive subsystems, it can act on these other systems at different levels at the same time. On the other hand, since emotions are related to goals, they contribute to the generation of richer, more varied and flexible behaviours in addition to motivations. These models are largely used for emotion synthesis (Ortony 1988; Frijda 1995; Cañamero 2001).

According to a review of emotion models, the most frequently modelled process among emotional models is cognitive appraisal, whereby external and internal stimuli are mapped onto a certain emotion (Hudlicka 2003). Several alternatives have also been hypothesized for these processes in the psychological literature (Frijda 1986; Ortony 1988; Lazarus 1991; Scherer 1993; Smith 2000). A number of these models have been implemented, both as stand-alone versions, and integrated within larger agent architectures (Scherer 1993; Velasquez 1997; Canamero 1998; Castelfranchi 2000; Breazeal 2003; Fiorella 2003).

Gratch and Marsella offer one of the more mature computational models of agent emotion (Gratch 2004). The Gratch-Marsella model (**Figure 3-1**) offers a sophisticated implementation of current psychological theories of emotion. It is more likely to be fitted in an affective computing system, rather than an emotional decision making model which can be integrated into a virtual human simulation system. Even there are a large number of proposals in emotion modelling, not many of them have been well developed as Gratch and Marsella's model after the OCC model. **Table 3-1** summarizes the correspondence between salient elements of the OCC model and Gratch-Marsella model (Parunak 2006).

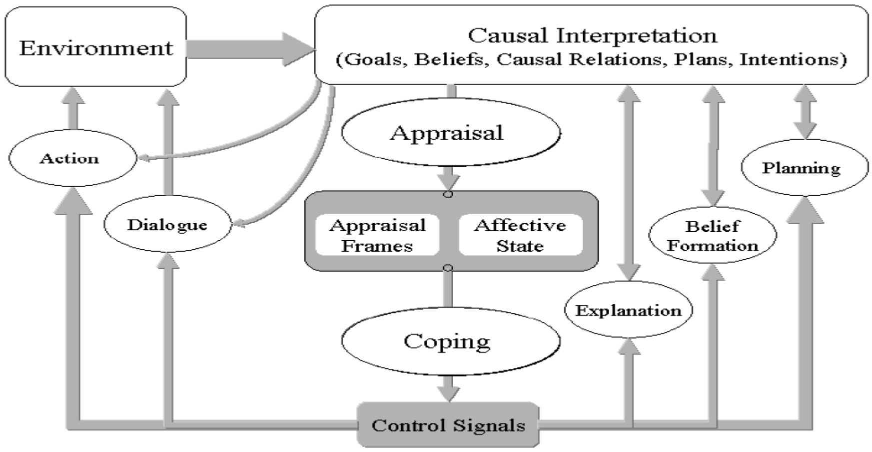


Figure 3-1 Gratch-Marsella Model of Cognitive-Motivational-Emotive System

Table 3-1 Comparison of models (Parunak 2006)

OCC	Gratch-Marsella
Environment	Environment
Perception	Casual Interpretation
Beliefs	Casual Interpretation
Appraisal	Appraisal
Emotion	Affective State
Analysis	Coping
Desires	???
Intention	Control Signals
Action	Action

An interesting figure which indicates a history of computational models of emotion has been found on Gratch's research links at University of South California. It might give researchers some ideas about the state of research in the field (**Figure 3-2**).

Other emotion model implementations include models of emotions based on facial expression (Ekman 1993; Raouzaiou 2005; Ioannou 2005; Malatesta L. 2007), models of emotion based on blends of basic emotions (Raouzaiou 2002), models as goal management mechanisms (Frijda 1987), models of interaction of emotion and cognition (Araujo 1993), explicit models of the effects of emotion on cognitive processes (Hudlicka 2003), and effects of emotions on agent's belief generation (Gratch 2004).

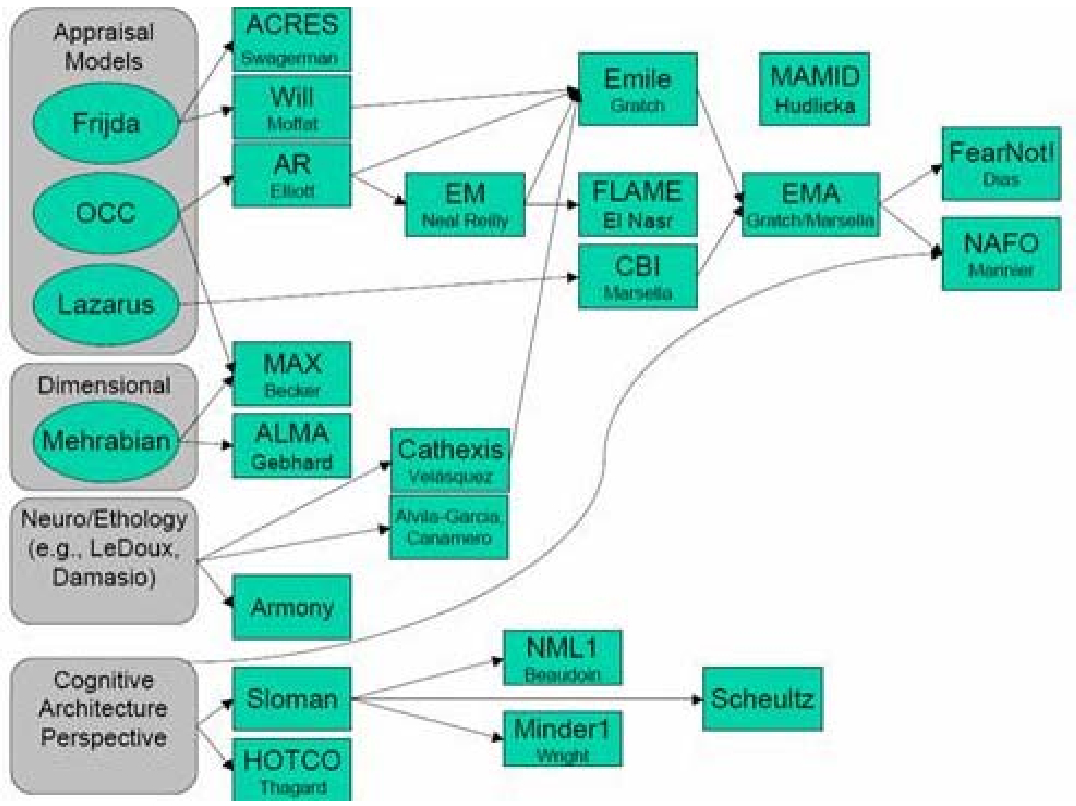


Figure 3-2 A history of computational models of emotion (Gratch's homepage at USC)

Even with considerable literatures in the research area, building emotion-based systems is still a difficult job. The computational conceptions of emotion are as problematic and complex as computational understanding of life. Through the mentioned projects above and my understanding, the emotion modelling here is divided into the following two sub-issues: first, is there well defined scientific framework to approach 'emotion modelling'? (The structure of emotions); Second, is there a psychological method which can measure the emergence of emotions? (Psychological measures of emotion).

3.1.1 The hierarchical cognitive structure of emotions

Numerous attempts have been made to characterise the structure of emotions. Examples of integrated architectures focusing on emotion include most notably the work of Sloman and his colleagues at the university of Birmingham (Sloman 2001). More recent, efforts to integrate emotion with a synthetic force model have been proposed in Soar Technology, Inc. by Jones et al. They intended to integrate emotion with a general cognitive architecture for developing systems that exhibit intelligent behaviour (Jones 2002). These attempts have been developed in different ways for different purposes. Emotion models have been proposed based on all kinds of variables, such as biological/evolutionary variables (Zhai 2005), phenomenal variables (Riveria 1977), behavioural variables (James 1884; Breazeal 2003), facial expression variables (Ekman 1982), and cognitive variables (Roseman 1984; Ortony 1988). As mentioned previously, most simulation-based models share the appraisal theory as the same root when tracing their link to a psychological theory.

Early appraisal models focused on the mapping between appraisal variables and behaviour, but largely ignored how these variables might be derived, focusing on domain-specific schemes to derive their value variables. The OCC emotion model introduced 22 emotion types in details and presented a cognitive structure for emotions (Ortony 1988). Affective Reasoner (Elliott 1992), created by Elliot, is based on OCC's appraisal theory. It required a number of domain specific rules to appraise events. More recent approaches have moved toward more abstract reasoning frameworks, largely building on traditional artificial intelligence techniques. Markov decision processes (MDP) have been introduced by El-Nasr et al to provide a very general framework for characterising the desirability of actions and events (El-Nasr

2000). The method could represent indirect results of actions by examining their effect on future reward, but the MDP method retains a disadvantage: it can only represent a relatively small number of state transitions and assume fixed goals. Moffat connects appraisal variables to an external model of plans (Moffat 1995). The plan model captures the causal relationships between actions and effects. However, it does not cover some basic emotion types and makes it incomplete as an autonomous system.

Gratch and Marsella's model, EMA, is known as one of the more comprehensive models, combing a plan-based model of appraisal with a detailed model of problem-focused and emotion-focused coping (Gratch 2004). W. Reilly proposed an emotion generation and storage process for his believable emotional agents (Reilly 1996). Reilly explained some emotion generation processes. For example, the intensity of distress is based on the importance of goal not to fail and the change in the likelihood of failure. However, he did not explain how these variables are measured and how the variables are changed with dynamic environments.

More recently, Ortony expatiated on his understanding of emotions again (Ortony 2007) with compares to the emotional intelligence proposed by Salovery and Mayor (Salovey 1990; Mayer 1997). He believes that "differences in concept of EI ultimately come to rest in different conceptions of emotions". He also presented a validated test to support his theory.

After reviewing these related works, it can be concluded that no existing approach can be clearly identified as well-accepted in emotion modelling and no researcher had declared that his model can take a dominant role in the field. However, it seems that the most frequently implemented theory in computer science is the OCC appraisal model, which is implemented in a number of systems and agents (Bates 1992; Elliott 1999; Andre 2000; Martinho 2000; Bartneck 2002; Parunak 2006; Garcia-Rojas 2007).

3.1.2 Physiological measures of emotion

During modelling emotion capability for virtual humans, it is also necessary to know how emotions change along the time. Therefore, besides modelling an emotion model as a computable structure, some literatures proposed to model emotion in virtual humans through measuring the bio-signal changes of the human body.

There are some discussions about how emotions can be affected in intensity by relative variables. Recent empirical studies have been influenced strongly by Lang's proposal that emotions can be defined by responses in three partially independent but interacting systems: verbal report, behavioural action, and expressive physiology (Lang 1978).

It has been over 100 years since the first empirical investigation of electrical changes in the human skin (Vigouroux 1888), and since that time, electro-dermal activity (EDA) has been one of the most widely accustomed systems in all of psychophysiology (Dawson 1990). The most widely applied method of electro-dermal response measurement involves the passage of an external current of constant voltage across the skin and then measuring the current flow across two electrodes placed on the fingers or the palm (Fowles 1981).

Emotion measurement techniques focus on measuring physiological signals of emotion to speculate emotion changes for psychology research and computer applications (Bauer 1998). Skin conductance response method (SCR), also known as Galvanic skin response (GSR), Electrodermal Response (EDR), or Psychogalvanic Reflex (PGR), is a psychological method of measuring the electrical resistance of the skin. In the emotion literature, SCR has been extensively studied because of its direct correlation with sympathetic nervous system activity. Some studies suggest the SCR amplitude is correlated with arousal ratings for both positive and negative stimuli (Greenwald 1989). SCR measurement is highly sensitive to emotion in some people, which can help researchers to identify particular rules between corresponding emotion to its stimuli (Bauer 1998). Lykken and Venables (1971) recommended direct measurement of the reciprocal of resistance, skin conductance, since this measure has a more linear relationship to the number of active sweat glands (Lykken 1971). The most widely used measure is the amplitude of skin conductance response (SCR), defined as the difference between base level measured in the immediate pre-stimulus interval and the maximum SC level attained in the immediate post-stimulus interval. One significant issue in quantifying SCR is the existence of large individual differences in the range of responding. Lykken et al have proposed a range correction methods that represents each response as a proportion of the individual subject's largest response (Lykken 1966).

Skin conductance has become such a popular measure in psychological research of emotion partly because it is so easy to obtain, and also because its underlying basis is so well understood. It is also relatively free of influences from somatic motor activity.

The SCR method has been extensively studied because of its direct correlation with sympathetic nervous system activity. There are some attempts of using the amplitude of SCR to differentiate among specific emotions (Ax 1953; Picard 2003). For example, R. Picard used SCR combined with other bio-signal methods to distinguish anger and grief. Some studies suggest that SCR amplitude is correlated with arousal ratings for both positive and negative stimuli (Winton 1984; Greenwald 1989).

As the SCR method shows the relationship between skin conductance and emotion related stimuli, the matured psychological method is adopted to measure how intensity of emotion changes based on different stimuli in this work. The increasing and decreasing curves of certain emotion will be modified and represented in equations for emotion calculation modelling. In this virtual human modelling, the SCR testing data are collected and analysed in order to identify the relationship between visual stimuli and corresponding emotion changes. After lots of tests and analysis, some basic rules have been found. Especially for different individuals, it is easy to distinguish different emotion arousing curves and interpolate equations for simulation processing.

3.2 Emotional behaviour and decision-making models

3.2.1 Behaviour models

Behaviour models focus on statistical research of human behaviour and its appearance in simulation. It is mainly applied in ergonomics and safety simulation. Before the 1990s, many behaviour models of reactive agents were accomplished by a simulation with 2D graphical output (Agre 1987; Howe 1990; Pollack 1990). Limited by the development of computer technology, these simulation environments are extremely simplified, discrete, and purely kinematic space.

Human's behaviours with emotions have been reviewed for several years. Most early literature and models were composed mostly of panic reactions, fire threats and sports. The first systematic investigation of human responses to threats of fire was completed in UK in the 1970s by Wood. He interviewed approximately 2,000 individuals who had been involved in almost 100 fires (Wood 1990). Wood looked at what actions people took and who took them, but did not attempt to explain these actions. David Canter compiled an anthology which provides case studies and information about some major incidents that occurred in the 1980s. He investigated how to model human's behaviour under fire situations in his book which is still one of the best available summary in the field (Canter 1990).

Jung presented a method for an animated human agent to construct motion plans to achieve 3D-space postural goals while avoiding collisions. The animated human agent can achieve multiple goals individually, and explicitly detect and remove conflicts between the suggested joint motions (Jung 1993). Reich presented a real-time behavioural reasoning system driven by several agent navigation units which include a terrain reasoning with behavioural constraints, simulation of a variety of locomotion techniques and a few simulated sensors (Reich 1994). Since then, more and more environmental factors have been considered in behaviour modelling. Complex environments are considered as an important factor, as "the complex behaviour is often due to a complex environment, where the agent responds to environmental complexity through simple feedback mechanisms of synthetic sensation. (Simon 1981)"

More recently, researchers have considered the behaviour models of groups (Pelechano 2005; Pelechano 2006). Sime tested a model based on a fire in August 1973 at a seaside leisure centre in the UK, where 40 people died in the fire. His model summarized that people facing potential entrapment would move toward familiar places and persons (Sime 1985). He argued that designers presume there is a deterministic relationship between an exit's location and its use in an emergency. However, he found there are two important factors other than proximity to an exit that affect human's behaviour: an individual's familiarity with a particular travel route and their ties to others elsewhere in the building. (Sime 1984)

The Pittsburgh Research Laboratory had interviewed 48 workers who escaped from 3 burning coal mines in the US during 14 years, and studied their experiences and behaviours in details. a model of the judgement and decision-making process in mine fires evacuation has been proposed and analysed (Vaught 2000).

There are also some researchers who have considered improving the behaviour modelling of virtual human from other aspects. Some considered attention behaviours to improve the realism of virtual characters (Chopra-Khullar 2001). Some consider cultural diversities when creating virtual characters (Allbeck 2004). Some other researchers try to model the Individual Spontaneous Reactive Behaviour of virtual humans (Garcia-Rojas 2007; Garcia-Rojas 2008).

Pelechano *et al* summarised the main existing virtual crowd models and established a baseline of techniques and requirements for simulating large-scale virtual human populations (Pelechano 2008). In the book, *Virtual Crowds*, they presented that most existing crowd simulations include only basic locomotive behaviours and possibly coupled with a few stochastic actions. They also presented a framework to realistically simulate crowds affected by psychological and physiological elements within complex virtual environments. Their framework includes both crowd and individual goals into a comprehensive computational model which expected to simulate the visual texture and contextual behaviours of groups of seemingly sentient beings.

Those behaviour models from different research areas have helped to understand people's behaviour under emotions, especially, under dangerous situations and inspired the direction of modelling virtual humans with emotion capability.

3.2.2 Decision making models

There are some traditional decision making mechanisms for robots and virtual humans which adopt unbounded rationality theory. A virtual human determines its behaviour by reasoning about what it knows to be true at a specific time. The classical planning systems provide predefined plans to instruct a virtual character how to satisfy some goals step-by-step (Rao 1991). Basically, these systems require fulfilling some preconditions in order to activate their effects. Giving a goal to a virtual character will trigger some plans and generally activate some sub-goals. For example, if precondition of a virtual character is hungry, the virtual character has to eat. The effect of the plan is to set up a goal as 'need food'. This goal then triggers some sub-goals, such as the virtual character should pick up a sandwich and put it into its own mouth.

Ethologists, observed in natural intelligence researches, already postulated hierarchical and fixed sequential orderings of actions into plans that are necessary to reach specific goals and to obtain proactive and intelligent behaviours for complex autonomous agents (Bryson 2000). Hierarchies reduce the combinatorial complexity of action selection. For example, the goal-oriented hierarchical classifier systems (Donnart 1994). It can reduce the number of options that need to be evaluated when selecting the next action. However, hierarchical systems have also been criticised because of their rigid, predefined behaviours (Brooks 1991; Maes 1991). To obtain more reactive systems, constant parallel processing has to be added (Tyrrell 1993; Blumberg 1996).

However, even with hierarchies, absolutely reactive architectures make the action selection extraordinarily complex. As most early artificial intelligence research followed these hierarchical models, action selection presented a great difficulty in coping with dynamic environments in real time. The set of actions is determined by contexts which include the internal state of the virtual agent. A choice is made at each level of the hierarchy with neglecting other possible choices. Decision-making architectures should be both reactive and capable of dealing with complex tasks. If hierarchical or sequential controls are avoided, then connecting behavioural models becomes difficult. To simplify the decision-making process, modularity is adopted because it allows the agent's intelligence, or some parts of it, to be decomposed into a few small, relatively autonomous units. These modularised units execute and communicate with each other to decompose the whole problem into sub-problems. At the same time, decision-making architectures should be able to detect virtual environments so that the virtual agent will make appropriate responses according to unexpected and opportunist changes in the scenario. In order to take advantage of both reactive and hierarchical systems, some researchers (Bryson 2000; Thorisson 2004) have implemented attention mechanisms, which reduce the internal information and thus simplify the action selection task. The main disadvantage of these kinds of architectures for decision-making and action selection is as clear as their advantages. They can perform better than absolutely reactive systems, but also loose interim information and are more likely lead to a middle course of behaviours.

Rather than using a top-down approach as in Artificial Intelligence, researchers have tried bottom-up solutions by using Artificial Life techniques. Langton pointed out that Artificial Life is literally ‘life made by Man rather by Nature’ (Langton 1990). It mainly relies on the notions of evolution and emergence. The idea is to firstly model a virtual character. Then new behaviours will emerge by simulating virtually natural-life evolution and the complexity of both the virtual character and its environment. Since the virtual character always repeats a sequence of three behaviours (perception of the environment, action selection, and reaction), it continuously updates information from its environment, which, in turn, influences the virtual character’s decision making and reaction as well. Bottom-up approaches can yield simple animal-like behaviours which are closer to a real human’s behaviour mechanism compared with top-down approaches, but it can not yield human decision-making, memory, and planning. It is still not enough to indicate the individual differences of virtual characters, as individual’s reactions are not always intelligent in the real world with limited time and knowledge. In most situations, people have to make quick, but not rational, decisions within limited time and with limited knowledge about situations. Therefore, when modelling virtual humans, it is necessary to consider some theories that can be adopted in complex situations with limited knowledge and time to help virtual humans make their own decisions and reactions.

One possible way to solve this problem is to limit the virtual human’s rational capability in order to match up with a real human. In 1947, Simon proposed the notion of Bounded Rationality: a property of an agent that behaves in a manner which is nearly optimal with respect to its goals as long as its resources allow (Simon 1957). Herbert Simon points out that most people are only partly rational, and are in fact emotional / irrational in the remaining part of their actions. In his later article, Herbert Simon, has explicitly rejected its reduction to optimisation under constraints: “bounded rationality is not the study of optimisation in relation to task environment” (Simon 1991). His vision of bounded rationality has two interlocking components: the limitation of the human mind, and the structure of the environments in which the mind operates. The first component is quite easy to understand as judgement and decision making should be built on what humans actually know about the mind's capacity rather than its fictitious competencies. The second component of his view explains when and why decision making strategies perform well: if the structure of the decision making is adapted to that of the environment. In the majority of situations, bounded rationality is a useful model of human behaviour. However, it has not defined when a 'nearly optimal' is good enough and can be called rational. This makes the method not distinguishable from many methods that deal with problem solving within limited resources. Therefore, a more flexible method which can integrate emotional units with rational decision-makings needs to be developed.

The application of virtual human modelling with behavioural animation capabilities has helped to create more life-like and believable autonomous characters for the entertainment industry. 'Creatures' was the first game to add neural networks, which let users teach virtual creatures how to behave. More recently, 'The Sims' focused on the simulation of virtual humans in their everyday life, with believable and fun results. Virtual human can also help training people in difficult situations, such as a pedagogical system (Rickel 1997) and expected to provide advice or inspiration for architectural and industrial design.

Another possible way to simulate realistic virtual human decision making is to simulate the role of emotion in decision making (Naqvi 2006). Sevin proposed an affective model of action selection for virtual humans. His work aims to implement progressively, an action selection model for virtual humans that should be in the end autonomous, adaptive and sociable. He presented a bottom-up approach by implementing a motivational model of action selection to obtain motivationally autonomous virtual humans. He also defined the interactions between motivations and emotions in order to integrate an emotion layer and improve the adaptability and the completeness of the affective action selection of virtual humans. He also declared that the motivations should represent more quantitative aspect of the decision making whereas emotions should represent a more qualitative aspect (Sevin 2005).

Heuristics, in psychology, are simple, efficient rules, hard-coded by evolutionary processes or learned, which have been proposed to explain how people make decisions, come to judgments, and solve problems, typically when facing complex problems or incomplete information. These rules work well under most circumstances, but in certain cases lead to systematic cognitive biases. For instance, people may tend to perceive more expensive beers as tasting better than inexpensive ones (providing the two beers are of similar initial quality or lack of quality and of similar style). This finding holds true even when prices and brands are switched; putting the high price on the normally relatively inexpensive brand is enough to lead subjects to perceive it as tasting better than the beer that is normally more expensive. One might call this "price implies quality" bias (Pearl 1983).

Much of the work discovering heuristics in human decision-making was proposed by Tversky and Kahneman (Kahneman 1982). Some researchers had developed the theory with merging heuristics with existing decision-making strategies. Gigerenzer proposed to examine simple alternatives to a full rationality analysis as a mechanism for decision making. He focuses on how heuristics can be used to make judgments that are in principle accurate, rather than producing cognitive biases (Gigerenzer 1999). He and his colleagues had shown that such simple heuristics frequently lead to better decisions than the theoretically optimal procedures. For example, in a case study, Gigerenzer investigated an environment consisting of eight objects and examined his theory by discussing the case from three different aspects. In particular, he examined the robustness of ‘take the best’ strategy (one of the simple heuristics strategies), and tested its frugal principles for starting or stopping a search.

After comparing different decision making models for virtual human modelling, a simple heuristics theory is more appropriate to present the emotion features of humans in virtual human modelling. As it is more likely to meet the nature of human’s decision-making process for modelling virtual human's decision-making under emergency situations. It is also possible to integrate emotion features into simple heuristic structures. Sevin had constructed some emotion features in his action selection model for virtual humans. However, he only presented the statistical results about how emotions can affect virtual human's behaviour, without comparing how emotions affecting difference behaviours (Sevin 2006). Furthermore, it is also easy to realise and manipulate simple heuristic decision-making architecture in the computer language. From a computational point of view, decision procedures can be encoded in algorithms and heuristics. An agent that has better algorithms and heuristics could make "more rational" (more optimal) decisions than one that has poorer heuristics and algorithms when all other properties are equal.

3.3 Synthetic perceptions and memory

3.3.1 Synthetic perceptions

During the research of virtual humans, many ways of simulating visual perceptions have also been proposed. Renault introduced the conception of synthetic vision and presented the method for high level animated actors (Renault 1990). His research target was to have each virtual actor moving in a corridor avoiding objects and other virtual actors. The synthetic vision in his research was to render off-screen scene pictures which are viewed by the synthetic actor and stored in a 2D array. The array was limited in size because of the time requirements of CPU calculation. Each object was identified by rendering with a unique colour. Each pixel of the view contained the distance from the synthetic actor's eye to the object point and information to identify one object from another. The resolution of the view was 30 by 30 pixels as Renault thought this was sufficient for the corridor problem. The method has also been successfully applied to animals, such as fish (Tu 1994). However, the method suffers from dynamic memory cost, as rendering the whole scene for virtual actors is costly in a real-time application. Therefore, a more practical method is required for real-time virtual human modelling.

Noser extended Renault's work and introduced memory and learning mechanisms. He presented an overview of some principles of synthetic vision and distinguished synthetic vision from artificial vision (Noser 1995(2)). He declared synthetic vision to be the simulated vision for a digital actor. Artificial vision is a process of recognising the image of a real environment captured by a camera. In synthetic vision, the synthetic actor perceives its environment from its own point of view by a small window of 40X40 pixels, and the synthetic actor can locate visible objects in its 3D space via the Z-buffer value of the pixels, the colour of pixels and its own position. Noser also proposed an occupancy grid model, such as an octree, to represent the visual memory of a virtual character (Noser 1995(1)). This method successfully reduces the amount of data in process.

Peters proposed a synthetic vision module based on the model described by Noser et al (Peters 2002). He added a model of bottom-up visual attention to his virtual human. The attention model is based on a "saliency map" (Itti 2005), which is an explicit two-dimensional topographic map encoded for stimulus conspicuity, or salience, at every location in the visual scene. The inputs of the saliency map are received from early visual processing. Then, the focus of attention scans the saliency map by an efficient control strategy in the order of decreasing saliency. He also proposed a memory model based on stage theory to provide a virtual human's attention to its environment. Kuffner also conducted research (Kuffner 1999) based on the model described by Noser et al. He increased the size of the rendering image to 200 by 200 pixels. Instead of depending on the object geometry stored in the environment, the visual memory model he proposed relies on a list of object IDs and their most-recently observed states. However, he did not specify the maximum view angle for his model as well.

Tu proposed a rudimentary model of fish perception, vision and sense of temperature, for their artificial fishes (Tu 1994). Each artificial fish has a cyclopean synthetic vision sensor which is limited to a 300 degree spherical angle extending to an effective radius. The visibility of a point *P* for their artificial fish is like this: a ray is shot from the origin point of the fish's view to the point *P*. If the ray $\overline{OP}$ is within the effective radius and effective direction, and, the ray $\overline{OP}$ does not intersect other objects, then the point *P* is visible for the fish. This synthetic vision sensor shows the field of vision on animals.

Nicolas Courty described the shape of his synthetic vision system as a pyramid volume with an vision of 120 degrees (Courty 2003). However, it is still far from the real boundary of human vision.

Besides synthetic vision, Bordeux proposed a perception pipeline architecture into which filters can be combined to extract the required information (Bordeux 1999). The geometric vision filter represents the basic entity of the perception mechanism. Such a filter receives a perceptible entity from a scene as input, extracts specific information about it, and finally decides to let it pass through or not. The criteria used in the decision process depend on the perception requirements. For virtual objects, they usually involve considerations about the distance and the relative direction of the object, but can also be based on shape, size, colour, or generic semantic aspects, and more generally on whatever the agent might need to distinguish objects. Filters are built with an object-oriented approach. For example, the very basic filter for virtual objects only considers the distance to the object.

Synthetic vision is considered as one of the most realistic methods to simulate human vision. It can correctly address vision issues such as occlusion. However, rendering the whole scene in real-time applications is still costly for virtual humans. In real-time applications, geometric vision has its advantage. However, the major problem with geometric vision is finding the proper formulas for the object that can have different shape from different perspectives. This makes the geometric vision method less accurate than the synthetic vision method. Meanwhile, both the synthetic vision and the geometric vision methods have not emphasised the range for human's field of view (maximum angle for vision). The conception of field of view, which is widely applied in ergonomics, has not been widely accepted by virtual human designers in computer sciences.

As mentioned in **Chapter 1**, the behaviour of virtual humans should be presented as a result of a multi-agent system sharing a virtual environment. For this purpose, architecture allowing the merging of individual virtual sensor modules with the current multi-agent model is being developed. Conde has presented an original model with methodologies that integrate different types of virtual sensors into the same multi-sensorial control architecture. It is called Artificial Life Environment (AlifeE) framework. The architecture is based on the standard theory of neuroscience, which allows the virtual characters unify signals related to the same virtual object but not coming from distinct sensory system (Conde 2004; Conde 2006).

3.3.2 Virtual memory modelling

The constraint of short-term memory means that humans can only recognise a limited number of objects which they glimpse at (Gross 2001). This means some objects may not be recognised in some real situations. In the virtual world, unrecognised objects will not affect the virtual character’s emotion state and reaction, even if those objects have been glimpsed at. In other words, objects may be "in view" but not perceived due to attention processing and cognitive bandwidth limitations. This is called "attention blindness".

Some form of memory is crucial for agents that are disconnected from the environment. In virtual worlds, autonomous virtual agents differentiate between what they have and have not observed through their memory. One of the simplest solutions is to let a virtual agent directly know the location and additional information of all objects in the virtual scene. For example, this method can be used when the number of virtual agents is high, such as, in Reynold’s flocks of birds (Reynolds 1987) and schools of fish, in Musse and Thalmann's crowd simulation (Musse 2001). As the positions of their neighbours are known directly, the virtual agents can work out a collision avoidance trajectory. However, this solution is far from the real situation. Therefore the application of the virtual human model is limited, even it can be useful in some cases. On the other hand, a virtual agent with no memory of surrounding information will appear to be unimpressive (stupid) in some way when conducting tasks. There are lots of instances where memory plays a large part in everyday human behaviour. For example, item searching when the item is out of vision. In this case, where an item has been seen previously and remembered, the searching process can begin with the position where the item has been remembered in memory. In contrast, one who had no memory of the position of a wanted item would be obliged to launch a lengthy search. These situations are part of daily human life, such as searching for door keys, and such imperfections may be a factor in decreasing the plausibility of a virtual agent's reactions with respect to a human. Virtual memory is a way to decide when such reactions are necessary. It has been suggested that a memory model entails the storage of multiple copies of the virtual world database (Gillies 2001). In the most extreme case, a virtual agent has to perceive all objects in its virtual world and its virtual memory has the same size as the virtual world database. The searching process then has to go through the whole virtual world database whilst assuming that the virtual agent autonomously knows the location of every object. In this case, filtering and forgetting mechanisms can be applied to the virtual memory system. Filtering ensures only important information is stored in virtual memory. Forgetting clears the information that is no longer valuable or too long ago to be remembered as human sense.

A memory model based on "stage theory" (Atkinson 1968), an influential concept of memory from the field of cognitive psychology, is presented for application to autonomous virtual humans by Peters and O'Sullivan. In their autonomous virtual human model, virtual humans sense external stimuli through a synthetic vision system. The memory model is used to store perceived and attended object information at different stages in a filtering process. The advantage of this method is it could be applied in any area where simulation-based agents are used: training, entertainment, ergonomics and military simulations (Peters 2002; Peters 2003). This method is also the basis of massive software for crowd modelling (Allbeck 2004; Pelechano 2006; Durupinar 2008).

Noser, et al used an occupancy grid model (for example, an octree) to represent the visual memory of each virtual character (Noser 1995(1)). Kuffner and his colleagues instead relied on the object geometry stored in the virtual environment, along with a list of object IDs and their most-recently observed states. It provides a compact and fast representation of each character's internal world model that is scalable to large environments with many characters (Kuffner 1999).

3.4 Summary

In this chapter, background works which related to this virtual human modelling has been reviewed. Based on this review, there is already sufficient work to support virtual humans with emotion capabilities. It is possible to create a more believable and realistic virtual human by modelling emotion processes and present these internal changes through their emotional movements and emotional decision-making. In order to justify this work, the related works in emotion modelling for computer sciences are also discussed. In **Table3-2**, existing models in this field are compared as well.

From the next chapter, the methodology of a virtual human model with emotion capabilities will be introduced. Some existing methods in emotion modelling will be mentioned again with necessary comparison and discussion in order to explain how the method in this thesis is designed and implemented from existing methods in computer science and other related research areas.

Table 3-2 A compare of the existing emotion models

<table>
<tr><th>Classification</th><th colspan="3">Existing Emotion models</th></tr>
<tr><td>Mechanism-level Emotion Model</td><td>Addressing a single task</td><td colspan="2">ACRES (Frijda 1987)</td></tr>
<tr><td rowspan="3">Task-level Emotion Model</td><td rowspan="3">Emulating some specific aspect of affective processing</td><td>Natural language understanding</td><td>(Raouzaiou 2005; Ioannou 2005; Malatesta L. 2007)</td></tr>
<tr><td>Specific problem solving</td><td>(Ekman 1992)</td></tr>
<tr><td>Facial expression</td><td>(Ren 2003; Plutchik 1960)</td></tr>
<tr><td rowspan="5">Architecture-level Emotion Model</td><td rowspan="5">Embodying emotion processing and attempting to simulate ‘true’ emotion</td><td>Cognitive model of emotion (OCC)</td><td>(Ortony 1988; Bates 1992; Elliott 1999; Andre 2000; Martinho 2000; Breazeal 2003; Fiorella 2003)</td></tr>
<tr><td>Appraisal and coping model (EMA)</td><td>(Gratch 2004)</td></tr>
<tr><td>Model as complementary roles</td><td>(Pribram 1984)</td></tr>
<tr><td>FLAME</td><td>(El-Nasr 2000)</td></tr>
<tr><td>MAMID</td><td>(Hudlicka 2003)</td></tr>
</table>

Chapter 4
Methodology

The previous chapters have introduced how to integrate emotion features with virtual humans. This chapter will propose ways in which emotion capability can be investigated with virtual human modelling. Based on the understanding of some existing virtual human models, an initial virtual human system is firstly modelled and implemented, followed by an improved model and a virtual human model with emotion capabilities. The initial model is a fully reactive system. The simulation results of this initial model will then be presented and the limitation of the system will be discussed. Components and processes which can display emotion features or help to display the emotional features for the virtual humans will be added. Further discussions of these updates and their advantages and disadvantages will be discussed. Data collection and analysis will also be addressed in this chapter.

4.1 Visualisation of the system

Before modelling virtual humans, the software environment which is used to build up and test this system needs to be introduced. All the results of this work can be perceived through the simulation of virtual scenarios in this interactive system.

One potential application of modelling virtual intelligent humans with emotion capability is associating the environment design. It was noticed that the majority of injuries occurred are in indoor environments (Wood 1990; Vaught 2000). Due to a relatively small space, it is more difficult to isolate people from dangerous sources and people’s emotions affect unexpected behaviours usually make the situation worse. Indoor environments which have converged lots of factors in a relatively small space become one of the main venues of human injury and death. Therefore, indoor virtual environments are on the top-priority as a scenario to test the virtual human model. A series of indoor virtual environments have been designed in Virtools™ with associating programming in VC++.

Virtools™ is an "interactive 3D software" editor. In other words, it is an editor for making interactive 3D software. It is similar to 3DS Max or Maya but it makes easier for designers to follow objects' behaviours and to run projects interactively.

Like many 3D programs, Virtools™ has a paned and tabbed interface that makes it generally easy to get around as there are so many different parts of the program. The real power of Virtools™ lies in its schematic system, which is also known as Virtools' visual scripting language. A schematic is automatically generated when drag and drop a building block into 3D view scene. Each building block is represented by a box with inputs on the top of that box or pIns (parameter In) as Virtools™ called them. These inputs values can come from static constants or they can come from variables. They can also come from the output of other building blocks. Some building blocks have outputs as they appear on the bottom of the building block. (**Figure 4-1**)

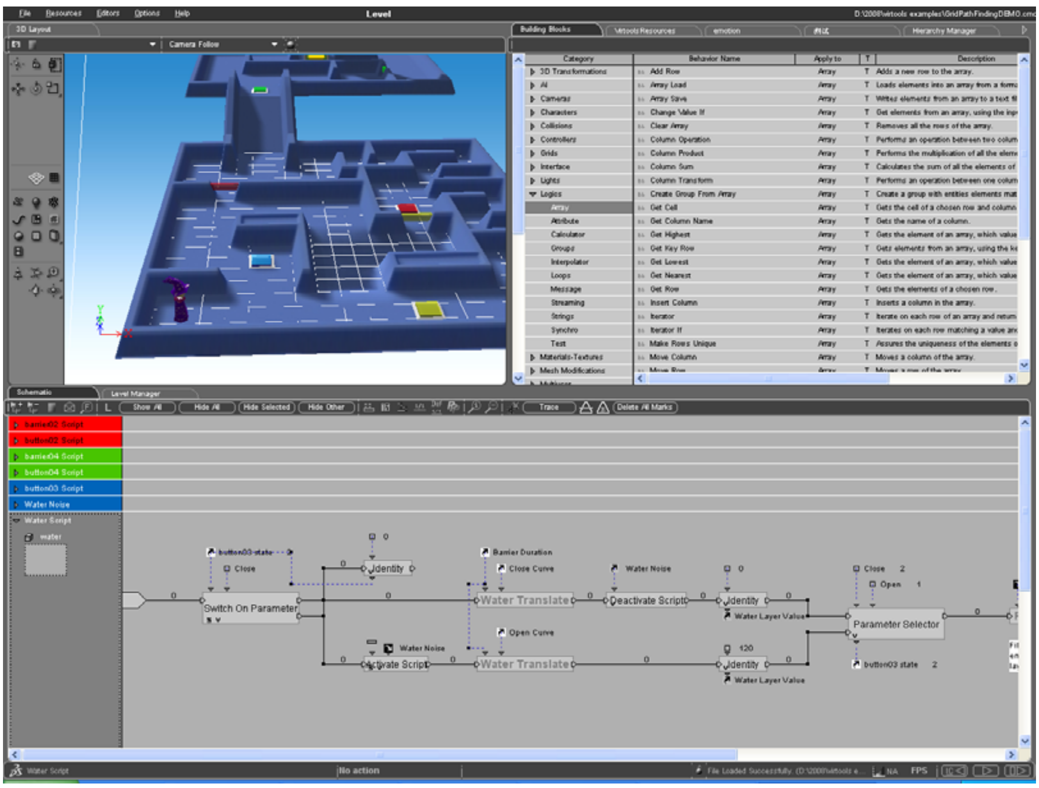


Figure 4-1 Virtools™ interface

Virtools™ also has a solution called VSL or Virtools Scripting Language with which one can make one's own building blocks (**Figure 4-2**). VSL is a powerful scripting language that complements the Virtools™ Schematic editor by providing script level access to the Virtools™ SDK. The VSL Editor supports an intelligent context-sensitive text highlighting (colouring) system, context-sensitive completion and automatic display of function arguments. VSL includes a full debugging mode with breakpoint support, watchable variables with value editing, and step by step debugging (including step into/out support). It requires previous programming or scripting (e.g. VC Script, JavaScript) experience before trying to use VSL. In addition, one must be reasonably familiar with or be willing to become familiar with the Virtools™ SDK.

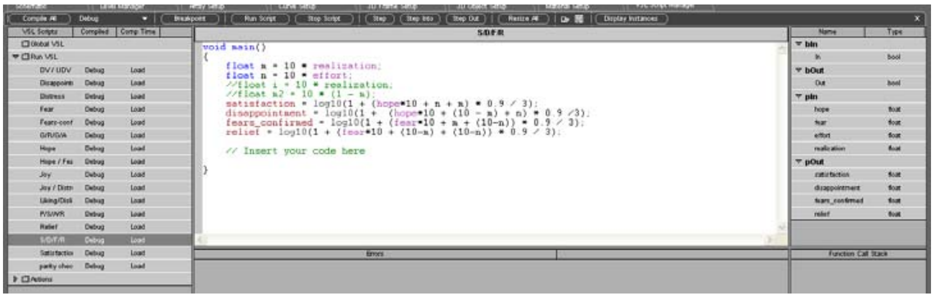


Figure 4-2 VSL Editor Interface

Beyond this, Virtools™ SDK provides Virtools™ Interface Plugin .NET 2003 Wizard. It allows one to make building blocks in VC. It's very useful when building complex character simulation system with physics features. For example, Virtools™ does not provide a specific building block for realising a first-in-first-out stack. In this case, a FIFO stack can be programmed in VC and imported into Virtools™ as a new building block with changeable size.

An adaptable virtual environment toolkit is also developed to provide changeable scenarios through add/delete objects and events. The details of scenario design and its systemic realisation can be found in **Chapter 8**.

4.2 Initial virtual human model

4.2.1 Overview of the initial model

Before modelling the emotional behaviours for virtual humans, a basic intelligent virtual human system without emotion functions was firstly designed. It is modelled based on my understanding of the existing virtual human models that were mentioned in **Chapter 1**. Like the majority of existing virtual humans, this virtual human model includes modelling realistic 3D body figures which have flexible motion capabilities and decision-making mechanisms with limited, predefined searching capability. This is one of the simplest virtual reality models for virtual human modelling. Endowed with these capabilities, virtual humans can make their own decisions accordingly to the changes in their virtual environment and react with movements which were motion captured. In this model, virtual humans react to their virtual environment in an 'input signals-decision-behaviour' loop (**Figure4-3**).

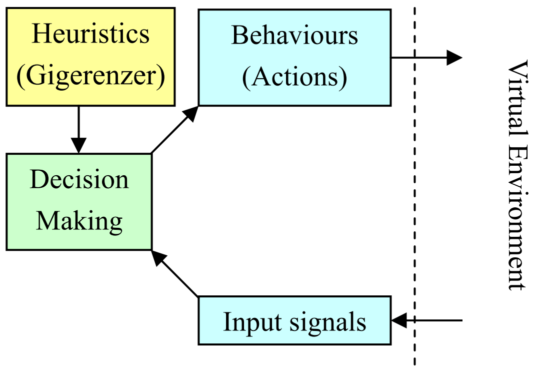


Figure 4-3 Virtual human modelling without emotion functions

In this initial model, a virtual perception module provides necessary information for decision making. A decision making module decides what to do to adapt changes in virtual environment. A behaviour module supports a mechanism for implementing the decision of the virtual human.

Several researchers had improved the reality of virtual human modelling through designing their virtual humans' decision making strategy depending on the environment and not the predefined representations in a database (Brooks 1991). The conception of virtual perception or synthetic perception has been developed in the last twenty years (Brooks 1991; Tu 1994; Conde 2006). Synthetic perceptions help virtual humans increase their degree of individuality. This means that synthetic perceptions are specific to each virtual human, which interprets its environment depending on the current situation and their own experience (domain knowledge).

A heuristics decision-making system manages reactive response according to the synthetic perceptions in this initial model. Necessary accessory information, domain knowledge, will be provided to virtual humans for decision-making. Then behaviour mechanism must choose an adequate reaction which allows behaviour to be interrupted. This is an essential action selection mechanism. For example, a motion pattern of a virtual human should be able to be interrupted by another motion at a time if necessary. This not only happens for human beings, some animals also act like this, simply because it is better for survival. Thus, behaviour is adapted to the situation with a mechanism that increases the capability of meeting an emergency to satisfy the optimisation in decision-making according to the purposes of the virtual human.

4.2.2 Initial virtual human modelling process

4.2.2.1 Motion patterns

A predefined motion database is provided for the virtual human to select appropriate motion sequences. In real life, humans have a lot of possible reactions to similar tasks. Therefore it is quite difficult for the predefined motion database to involve all possible motion patterns for the virtual human. This is a limitation of this method. However, the motion database can be predefined large enough to cover all reasonable motion types based on a behaviour taxonomy method (Kang 2006; Badi 2007) (**Table 4-1**). Furthermore, motion synthesis can generate motion variation from existing motion types.

4.2.2.2 Motion capture

An appropriate motion generating method needs to be adopted to provide motion patterns. An optical motion capture technology is utilised for virtual human motion modelling after reviewing lots of the existing methods (Motion Analysis Corporation 2005; Kertesz 2006; Mündermann 2006).

Table 4-1 Standard motion patterns for initial virtual human modelling

Basic movements	T-pose, stand still, hand raise, hand lower, object pickup, put down object, hand extend, handshake, hand wave, head nod, etc.
Cyclic motions	Walk, run, jog, skip, walk in circle, run in circle, jog in circle, skip in circle, etc.
Advanced movements	Jump, sit down on floor, sit down on seat, stand up, step up, step down, backwards, jump off, turn left, turn right, toss object, throw object, squat down, sit down from, squat, turn around, intermittently, turn around, smoothly, lying down, getting up, lying squirm, lying turn around, etc.
More advanced movements	Fall over, trip over, collapse, climbing, crawling, kicking, pouncing, dancing, fighting, sports, martial arts, acrobatics, etc.

The Eagle Digital system tends to utilise proprietary video cameras to track the motion of reflective markers attached to joints on the actor's body or face. It helps to capture and analyse the peculiarities of emotional motions from real human, and builds up an emotional motion pattern database for the virtual humans. A 7-Camera Eagle Digital system is applied to full-body motion capture in this virtual human modelling as it is the quickest way to build up a motion database with sufficient detail. **Figure 4-4** and **Figure 4-5** show examples of the motion capture system on operating. A detailed user guide for this optical motion capture system can be found in **Appendix A**.

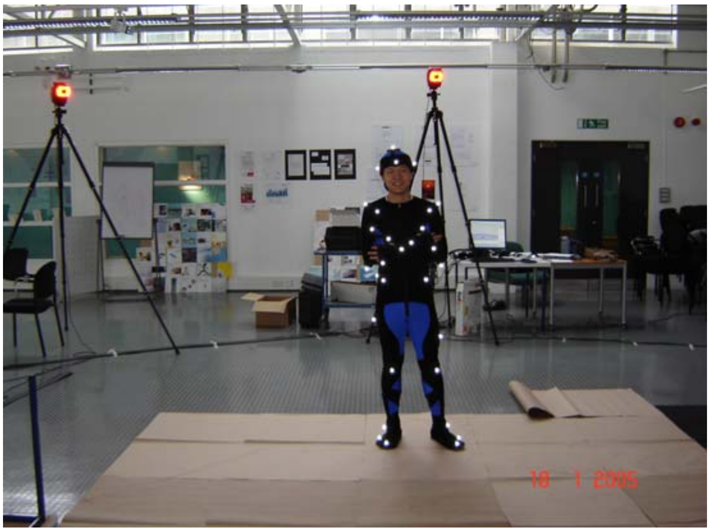


Figure 4-4 Eagle Digital Motion Capture System

Figure 4-5 the special fabric suit used in motion capture

4.2.2.3 Motion modelling

When designing a skeleton model for a virtual human a request must be met: the model must transform sufficient movement details of every body part from motion capture data. The skeleton model must have sufficient bone segments to display emotional body motions. It is well-known that human beings have 206 bone segments. However, it is unnecessary to remodel all the 206 bone segments to drive a realistic virtual human. Necessary simplification needs to be done which allows limited bone segments to drive a 3D stick figure and represent emotional body motions without losing too much detail.

To simplify the complexity of virtual human modelling, a novel virtual human skeleton structure is devised to deliver sufficient body language features of emotional motions. A specific 28-segment hierarchical skeleton structure has been used in the modelling (**Figure 4-6**). The skeleton structure is designed to transform sufficient motion details and support a corresponding skin mesh to recreate a vivid avatar model. The skeleton data for all motion capture sections have been calculated and modified in the EVaRT system. Movement information of all the 28 skeleton segments is saved in .HTR (hierarchical translations and rotations) files. **Table 4-2** presents a list of segments with joint type information. The length of bone segment of each individual who attended the motion capture is measured. The details of the hierarchical skeleton structure will be indicated in **Appendix B**.

Table 4-2 The name list of 28 bones segments and their joint types in the 28-segment skeleton modelling

Segment	Joint Type	Segment	Joint Type
Root	Global	RUpperArm	Gimbals
Spine1	Spherical	RLowerArm	Hinge
Spine2	Shared Spherical	RHand	Universal
Spine3	Shared Spherical	RFinger	Hinge
Spine4	Shared Spherical	LThign	Gimbals
neck	Spherical	RThigh	Gimbals
Head	Spherical	LSpin	Hinge
Headend	Spherical	LFoot	Gimbals
LClavicle	Universal	LToe	Hinge
RClavicle	Universal	LToeNail	Hinge
LUpperArm	Gimbals	RSpin	Hinge
LLowerArm	Hinge	RFoot	Gimbals
LHand	Universal	RToe	Hinge
LFinger	Hinge	RToeNail	Hinge

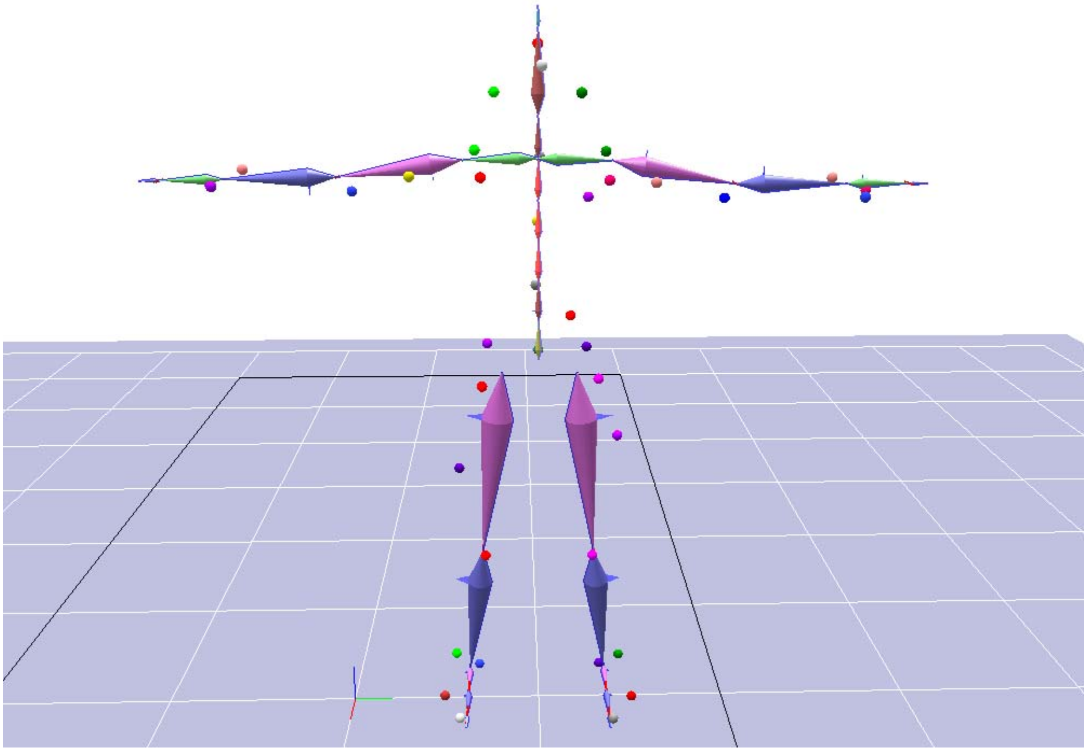


Figure 4-6 Hierarchical skeleton structure created for virtual human modelling

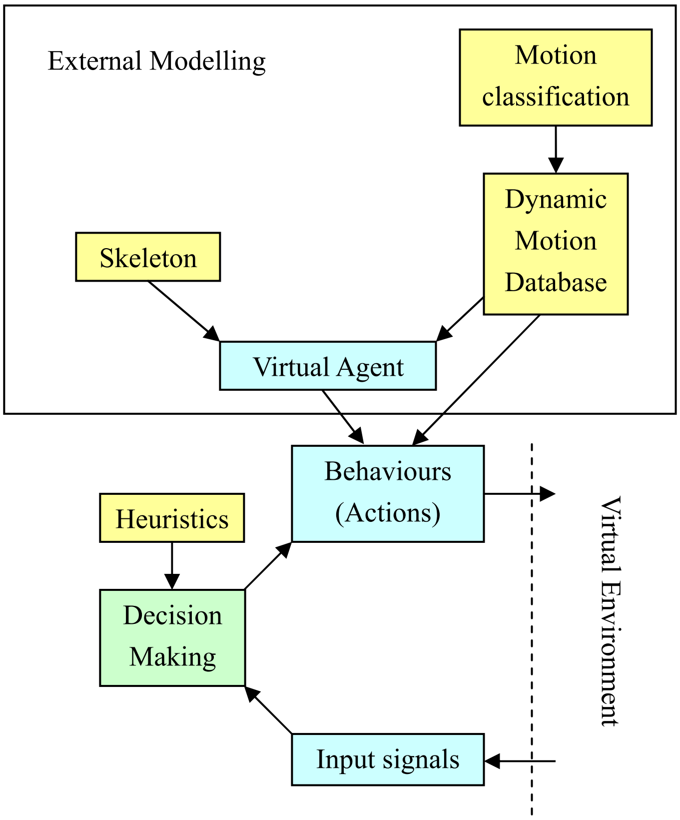


Figure 4-7 Schematic View of Virtual Human Modelling (initial model)

4.2.2.4 3D body model

After the skeleton structure had been constructed, it is still quite difficult to distinguish from different virtual humans. As the skeleton figure is a highly simplified object, it cannot provide sufficient details to display a virtual human's behaviour, especially the motions with emotional features. One can distinguish a female stick figure from a male stick figure through their different body language during the movement. However, imagination is still in need to figure out a virtual human when just looking at its stick figures. This is impractical when simulating emotion features of the virtual humans, which need to display more details of one's body language.

Virtual human models with diverse appearance were recreated to tell difference in gender, height, age, etc. A digital figure with accurate proportions of each virtual human is expected to be created rapidly and is easy to map with motion capture data. Therefore, an accurate body-sized scanning technology is required with relative short time for operation. Each motion capture performer is scanned by a 3D digital body scanner in order to increase the reality of the virtual human model and provides more mimic, visible information when simulating the virtual human system.

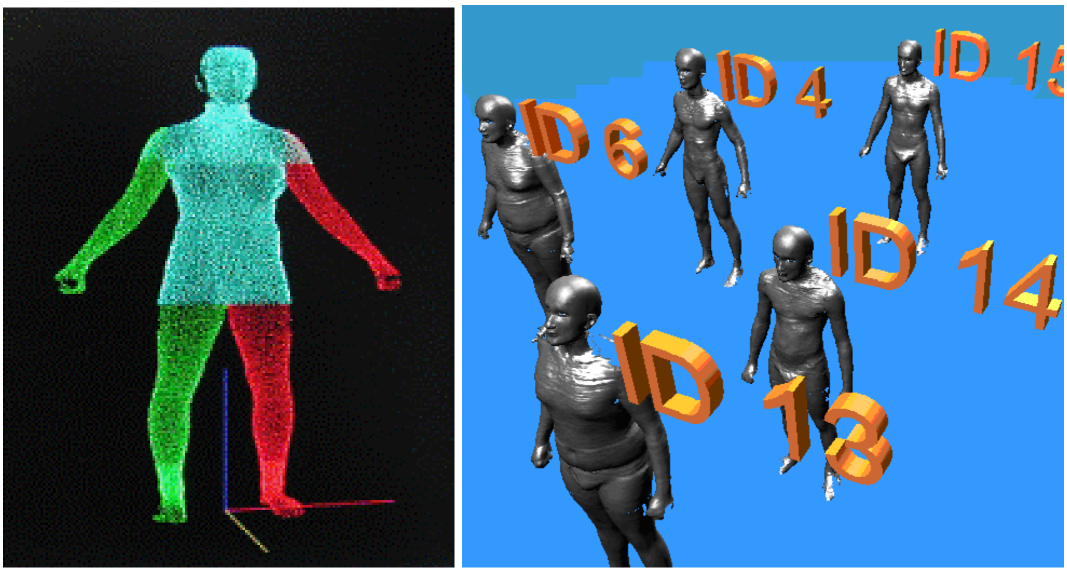


Figure 4-8 Data acquisition of 3D body model by body scanning

After a review of some of the most recent industry scanning products, TC2 3D body scanner is selected to recreate a 3D body model from a real human figure for the virtual human modelling. The scanner allows scanning of the whole body in less than 6 seconds with point accuracy less than 1 mm. Moreover, it can also rapidly produce a true-to-scale 3D body model and automatically measure extraction. More than 30 subjects were scanned and some examples are presented in **Figure 4-8**. Then the skeleton models and skin models from the same subject are combined together and exported into a dynamic emotional motion database in the virtual human system (**Figure 4-9**).

After the combination of the skin mesh with the corresponding hierarchical skeleton model, all the motion tracks of the virtual humans were converted from 3DS MAX to .NMO files and exported into a dynamic motion database in Virtools™. Even though the presentation was still not as good as what we could see from the animation industry, it is a solution for virtual intelligent human behaviour research as it could meet sufficient details and diversities of human motions (**Figure 4-10**).

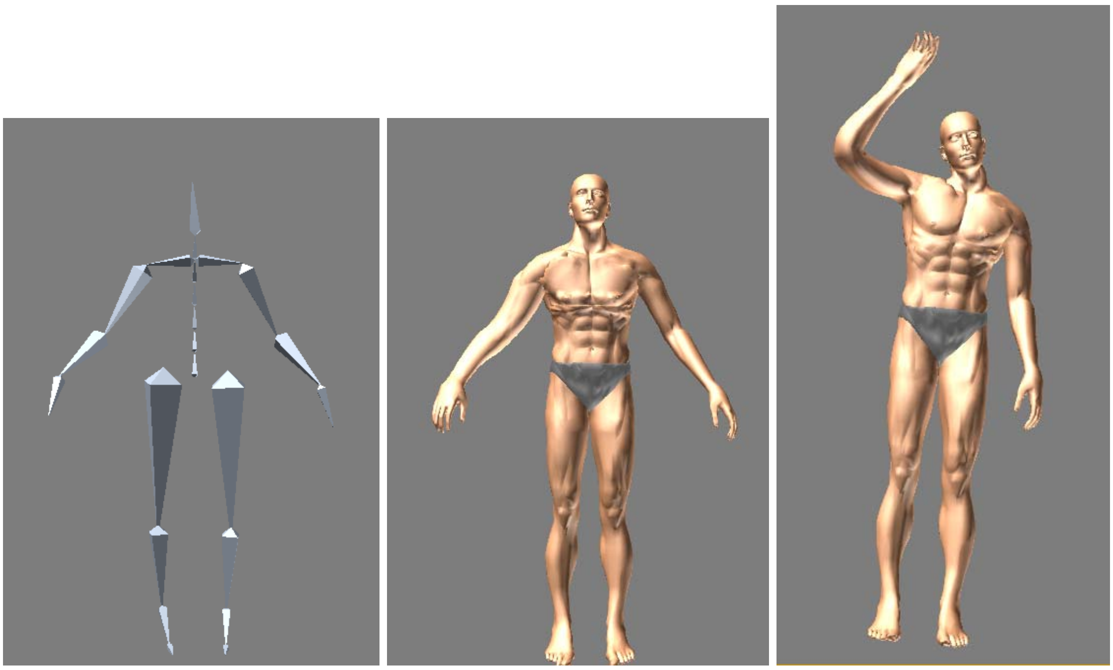


Figure 4-9 an initial-pose skeleton + an initial-pose mesh → an animated mesh

Figure 4-10 Examples of finished skin models

4.2.3 Problem of the initial model

4.2.3.1 The problem with motion modelling

As mentioned previously in this chapter, the initial model of virtual humans lack emotion features which is similar to the most existing virtual human modelling methods. There is insufficient research on the role of emotion in virtual humans. The applications of virtual humans are also limited because of this. In **Chapter 3**, the role of emotion has been studied in order to improve the reality of virtual human modelling. The objective of this work is to model a virtual human that not only can move around and perceive environments like a real human, but also have emotion capabilities to make decisions and behave based on these emotion states.

Emotion impacts humans' behaviour and decision in several ways. It focuses attention, increases the prominence of an event in memory, affects cognitive style and performance, and influences judgments (Brave 2003). Emotion in virtual humans can be developed as the following aspects: the role of emotion in decision making (Naqvi 2006), the expression of emotion, emotional behaviours and facial expression (Henninger 2003), etc.

Based on the experience of combined 3D scanning techniques with motion capture to provide a relatively rapid solution for building virtual humans, the motion capture based virtual human modelling method is extended to create virtual humans with flexible and diverse emotional motion capabilities. It allows virtual humans to interact with complicated and volatile virtual environments in real-time. Virtual humans are expected to use emotional behaviours rather than limited simplified motion sequences to interact with virtual environments. This is the first step to make the virtual humans more realistic without the consideration of adding emotion capabilities.

4.2.3.2 The problem with synthetic perception

The initial virtual human model does not have synthetic perception. It only allows limited input signals from users to interactive with virtual humans. However, synthetic perception is very important to support the autonomy of the virtual human model. As one characteristic of human beings and the majority of life-form, one needs to perceive the environment in order to survive. Different kinds of animals usually have different perceptual organs specialised to their particular habitats. The functions of sense organs can be determined by studying their structures. However, even for those animals with rather simple sense organs, it is still hard to ascertain how perceptual information is interpreted, as perceptual processes are diverse and complex (Wilhelms 1990; Tu 1994; Thalmann 1997). For example, birds are known to recognise their mates by the colour of their feathers, but when such features are absent they are still able to recognise mates by studying the behaviour and the dancing and posturing which may be associated with courtship (Tu 1994).

When modelling an autonomous virtual human, the perceptual capability of the virtual human is the first module which needs to be realised. Synthetic perception should be the only bridge between a virtual human and its virtual environment.

In this virtual human modelling, synthetic perception is proposed as the only interface where virtual humans can get information from virtual environments. It provides virtual human a series of information sensors which can help virtual humans to detect the surrounding virtual environments. Synthetic perception is not only an essential step to create real-time virtual humans with emotional reaction capabilities, but also a key feature to distinguish an autonomous virtual human from a sophisticated animation virtual characters used in video games.

Besides synthetic perception, virtual memory is also proposed as an important component for emotion generation and reactions. It is an interesting topic to discuss how memory is organised and how the span of memory affects one's emotional state. In this virtual human model, a simplified memory structure (first-in-first-out stack) has been modelled for the virtual humans. Different memory structures and how these memory structures can affect virtual human's behaviour can also be an interesting topics for further work.

4.3 Improved virtual human model

Considering some problems in the initial model, adding emotion features are considered in the virtual humans. Before modelling the real emotion generation capability for virtual humans, the virtual human model in this section is trying to integrate some emotion features and provide an emotional motion organizing structure for the virtual humans. The existing virtual humans provide either gestures or facial expressions as fundamental outputs. In this improved virtual human model, virtual humans can display a wide range of emotional behaviours, even if the virtual humans still have no idea what emotion is at this stage. The facial expressions are not considered in the improved model.

There are two main problems that need to be solved in this improved model: how to model the motions of a virtual human with emotion features, and how virtual humans organise these emotional motions in virtual worlds. To solve the first problem, motion capture techniques are studied to help create a series of motion patterns. Motion synthesis techniques can also be considered to generate motion variation from the existing motion patterns. For the second problem, a framework of emotional motion database is created. The framework classifies all the captured motion patterns according to their emotion styles (**Figure 4-11**).

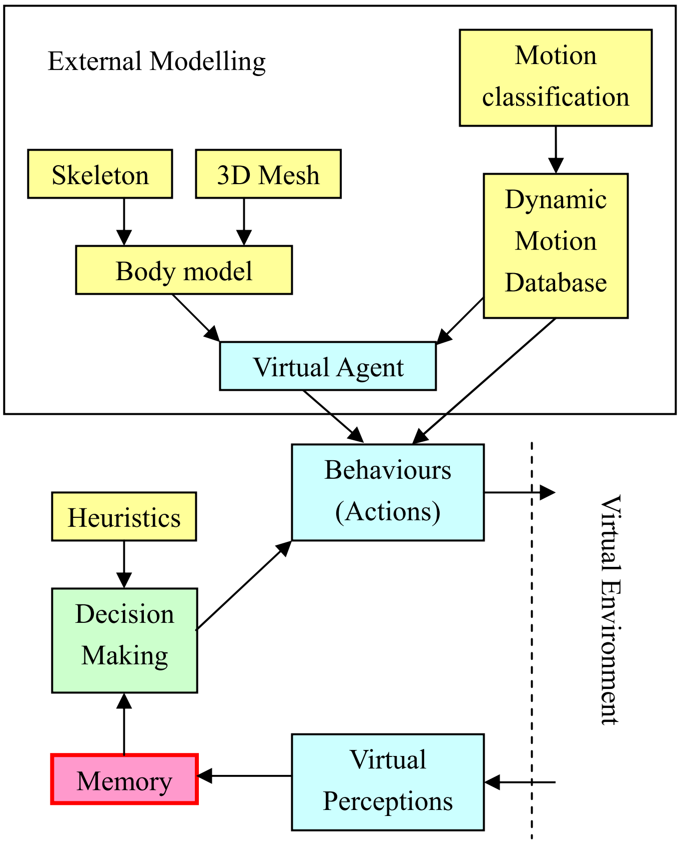


Figure 4-11 Schematic view of the improved virtual human model

4.3.1 Classifications of motions and framework of motion database

To analyse the complexities of emotional motions effectively, it is necessary to decompose emotional reactions into simple and manageable architectures and hence different levels of details. Recognition of human motion requires characterisation in terms of its taxonomy. Pollick *et al* had conducted research in the perception of human movement, the cognitive and neural processes that underlie human's abilities to understand the actions of others (Pollick 2002; Ma 2006). Their research suggested that one's emotion can be perceived through observing one's body movement. In this work, human motions have been divided into different sub groups incorporating with a hierarchical structure. To find out the influence of emotion to a type of motion (reaction), a series of experiments was carried out with some volunteers participated. These experiments include inducing participants to perform emotional reaction according to the framework of the emotional motion database.

The subject of motion capture was asked to perform some emotions through body gestures in their own way (Badi, 2007). All possible emotional motions for each subject are saved and organised into a hierarchical structured database based on experimental observations and psychological theoretical studies. The motions are divided into different levels depending on the targets of simulation.

First, some standard motion patterns without emotionwhich are called motions of a functional level are defined. Each subject was asked to act out these movements in order, and after some time, a sudden interruption was given to the subject to capture his/her emotional reactions.

Secondly, emotions were added to these basic motions. These motions are called emotional motion patterns. As mentioned before, subjects are asked to act different emotional motions with different levels as many as possible in their own ways. An example of instruction to motion capture subject is presented in **Appendix C**.

All these motion patterns are labelled with different emotion thresholds and saved in a dynamic emotional motion database after being post processed. The emotion threshold of each motion pattern determines when it should be active for a virtual character. For example, a fear gait pattern with a fear value equal to 0.7 as an emotion threshold, in which the value of fear is defined as a number between 0 and 1 (unified output value format in the emotion calculation module). In this case, the threshold means this fear pattern will not be used by the virtual character until the emotion ‘fear’ reaches 0.7.

In the emotional motion database, each single motion pattern will have its own particular emotion threshold. A motion pattern will not be active until the virtual characters emotion states reach the threshold. As the virtual character updates its emotion states through its virtual perceptual sensors in real time, the activation of each motion pattern will be changed synchronously. Therefore the number of active motion pattern in the emotional motion database is always changeable along with the emotion states of the virtual characters. This is also why the motion database is named as dynamic emotional motion database.

4.3.2 Virtual memory system

The sole provision of an emotional motion database with a mass of motion patterns is insufficient for virtual humans. As mentioned in **Chapter 3**, a short-term memory module is also considered to contribute to a more advanced virtual human model. It is assumed that all decision-making is memory-based and that virtual perception only affects the virtual human’s memory. Such virtual memory is used as a basis for decision-making. It actually provides a unified information format for decision making module after collecting information from different virtual perception. Therefore there is no direct linkage between virtual perceptions and decision-making, as all this information captured by virtual perceptions will be stored in a virtual short-term memory stack first. A decision-making module can access information from a short-term memory stack and make decisions based on it. Only the short-term memory has been simulated in this virtual human modelling (**Figure 4-11**), not long-term memory or some other complex memory styles, such as recalled memory, etc. This is because long-term memory can also be simulated in the form of a predefined domain knowledge, which is similar to the achievement in AI modelling (Funge 2004). Recall can be understood as a random recover of previous memory information.

4.3.3 Summary of the improved virtual human model

During the motion capture process, it's realised that some emotions were easier to be expressed by motions than others. Some could hardly be expressed by a single motion but could be identified by behaviour, which is considered as a combination of motions. For example, the emotion 'relief' is hard to be directly performed. However, some other emotional motions can be combined to display a "relaxing" behaviour. For example, a "panic walking" motion and a "standing with a deep sign" motion can be combined to display a "relaxing". Emotion not only affects ones motion style, but affects one's decision making. Different performers have shown distinct personalities during motion capture sessions and fine details of body languages for emotional reactions are noticed.

Whether there was a link between the level of reaction and emotion traits during the motion capture process is studied. In some cases, there was a distinct linkage between level of reactions and emotion traits for some subjects. For example, some subjects for the test always preferred to have protective movement. In a more general level, when considering the correlation between reaction and emotion for a group of subjects, the link is not as distinct as it is for the individual level. However, in general, females are easier to show distinct emotional reactions than males, and young subjects tested show emotional reactions more quickly than aged subjects.

Finally, transform and connection techniques between transformations of different motion-tracks are reviewed. As motion capture is a kind of pre-defined method in animation, an initial pose (**Figure 4-12**) is designed to guarantee the transformation between different motion-tracks can be smooth on each performer. In general, all motion-tracks in a motion database start with an initial pose and finish in the same pose as well. Synthetic-motion technologies are also reviewed to provide smooth transformation between different motion sequences or a separate pose in a body part from an interrupted motion (Yu 1998; Badi 2007). However, motion synthesis and some movement characteristics were not considered, such as the power of the movement, the speed, etc. These features are beyond the scope of this thesis.

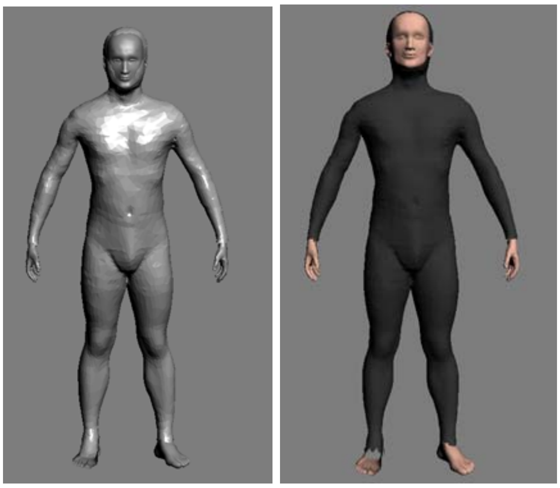


Figure 4-12 Initial pose for motion capture

The design and implementation on synthetic perception and virtual memory are relatively independent topics in this work. It is the only information path between virtual human and its virtual environment. It provides and updates information which is needed in the emotion generation process. At the same time, it affects the reality of virtual human's behaviour and decision by controlling the acuity of information that virtual human can get. The details of a synthetic vision model and its implementation will be investigated in **Chapter 5**.

4.4 Virtual human model with emotion capability

4.4.1 Overview of the virtual human system with emotion capability

After building up an emotional motion database and improving synthetic perception-virtual memory system, some 'real' emotion function and calculation processes for virtual humans needs to be dealt with. Only adding up limited vivid emotional motion patterns and updating the virtual perception system is not enough to provide more realistic reaction when virtual humans are interacting with virtual environments. The virtual humans are expected to have emotional decision-making capabilities and behave emotionally when interacting with dynamic virtual surroundings.

Literature reviews of previous research on emotional computing and robotics have helped to identify the problems that need to be considered in this virtual human modelling. The following list gives a summary of questions that is thought as important issues in this work. It also contributes to a flowchart of how the virtual human model with emotion capability is implemented (**Figure 4-13**):

- How to measure emotions and regenerate emotion processing in virtual human?
- Is there proper emotion model/theory for virtual human modelling?
- Is there any emotion structure suitable for emotion generation in virtual human?
- What is the role of emotion in virtual human's decision making and behaviour?

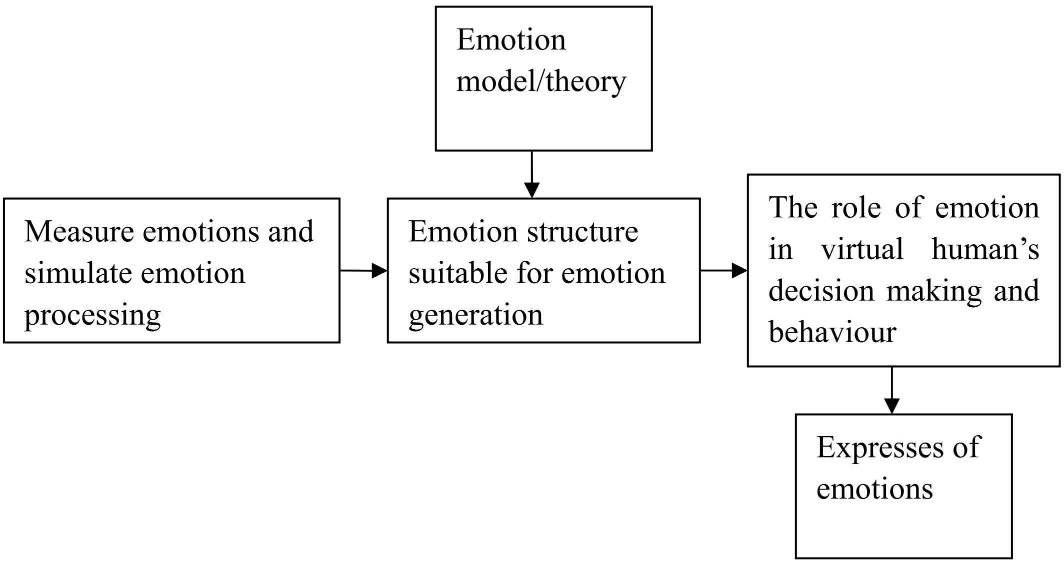


Figure 4-13 main problems that considered when modelling emotion processes for virtual humans and flowchart for this work

In order to integrate emotion generation capability with virtual human modelling, the first problem is to find a proper emotion structure model for virtual humans. The proper structure of emotion then can be integrated with virtual humans to support the virtual human's decision making and behaviour. Within this emotion structure, a virtual human can select intentions of its behaviour, based on its own emotional decision making.

It is also important to define how the intensity of emotion changes with the time and to identify how to measure the intensity of emotion. The measurement and regeneration of emotion is also an important question needs to be considered when modelling the virtual human's emotion.

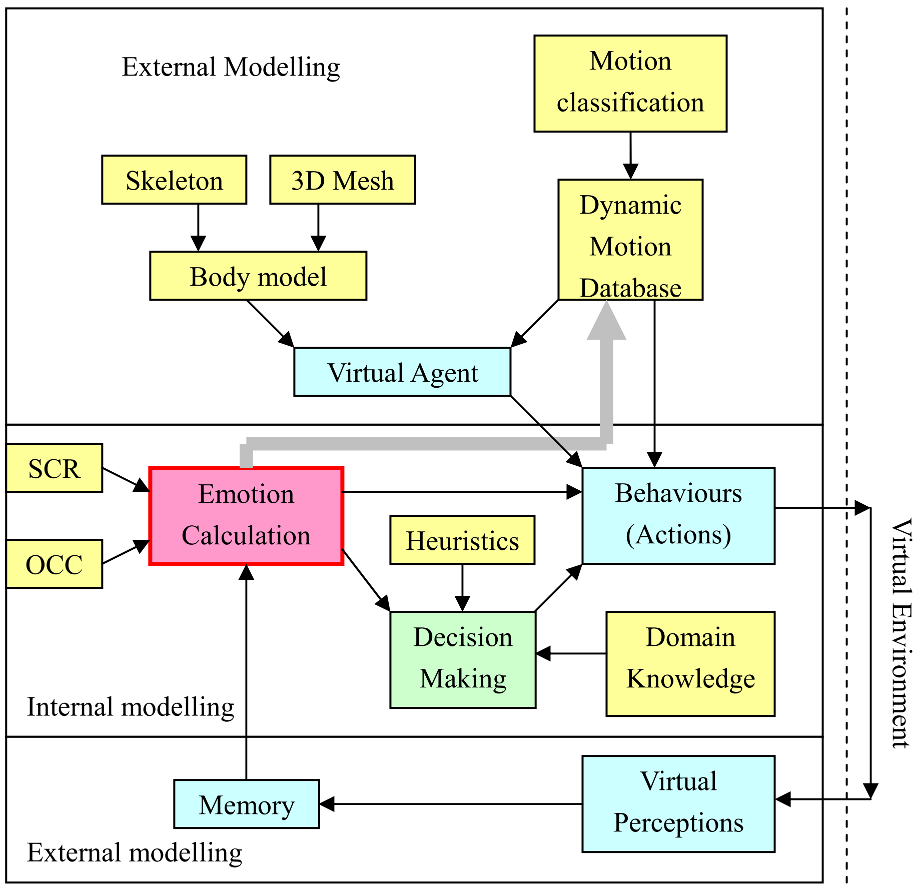


Figure 4-14 Schematic view of the virtual human modelling with emotion capability

Figure 4-14 gives the schematic view of the structure for the virtual human modelling with emotion capability. The figure also distinguishes the internal module parts from the external module parts.

4.4.2 Structure of the emotion model

It is important to define the structure of emotions when trying to program convincing emotion processing on computer (Sloman 2004). The inputs for virtual human's emotion calculation are variables (Ortony 1988; O'Rorke 1994), which are default properties of events and objects in the virtual environment, and linked with virtual human's synthetic vision and short-term memory information. In other words, inputs for the current emotion modelling are based on the virtual human's understanding of visible and remembered information.

After reviewing psychological literatures of emotions structures, it is realised that cognitive appraisal process is the most frequently modelled process when modelling emotion. The OCC model is one of the most frequently implemented theories when modelling cognitive appraisal process as it is easy to understand and the cognitive structure proposed in the theory is suitable for programming a computationally tractable model of emotions. In this study, it is more appropriate to model cognitive perspective on emotions than directly programme a serial of emotional strategies for virtual humans. Therefore, the OCC appraisal model is selected as the fundament when developing methodology for the virtual human model with emotion capability. A hierarchical emotion calculation structure has been inspired and designed based on the OCC model. The fundamental concept of OCC model is that emotions are "valenced reactions to events, agents or objects, with their particular nature being determined by the way in which the eliciting situation is construed." (Ortony 1988) In other words, the strength of a given emotion depends on the events, agents, or objects in the environment of the agent exhibiting the emotion. Their presence is mapped to a "valence," a positive or negative score, by a process called "assessment" or "appraisal."

4.4.3 Emotion calculation

The virtual human's emotion calculation modelling is designed as a hierarchical structure. 18 variables that affect the intensity of emotions, including 4 global variables and 14 local variables, have been specified in this hierarchical structure. All those variables are assumed as measurable effective factors and appropriate to evaluate the human's emotion. The OCC theory has explained these entire variables in detail. The theory also distinguishes those terms of emotion from the linguistic level and comes replete with ambiguity, synonymy, and an abundance of lexical gaps and linguistic traps. It is necessary to point out, emotions are not linguistic, but the most readily available non-phenomenal access to them is through language.

Several studies have shown that SCR results from the presentation of significant stimuli (Bernstein 1979). This notion has led to the use of SCR in emotional situations (Tang 2001; Barreto 2007) where SCRs are reliably elicited by the stimulus that signals upcoming stimuli. Tang proposed two theoretical equations that can be used for emotion generation in computers. I tested his equations through quantitative analysis of some SCR data and proposed a series of new equations for emotion generation. The SCR data and analysis have lots of different explanations in psychological research. However, the equations used here are still reliable as it presents the relationship between intensity of skin conductance and emotion related stimuli objectively. These emotion equations can be derived for emotion calculation by interpolating SCR measurement data. The following is an example of an emotion equation derived from SCR measurement.

$$E = A \cdot \log(a \cdot t + b) + c$$

In this general form of emotion calculation equation, E is the intensity of certain emotion; a, b and c are indexes which decide the shape of emotion curve and the change of the emotion along time t.

These equations have then been used to generate emotion states in a hierarchical emotion calculation structure based on the information of a dynamic memory stack. By using these interpolating equations, virtual humans are allowed to generate their own emotion states based on their own virtual perception and memory in the virtual environment. The details of the emotion equations and emotion generation processing will be investigated in **Chapter 6**.

4.4.4 Emotional decision-making and behaviour

The virtual human model focuses on the impact of emotion on decision-making and behaviour, and consists with the justification of the OCC model as a psychological theory, in which "behaviour is a response to an emotional state in conjunction with a particular initiating event." (Ortony 1988) There are two main advantages of emotion in decision making and behaviour selection: First, rapid reactions, the emotional decision or behaviour are normally fast adapted; second, emotions contribute to resolve the decision-making among several goals. Especially in emergency situations, it has been proven that emotions help humans make quick decisions. These are also the two main aspects how emotions affect heuristic decision making in this system. Emotion actually provides a new cue for decision making in heuristics theory, especially under those decision making with equal-weight options.

4.4.4.1 Emotional decision-making

With emotion capability, a virtual human's decision-making can be very different to traditional bounded rationality approaches. Emotional decision-making often occurs in the form of uncertainty about whether one's choices will lead to benefit or harm. For example, emotion can take control when a virtual human panics. Rationality is less helpful when emotion reaches a certain level. There is a large grey area between pure rationality and totally emotional. In most cases, emotions are associated with rationality to accomplish decision-making. Both emotion and rationality are involved in decision-making with different weights (Pham 2007). Therefore, lots of derivative strategies could be designed for a virtual human's decision-making processes in order to keep the balance between emotion and rationality.

The basic problem when implementing an emotion in a decision making mechanism is to know which variables in a decision making model will be influenced by emotions. On the one hand, since an emotion system can be considered as a system which is connected to many other cognitive and behavioural systems, emotion should be able to affect and even take the control of the decision making in order to protect the virtual agents in some circumstances, such as danger because of fire. Therefore, emotion can be modelled as affecting decision-making in a more subtle way and can evaluate and modulate many things. In this system, emotion can modulate several variables in decision making, such as the cue for decision makings. On the other hand, since some emotions are related to goals, rather than particular behavioural responses, emotions contribute to the generation of varied and flexible reactions. In this model, emotions evaluate and influence the reactions through a dynamic emotional motion database. Many reactions that are normally attributed to rational decision making are now affected by the emotion threshold of emotional motions. Moreover, emotions can also be considered to influence synthetic perceptions through draw virtual human's attention.

The simple heuristics hypothesis is originally psychological theory, which have been proposed to explain how people make decisions, come to judgements, and solve problems, typically when facing complex problems or incomplete information. The theory works well under most circumstances. Gigerenzer has done lots of research on how simple heuristics can be used to make decisions 'fast and frugal' (Gigerenzer 1999). In this work, the simple heuristics hypothesis is developed by introducing emotion as a cue for simple heuristic decision-making. The case studies of implementing simple heuristics theory on realising emotion affected decision making will be investigated in details in **Chapter 7**.

4.4.4.2 Emotional behaviours

Emotional behaviour is human behaviour with emotion features. It is the result of emotional decision-making. It can be especially distinguished under emergency situations. In computer animations, unpredicted reactions can be generated through utilising random function in programming or adopting statistic data. Some virtual human models can respond accurately to limited situations based on 'pre-recorded and then played back' methods. Rather than guiding the virtual human to adopt appropriate emotional motions to fit in more possible situations, some works have been done to realise emotional reactions within limited and predefined situations (Salovey 1990; Frijda 1995; Bryson 2001; Brave 2003). This makes previous virtual human models incompetent agents for unpredictable situations. The method mentioned here is quite different from computer animation as no reaction should be predefined. Virtual humans have to make decisions and select reactions based on their own emotional state and available motions in an on-board database in real-time. In other words, virtual humans are not directly reacting to the appreciable changes of surrounding, but the changes of their emotion states. In the current system, emotion affects virtual human's reaction through blocking inappropriate motions from the emotional motion database and guide virtual humans to adopt corresponding emotional motions.

4.4.5 The operation and information pipeline of the system

The operation of the virtual human system is: setup the environment → setup virtual characters → change of environment as stimuli.

Firstly, virtual human systems require operators to predefine environments and virtual characters. For example, choose simulation scenarios, the number of virtual characters and their age, sex, body build, and personality, etc.

The information pipeline of the virtual human system with emotion capability is: virtual perception and memory module → emotion module → decision making and behaviour module.

During the simulation, the virtual character detects changeable virtual environments with a virtual perception module. The virtual character then saves predefined feature information in a virtual memory module, and evaluates variables for emotion generation. The virtual memory module also provides virtual humans with a first-in-first-out (FIFO) memory mechanism. When there are too many objects to remember at the same time, the FIFO memory mechanism lets the virtual character forget the oldest object that has been detected in the memory stack. A time tolerance allows the virtual character to keep the previously detected object in 'mind' for a reasonable period of time even if it is no longer detectable by the virtual character's perception modules. The system also allows operators to add random events to create unexpected changes in virtual environments, such as fires and obstacles.

Thereafter, all the virtual objects stored in the virtual memory stack include up to 14 feature evaluating values. These evaluating values are saved in an array with 14 input variables which are inputs of an emotion generation module in the system. The 14 inputs are concluded from feature evaluating information of all the detected objects in the virtual character's memory stack. The emotion measurement and calculation mechanism in this emotion module are calibrated from a group of SCR test data. Emotion structures and input variables are designed based on the understanding of the OCC theory. The abstracted 14 evaluation variables are used as input for the emotion module to generate up to 22 emotion types in real-time as shown in the schematic figure in **Appendix D**.

It is necessary to say, a different combination of weighting coefficient on input variables will lead to different emotion values. Therefore, different weighting coefficient settings are designed into the emotion module to represent different personality styles. The weight coefficient setting is used to represent different personalities for the virtual humans in this system.

The output of the emotion module can affect three downstream modules in the virtual human modelling system. First, the real-time output of emotion states can affect the activation of emotional motion tracks in the motion database. For each emotional motion pattern in the motion database, there is a threshold emotion value to 'switch on' the pattern. For example, it is assumed that the emotion threshold value for motion pattern 'fear gait 1' is 0.4, which means the pattern is inactive before the value of emotion fear reaches to 0.4. Once the value of fear reaches 0.4, the state of pattern 'fear gait 1' is active. It also means the pattern is available for the behaviour module for generating emotional reactions. Second, the output of emotion states can affect the decision-making module. The emotion state generated by the emotion calculation module can be used as a cue for the heuristics-based decision making module. A virtual character does not need to search all possible options and make quicker decisions that look more sophisticated. Third, real-time emotion states can affect the behaviour module directly in some extreme situation. For example, when a virtual character has to interrupt a current motion pattern and implement some other reaction.

In more general cases, the decision-making module will produce emotional strategies after the generation of emotion states. These strategies are different to strategies generated from calculative rationality, as these might include emotion features and are irrational in some way. The simple heuristics mechanism can realise and enlarge this kind difference allowing virtual characters to make quicker decisions, but not fully searching all possible options in the database, and give additional emotion cues for decision making. This mechanism is supposed to more like the real life behaviour than the calculative rationality. The consequence is therefore a reaction that looks more realistic / lifelike, rather than more rational.

4.5 Data collection and analysis

There are two data collecting processes in this methodology, one is collecting data for emotion measurement, the other is collecting data from this virtual human system. The former data collection is to identify how emotion changes and is used to modify emotion calculation equations; the latter data collection is to track whether the proposed emotion model works properly and shows the possible outcome of the proposed methodology.

The method of collecting data from SCR and how emotion calculation equations can be interpreted based on SCR data analysis will be investigated in **Chapter 6** (emotion modelling). A discussion of this methodology based on several simulation results will be presented in **Chapter 8** (case study and discussion).

4.6 Conclusions

In this chapter, virtual human is modelled and implemented at three different levels: an initial model, an improved model and a model with emotion capabilities. The main idea of this method is to build up a series of test beds to verify a better approach to model virtual humans which can perform more closely to real human. The initial model is firstly implemented based on the understanding of some existing virtual human models. Then, it is improved by modifying its motion modelling and synthetic vision modelling. A virtual human model with emotion capability is modelled by adding the emotion generation capabilities and emotional decision-making mechanism into the improved model. The main aspects of modelling and testing the emotional virtual humans with emotion capability have been presented. The development of the three virtual human systems and their structure are discussed. Different functional modules inside the virtual human and their relationship are indicated. The information pipeline of the virtual human system has also been presented.

Firstly, a “basic virtual human external modelling method based on motion capture” is modelled. The method creates live virtual humans by transferring a real human body motion character into a plausible 3D virtual human through motion capture technique. It helps to individualise virtual human models. As mentioned previously, it is very important to obtain believable virtual humans interacting in society and having their own way to express emotions and personalities. The generic model studied in this method is a skeleton driven virtual avatar model. Some improvements have also been proposed. A 28-segment hierarchical skeleton structure has been employed for whole body human behaviour simulation. An emotional motion pattern database has been proposed and built up through motion capture technology for simulating human’s behaviour under emotions, especially in dangerous environments.

External appearance modelling (virtual agent modelling) is considered as an important preparation for modelling a virtual human’s emotion generation and decision making. And it is also a necessary part to display the internal changes in a virtual human.

After external appearance modelling, a “collision-based virtual vision system” and a “first-in-first-out virtual memory stack” are presented. Different to previous synthetic vision methods, the collision-based vision system, considers the shape of a real human’s vision, which is called field of vision. It contributes directly to the virtual human’s memory and provides information channels to help the virtual human generate an emotion state for decision-making and reactions. The external appearance modelling, virtual perceptions and memory modelling make up of the external modelling for the virtual human design in this work.

The emotion generation module is responsible for the generation of unified emotion states for a virtual human in format as a group of numbers between 0 and 1. The values of these emotions decide the emotion style of the virtual human’s behaviour. They also change the virtual human’s reaction by supporting key cues for decision-making processes. In order to speed up a virtual human’s reaction, simple heuristics has been introduced into the decision-making model. It helps a virtual human to make quick decisions by supporting key emotion cues.

In this virtual human modelling method, motion capture is accomplished in the Eagle Digital system. In order to improve the appearance of the virtual human model, a body mesh of each subject is scanned in the TC2 NX12 Body Scanner. One's motion patterns and body mesh are compounded in 3DS MAX. Finally, a virtual human simulation system is implemented in Virtools™ with some function blocks programmed in VC++.

From the next chapter, the main module parts of the virtual human will be investigated as the following sequence: virtual perception and memory module (**Chapter 5**), emotion module (**Chapter 6**), decision making and behaviour module (**Chapter 7**). This is also the sequence for information transformation in the virtual human.

Chapter 5
Synthetic Vision and Virtual Memory Modelling

As mentioned by the end of **Section 4.3.3**, synthetic vision and virtual memory modelling is a relative independent topic in the improved virtual human model. In this chapter, a new synthetic vision and virtual memory model is presented as a part of the improved virtual human model. In the improved model, synthetic vision is the first filter to reduce the amount of data that must be stored and processed by virtual humans. Virtual memory is implemented as the main filtering mechanism. Only the information which is deemed to be important will be stored in the virtual memory for a certain length of time. The structure and basic operations of the short-term memory model is also investigated. An in-depth discussion of the control of both synthetic vision and short-term memory modules are presented with case studies.

5.1 Synthetic vision modelling

As vision is one of the most important perceptions for humans, synthetic vision is assumed as the main channel of information between a virtual human and its environment. This is not to say other sensors are less important for virtual human modelling. More complex multi-sensorial systems can be developed and integrated into the virtual human model. The idea is consistent with the standard theory in neuroscience for multi-sensorial integration (Elfes 1989).

5.1.1 Field of vision

One target of synthetic vision modelling is to simulate the biological / optical abilities and limitations of human vision. After reviewing the function of human vision (Costella 1995), the “field of vision” (FOV) has been proposed as an important notion in this synthetic vision. It can be described as a field with an irregular boundary, **Figure 5-1**. The FOV for real humans is not simply a square or a spherical area, as which had been modelled in previous synthetic vision methodology (Renault 1990; Noser 1995(1)). It is actually an irregular conical-shaped volume. A comparison between the actual human vision field and traditional vision field used in synthetic vision is given in **Figure 5-2**.

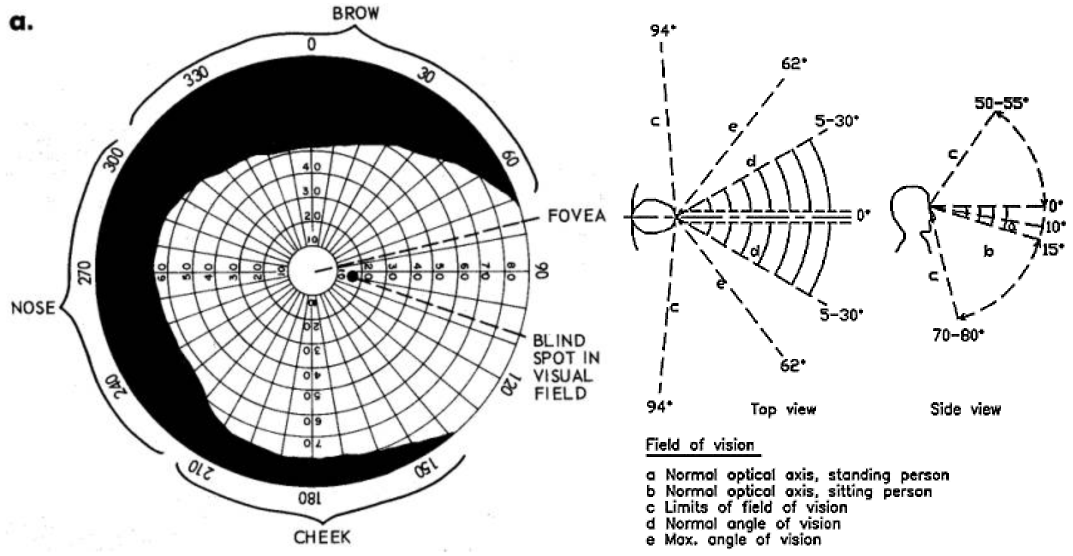


Figure 5-1 Anthropometric data of the monocular visual field and its graphical illustration (Webb 1964)

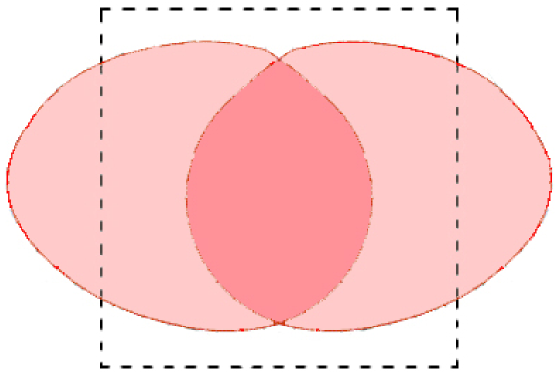
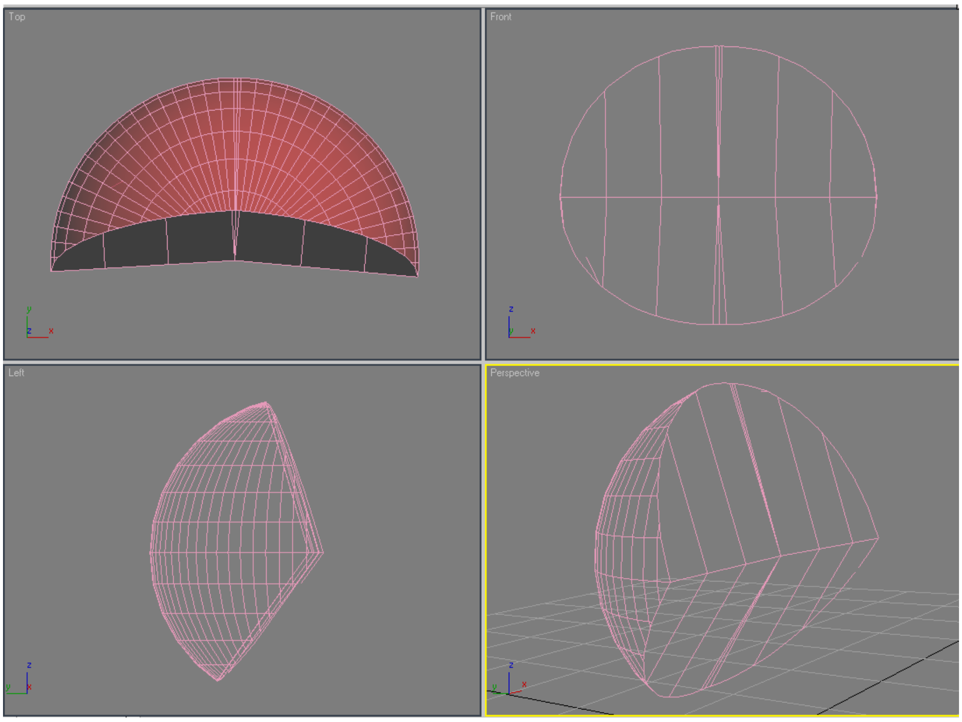
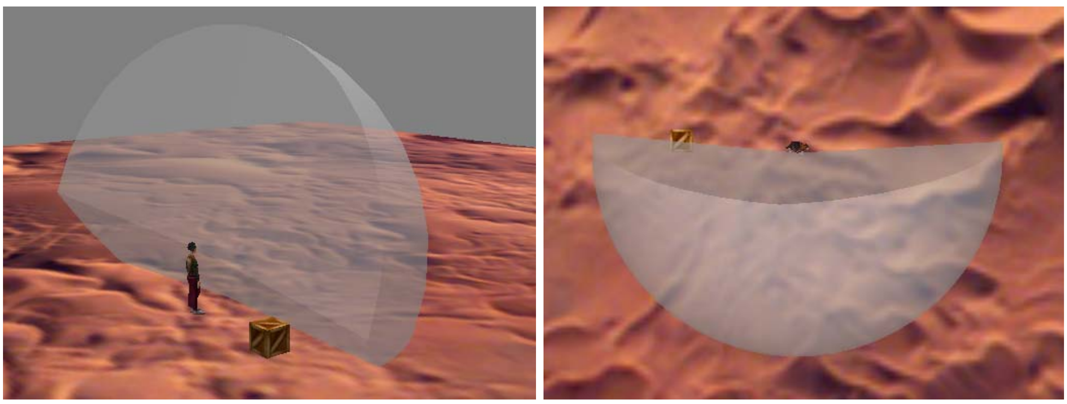


Figure 5-2 The pink area is the binocular visual field based on Anthropometric data (Webb 1964); the dash square is field of vision which normally used for synthetic vision modelling based on graphic processing (Thalmann 1996(2)).

The conception of field of vision (FOV) has been wildly applied in ergonomics or human factor research. Unfortunately, only a few research has paid attention to this concept (Reich 1994). In this chapter, the expression ‘tapered volume’ is used to indicate this irregular conical shape for virtual human synthetic vision modelling. After reviewing the biological function of a human’s vision system, a tapered volume is modelled to simulate a virtual human’s field of vision. **Figure 5-3** depicts a scaled-down view of what the FOV volume looks like in this synthetic vision modelling.



A



B

Figure 5-3 A, Snapshots of the field of view (FOV) in the collision-based synthetic vision modelling; B FOV model in a scenario.

The tapered FOV volume projects forward from the face of the virtual character.

When the virtual character is looking horizontally forward, the tapered volume is an irregular taper with a spherical angle of approximately 60 degrees above the horizon, 74 degrees below the horizon, and 100 degrees to both the left and right hand sides. It is necessary to point out that all the illustrated FOV volumes in this chapter are presented as a semitransparent volume. This is only in order to explain it intuitively. Actually, the FOV volume is a transparent volume in this simulation.

The tapered FOV volume extends to a reasonable distance, which is called the effective radius R_{fov} of the synthetic vision system. The radius should be appropriate for the visibility of the 3D environment. The relative location between the FOV volume and the virtual character's head is fixed, which means the tapered FOV volume will be moved in relation to the position of the virtual character's head. This tapered FOV volume is modelled based on ocular data for field of vision (Spense 1992), and hence it is a biologically plausible model of human vision.

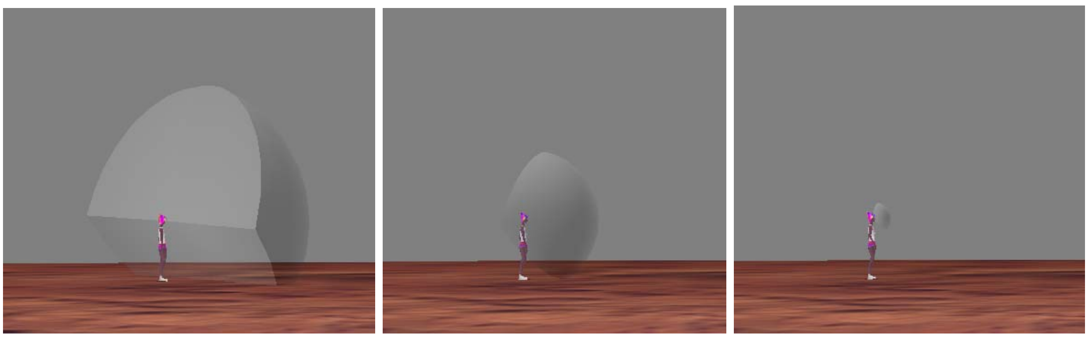


Figure 5-4 Changeable FOV volume for synthetic vision system

The radius R_{fov} should be influenced by the visibility in the environment. A dangerous environment may be full of smoke, such as fire or fog. It is very important to model this effect so that the sensibility of a virtual character's vision can be different in different situations. A visibility index V_x (≤ 1) is set for the FOV volume. $V_x < 1$ meaning the visibility of the environment has decreased and the FOV volume will be reduced as well (**Figure 5-4**). The effective radius of the synthetic vision system could be modified as follow:

$$R'_{fov} = V_x \bullet R_{fov}$$

This is to guarantee that the size of the FOV volume is changeable in the environment and adjustable depending on different environments. When virtual objects collide with the surface of FOV volume in the virtual environment, the objects in the FOV volume will be stored in the FOV stack. This feature is similar to that of Jack.

5.1.2 Collision-based synthetic vision

The image processing method for synthetic vision is quite good for distinguishing objects from the environment background, but does not work very well when attempting to understand the visible objects (Noser 1995(2); Kuffner 1999; Courty 2003). It is still hard for computer to identify and understand a deformable object from different perspectives without sufficient background information. A case in point is shown in **Figure 5-5**.

Figure 5-5 Computer Vision Problems: it is difficult for computer to recognise these two images are representing the same object.

Specifically, the goal of modelling synthetic vision in this improved virtual human model is to simulate how virtual humans recognise visibility of objects in the field of vision in an interactive virtual environment. Therefore, instead of teaching the computer how to identify objects through synthetic vision, it is assumed that virtual humans automatically understand the majority of visible objects which are detected by their own synthetic vision in virtual environments. The unfamiliar objects in this system are treated as exceptions. Based on this assumption, a peripheral vision detector model is proposed, named as collision-based synthetic vision.

Different to the computer graphic methods which analyse the snapshot images from virtual human's field of view, a collision-based synthetic vision system has been designed and implemented for virtual humans to detect their virtual environment (**Figure 5-6**). When an object is collided with the surface of FOV volume, the time of collision will be recorded. The time of collision decides whether the object should be stored in a FOV stack. It is assumed that all virtual objects were initially out of the FOV volume. Once a virtual object is collided with the surface of FOV volume, the time of collision will add up to 1 and the object will be stored in a FOV stack. Then if the object is collided with the surface of FOV volume again, the time of collision will be added up to 2 and the object will be deleted from the FOV stack. In this case, if the collision time is an odd number, the object must be inside of the FOV volume; otherwise, it must be outside of the volume. This method is reliable when the colliding object is convex. For those objects with more complex shape, such as human body, the method can be modified through using "bounding box" technique or divide the complex shape into different colliding parts.

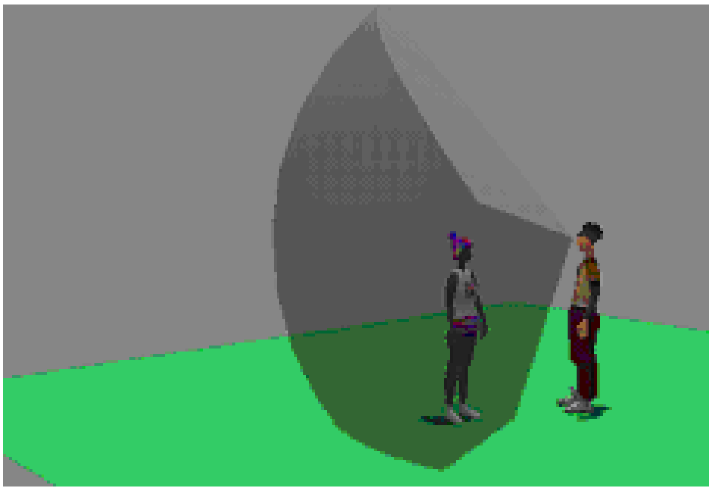


Figure 5-6 Perspective view FOV model in a scenario

It is believed this collision-based method not only makes a virtual human's vision function more like real human eyes, but also useful to speed up synthetic vision processing and saving computing resources. The irregular shape of the FOV volume is modelled in 3DS MAX and programmed with Virtual Scripting Language after imported into Virtools™.

5.1.3 Basic principles of visibility for the synthetic vision system

There are two necessary conditions for the virtual human to recognise a virtual object through this synthetic vision model: first, the visible objects have to be in the FOV volume; second, the visible objects are not fully blocked by any other virtual objects in the FOV. These principles are actually two basic features of visibility for human eyes as well. When virtual objects collide with the surface of FOV volume in a virtual environment, the objects in the FOV volume will be stored in a FOV stack as mentioned. The 'visible' virtual objects will be stored in a visibility stack. This visibility stack is actually a subset stack of the FOV stack.

5.1.4 Sensibility of synthetic vision system

Minimum visible angle is a nature factor for human eyes. It is used to describe the limitation of human's visual sensibility. When an object is too far away for the observer, the object can be too small to be noticed in the distance.

$$\frac{distance}{size} > C$$

The minimum visible angle is originally determined by the cell size of the retina. The distance between two cells of the retina will decide the sensibility of one's vision. Normally, for a mature adult, the value of minimum visible angle is in a range of $\cot(0.5') \sim \cot(1.3')$.

5.1.5 Relative visual acuity of synthetic vision

Relative visual acuity of an object is another important feature of human vision (Blank 2002). The visual acuity value is assumed as a number between 0~1. The greater the acuity value, the more accurate evaluating information can be obtained from this object. Further details of variables that can be used to generate evaluating information are presented in **Appendix D**. The relative visual acuity equation used in the improved virtual human model is developed from Kim's formula for relative visual acuity (Kim 2004).

$$f_{acuity} = e^{-7(1-\cos\theta)^2}$$

θ is the angle between the target vector, which is from the eye to the target object, and the vision vector, which emanates from the eye perpendicular to the face.

5.2 Virtual memory modelling

5.2.1 FIFO short-term memory system

All the objects in a virtual human's FOV stack will be checked whether been blocked by other virtual objects in the volume. These objects, which have been checked and judged with no other objects blocked in the direction to the virtual human's eyes, will be stored in a visible stack. A first-in-first-out (FIFO) short-term memory system is then developed, which allows the virtual human to remember what has been 'seen' through its collision-based synthetic vision. The memory stack is also the direct resource which helps the virtual human to generate consequent emotions for decision making and reaction.

The particularity of a memory stack is that it allows a virtual human to remember some previously detected objects. For example, based on the principle for a synthetic vision system, a virtual object is deleted directly from the FOV stack and visible stack when it collides out of the FOV volume. However, it may still remain in the memory stack for a little while, which is to represent the memory span of those previously detected objects. In other words, each virtual object in the memory stack will remain for a certain span and be deleted when the span has expired as it is forgotten. This virtual memory is trying to simulate a function that humans can only remember limited objects in surroundings, especially under emergency, and will also forget previous observed objects without necessary review. The FIFO short-term memory stack is actually a dynamic database for virtual humans to generate their own emotion for decision-making and reaction, which, as I believe, is more similar to the cognitive processing in the real human brain.

The memory stack provides a unified interface for all virtual perceptual sensors to save detected changes in the virtual environment as well. It is also a unified input format for the downstream emotion calculation module to generate corresponding emotion states in real-time based on the changes of a virtual environment. The information that contributes to short-term memory is the main resource for a virtual human's emotion generation model. Not only this, virtual memory can also affect a virtual human by updating the virtual human's knowledge for decision-making. Therefore, a virtual human can improve its reaction based on the previous experience.

Beyond visibility, in the real world, one does not remember all objects that have been glanced at. Especially, in a new environment, it is difficult for the majority of people to remember all objects that have been glanced at. Actually, one's reactions to the environment are more likely based on the limited information that one remembered rather than what one had seen. Is this case, humans have to make decisions with insufficient information caused by limitations of short-term memory. This phenomenon inspired the following hypothesis: the simulation of a virtual character's short-term memory may create a more believable decision making for virtual humans.

5.2.2 Limitation of the short-term memory

A short-term virtual memory module with limited memory capability has been proposed in order to increase the reality of virtual humans' decision making and reaction. The module simulates human-like short-term memory based on what is glanced at by the virtual character. For example: A man tries to walk out of a maze. His reaction relies on the latest observed and remembered paths.

5.2.3 FOV stack, visibility stack and memory stack

A FOV stack is modelled first, which saves the virtual objects which are collided with the surface of FOV volume. Then a visibility stack is modelled to filter the objects in the FOV stack based on the visibility principles as mentioned in **Section 5.1.3**. A short-term memory stack is modelled to filter the objects in the visibility stack. It is implemented to simulate a virtual character's memory. The main principle in the memory stack is a constraint called 'time tolerance'. It is added to retain objects, which have left the visibility stack, or even the FOV volume, in the virtual human's short-term memory stack for a short period (**Figure 5-7**).

As mentioned earlier in this chapter, the short-term memory stack is a first-in-first-out stack. It allows virtual humans to remember and forget the earliest environmental information and always keep the virtual memory being updated with the latest changes. A short-term memory stack is not a subset stack for either the FOV stack or visibility stack. It is used as a database to generate necessary inputs for a planning, navigation algorithm and emotion calculation system. It is different to the visibility stack, which directly deletes virtual objects when those objects do not meet the visibility principles. It is also different to the FOV stack, which deletes virtual objects when those objects leave the FOV volume. For example, when a virtual object collides out of the FOV volume, it is directly deleted from the FOV stack and visible stack. However, the 'object' may still remain in the memory stack for a little while, which is to represent the memory span of those previously detected objects. In other words, each 'object' in the memory stack will be remained for a certain span before it is deleted.

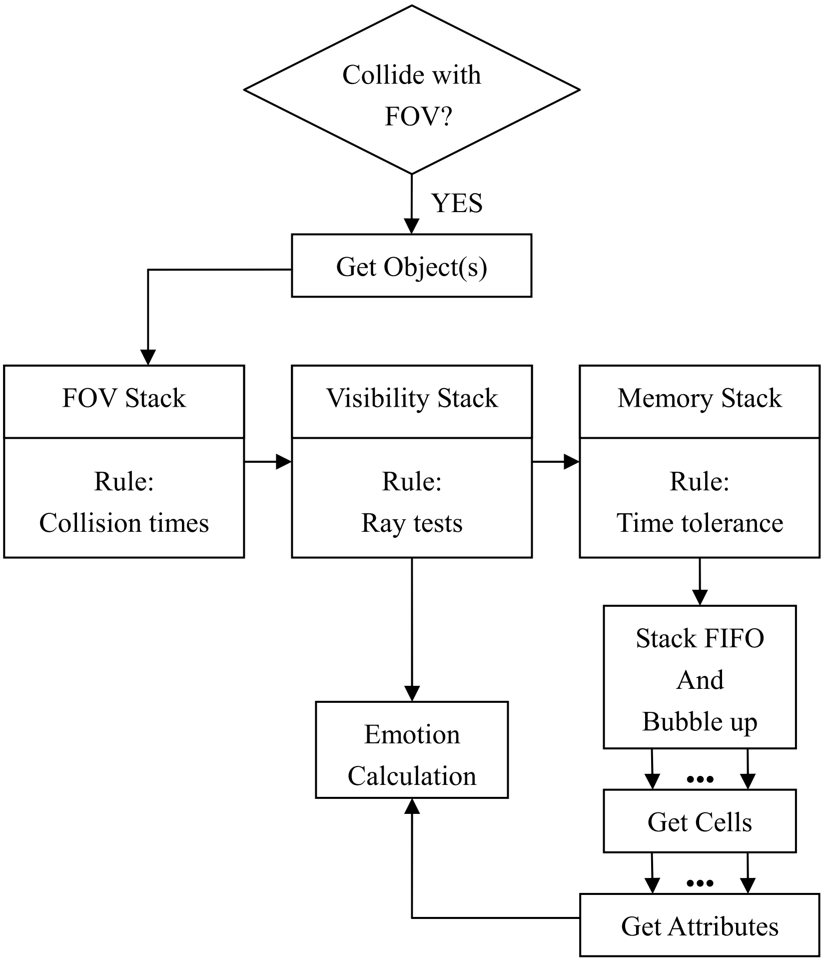


Figure 5-7 Flow Chart for FOV, Visibility and Memory Stacks

This virtual memory stack simulates a function that humans can only remember limited surrounding information. The observed objects will be forgotten if them have not been reviewed in time. **Table 5-1** indicates all possible states among the FOV stack, Visibility stack and Memory stack. It also shows whether the states exist or not. If the states exist, the table presents whether it is transient or steady.

Based on the principle of context, the virtual object stored in the Visibility stack has to be stored in the FOV stack first. Thus, there are only five possible situations for an object to be stored in the three stacks.

Table 5-1 All possible relationships between the FOV stack, Visibility stack and Short-term memory stack.

Situation	1	2	3	4	5	6	7	8
FOV	√	X	√	√	X	√	X	X
Visibility	√	X	X	X	X	√	√	√
Memory	√	X	X	√	√	X	X	√
state	steady	steady	steady	transient	transient	Not exist		

The relationship between the FOV stack, visibility stack and short-term memory stack can be described through the following example. Virtual object A and B both exist in the virtual character's FOV volume and are visible. Therefore, both of them are stored in the FOV stack, visibility stack and short-term memory stack (Situation 1). When the virtual character changes its position, object A is blocked by object B. Then object A should be treated as invisible for the virtual character. Object A is then deleted from the visibility stack but still be stored in the short-term memory stack (Situation 4). Object A will be deleted from the virtual character's short-term memory only when it meets both of these limits: 1. the time limit of the short-term memory expired (Situation 3); 2. It is left in the FOV volume (Situation 2). A case study of the memory stack is presented in **Figure 5-21** to show the relationships among these stacks in details.

5.3 System realisation

5.3.1 Implementation of the synthetic vision system

The synthetic vision system of the improved virtual human model, illustrated in **Figure 5-8**, comprises a perceptual range controller and a set of virtual onboard sensors. The virtual human is equipped with those sensors that provide information about the dynamic environment.

A perceptual range controller measures the ambient (virtual) range of vision at the centre front of the virtual character's face. It also decides the distance of the virtual character's vision. An onboard occlusion sensor allows virtual humans to judge if an object in the field of vision is fully occluded behind some other opaque object. The sensibility sensor is responsible for deciding if an object is too tiny to be 'seen'. The whole synthetic vision system is a filter to decide which objects in the virtual environment are visible for the virtual characters. All these detected objects will be temporarily stored in short-term memory stack and support the down steaming emotion generation and decision making modules.

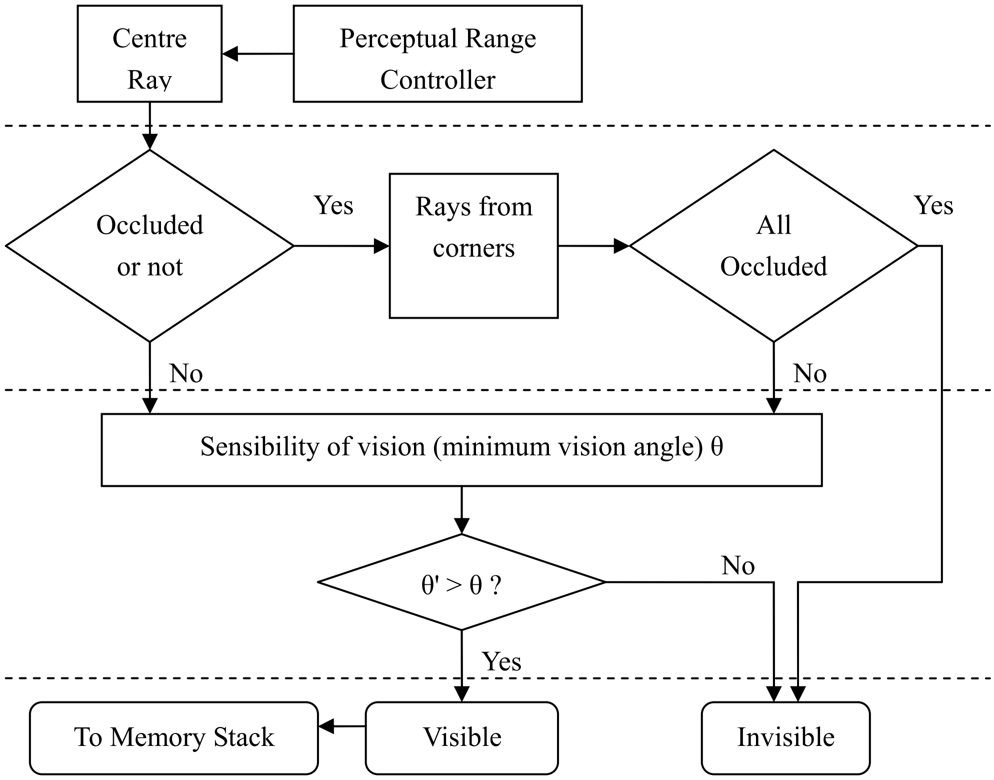


Figure 5-8 Flowchart of the synthetic vision system: FOV optimisation > Ray from centre > ray from the corner (occlusion judgement) > minimum angle (visibility judgement)

5.3.2 Collision-based synthetic vision

Initially, it is assumed that there is nothing in a virtual human's FOV volume. The visibility of a virtual object to the virtual human could be simply presented as the time of collision between the FOV and the object: if the time of collision is an odd number, then the object must be inside the FOV and visible to the virtual human. On the other hand, if the time of collision for a certain object and the FOV is an even number, then the object must be outside the FOV and not visible to the virtual human. (**Figure 5-9**)

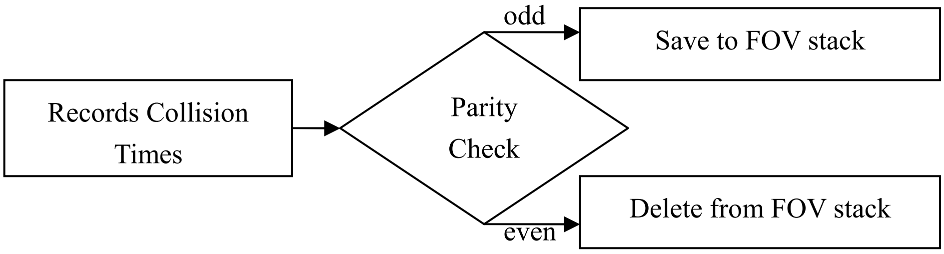


Figure 5-9 Flow chart of FOV collision test

The collision-based synthetic vision function is realised in Virtools™ with Visual Script Language. The programming scripts are presented as follows:

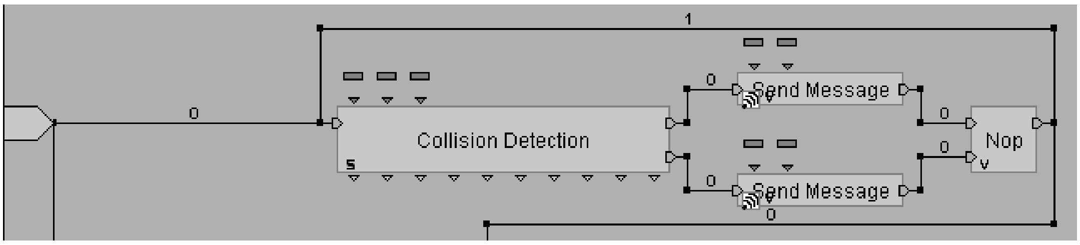


Figure 5-10 The part of collision test

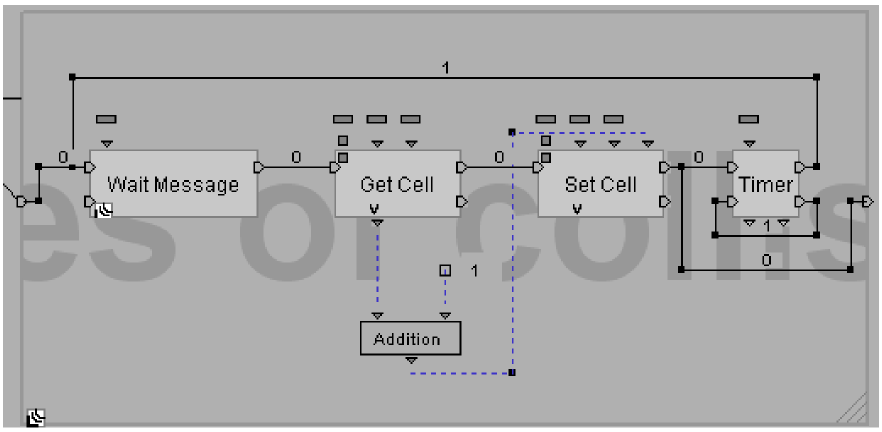


Figure 5-11 The part of collision times recording

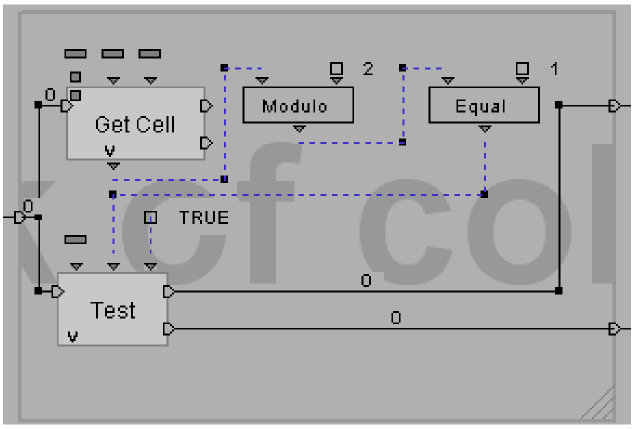


Figure 5-12 The part of parity check

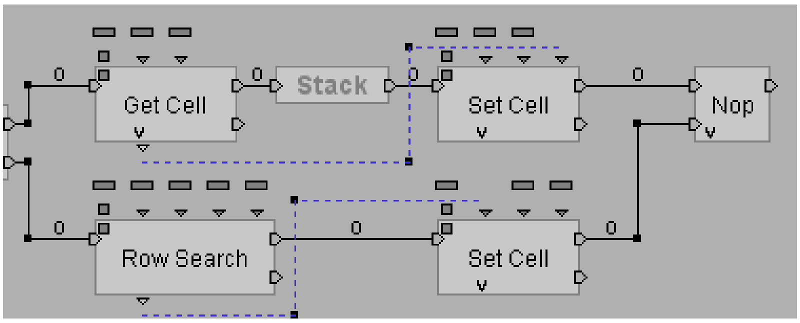


Figure 5-13 The part of records in FOV stack

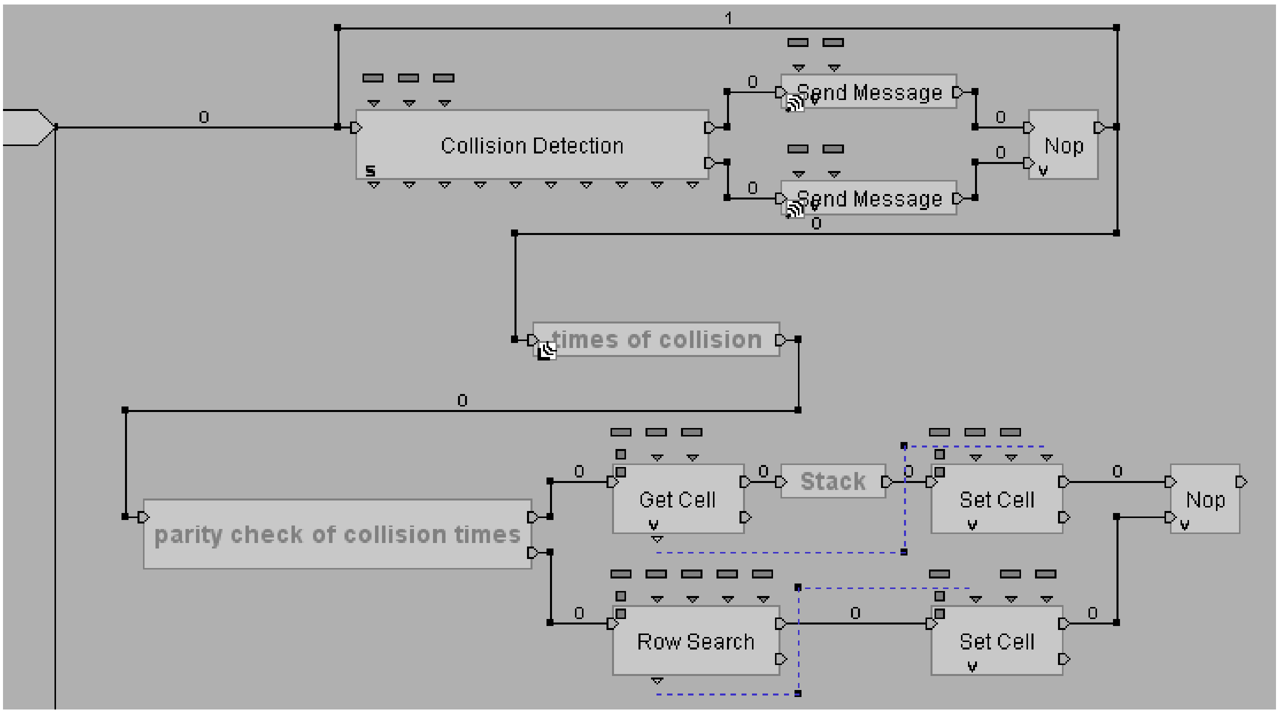


Figure 5-14 Overview of collision-based synthetic vision system

5.3.3 Visibility test

In a visibility test, it is necessary to get the coordinates of both of the virtual character's head (accurately, the peak of the FOV) and the virtual object. In the virtual reality environment, it is relatively easy to get the coordinates of all objects and characters. The direction vector from a virtual character to any object can be calculated based on those coordinates.

In general scenarios, if the direction vector from a virtual character to a virtual object is similar to the direction vector to other virtual objects, then the distance from the virtual character to each objects can be calculated. The closest object will be judged as 'visible' to the virtual character. The other objects will be required to shoot rays from their vertexes to the peak of the FOV volume. If one of the rays does not intersect any other virtual objects in the 3D space, the object is judged as 'visible' for the virtual character. This method is an improvement of Tu's occlusion test for visibility of seaweed (Tu 1994). For a simplified example, see **Figure 5-15**.

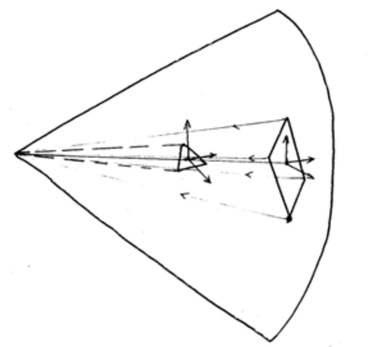


Figure 5-15 The visibility test of objects in the FOV volume

The flow chart of visibility test is presented in **Figure 5-16**. It indicates that not all rays have to be shooting out in a visibility test. A visibility test can be terminated as soon as the virtual object is judged as 'visible'. A part of the programming script for this visibility test function is presented in **Figure 5-17**. It presents how a testing ray is generated in between a virtual character and a virtual object.

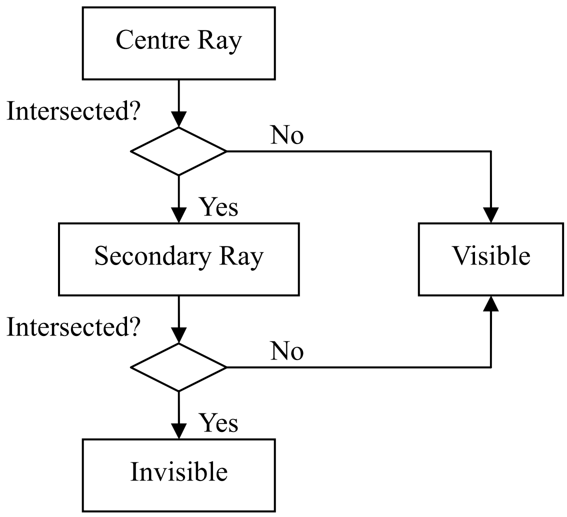


Figure 5-16 Flow chart of visibility test

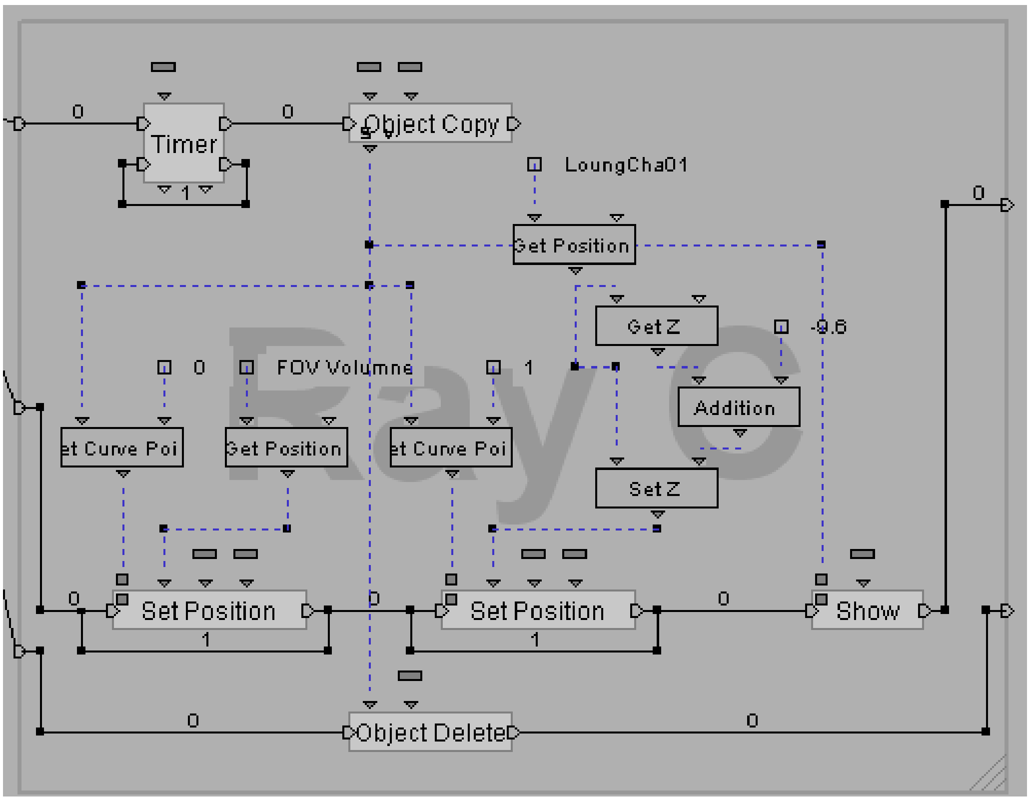


Figure 5-17 Visual script of visibility test (part)

5.3.4 Visual acuity

The visual acuity function, described in **Section 5.1.5**, is implemented as well to provide a different level of object detail for emotion generation.

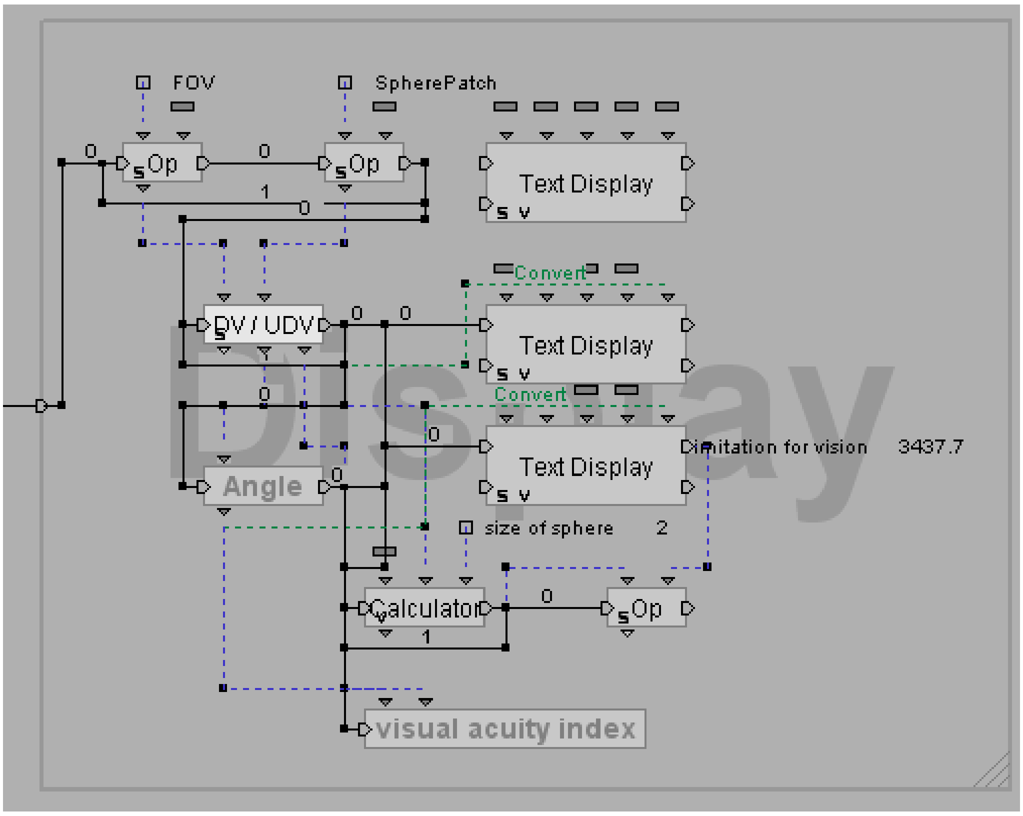


Figure 5-18 Visual script of visual acuity

5.3.5 FIFO stack for virtual memory

A first-in-first-out (FIFO) memory stack is designed for the synthetic vision system. The size of the virtual memory stack is limited as M, which means a virtual human can remember maximum M virtual objects in its virtual memory. When the number of detected objects, N, is bigger than M (N>M), without considering the time tolerance, the memory stack will delete the first object that has been saved in the memory stack and replace the empty cell in the memory stack with the latest visible object. The programming scripts of this kind of FIFO memory stack in Virtools™ is presented in **Figure 5-19**.

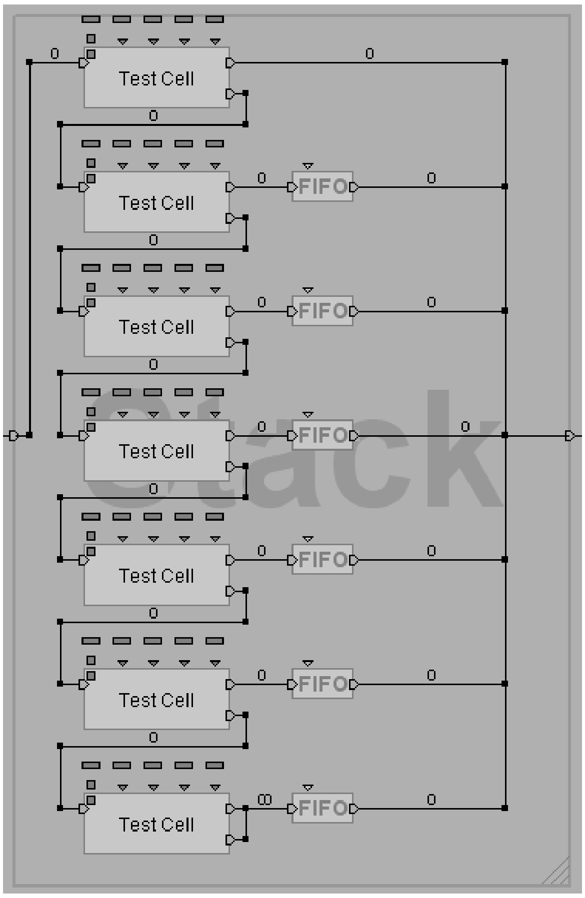


Figure 5-19 FIFO memory stack (initial size: 7)

5.4 Case study and results

The entire synthetic vision system has been applied to the virtual human model and tested in some virtual scenarios. For example: a lounge scenario has been used to test the synthetic vision system for an improved virtual human model. The scenario includes a virtual lounge with a couch, a tea table, a TV set, two end tables, and two sofas, as exhibited in **Figure 5-20**. In this scenario, a virtual character is expected to wander around the lounge and detect the environment through its onboard collision-based synthetic vision system. While wandering, the virtual character will store the objects in its FOV stack; visibility stack and short-term memory stack according to the principles mentioned earlier. What is stored in those three stacks will be used to generate inputs for processes which affect different aspects of virtual character's reactions, such as, attention process, emotion calculation process and decision making process. The information in the synthetic vision system will be updated in real-time as the virtual character changes its position to provide real-time short-term memory, and consequently affect the virtual character's emotion states and decision making.

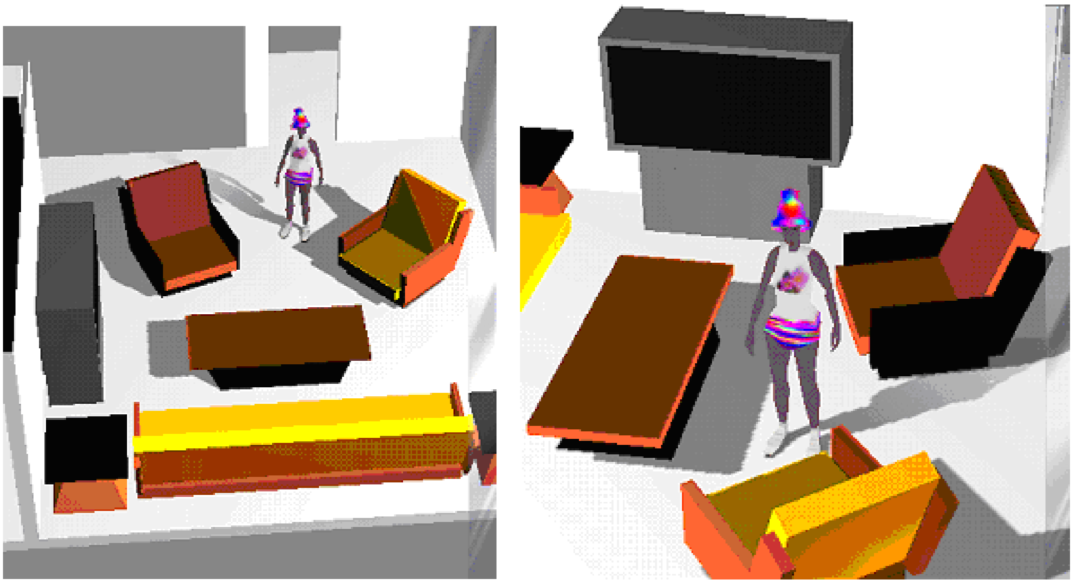


Figure 5-20 Virtual environment (indoor) scenario design: character in lounge, in Virtools™

Several case studies were implemented here as examples to show how the synthetic vision system was realised in Virtools™.

5.4.1 Case 1: FOV, visibility and memory stack

One criterion of testing the synthetic vision modelling approach is to validate whether virtual visible objects were stored in corresponding stacks correctly. **Figure 5-21** demonstrates four possible situations in the virtual environment and the corresponding states of the short-term memory stack. In Case 1, one virtual character can see the other virtual character and an object (cube); in Case 4, an object (cube) is blocked by the other virtual character, however, the time tolerance allows the object to exist in the short-term memory stack for a short period, even if the object has left the FOV volume as shown in Case 4; Case 3 shows the object will be deleted from the short-term memory stack after the time tolerance in Case 4 expires.

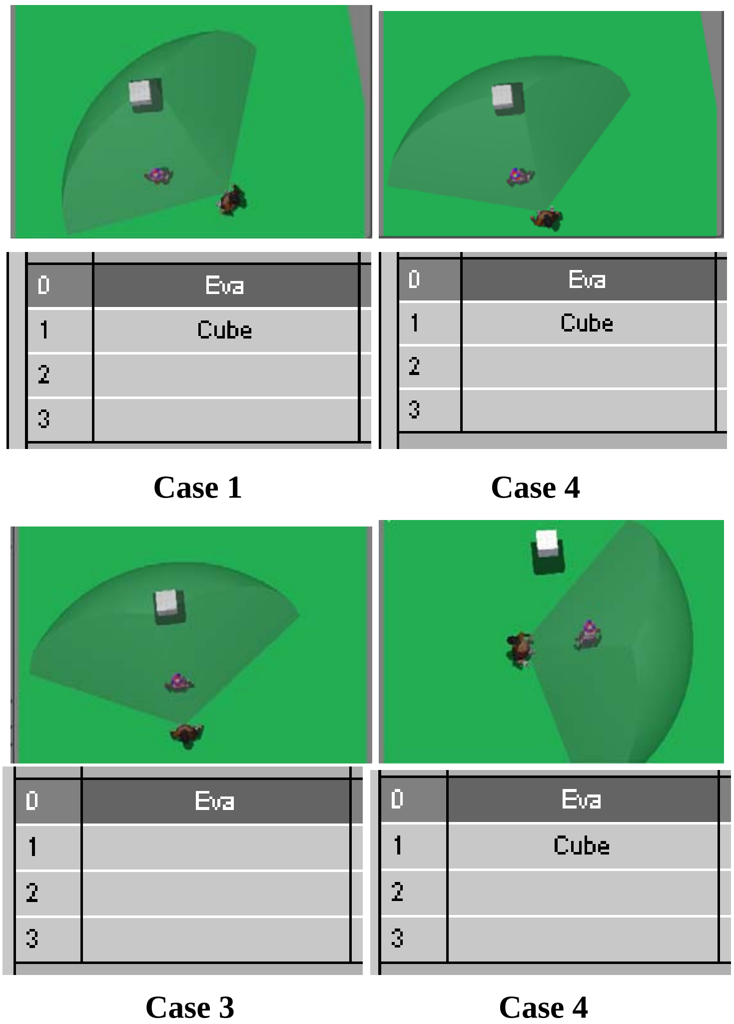


Figure 5-21 four possible situations and corresponding states in the short-term memory stack

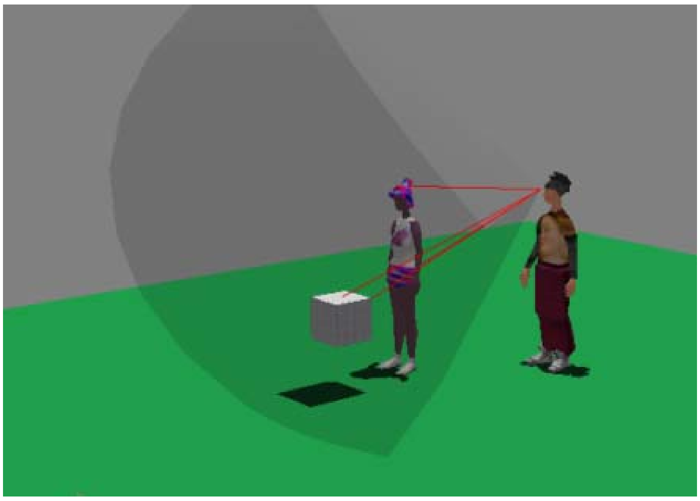


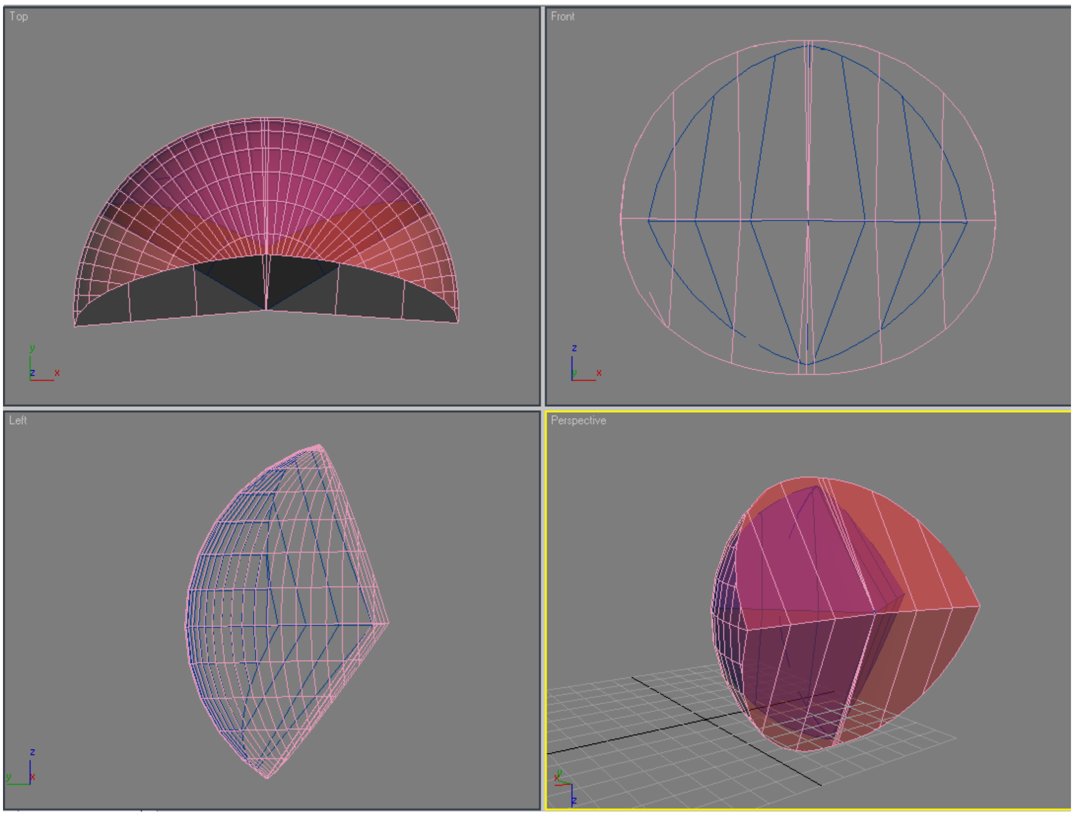
Figure 5-22 the visibility of possible obstructed object testing

5.4.2 Case 2: Visibility test

As mentioned earlier, a partly visible object will shoot rays from its vertexes to the origin point of the FOV volume. If one of the rays does not intersect any other object in the FOV volume, the object is visible. The snapshots of the visibility test in this system are shown in **Figure 5-22**.

5.4.3 Case 3: Relative visual acuity and visual sensibility

Besides using a visual acuity index to represent the vision acuity of virtual humans (**Section 5.1.1.4**), a visual acuity volume has been adopted for virtual humans as an alternative method to distinguish the acuity of the synthetic vision in the system. As shown in **Figure 5-23**, the smaller volume represents the field of view with high visual acuity. Those objects in visual acuity volume (the inner, smaller one) could provide feature information of all 14 evaluating variables from objects for emotion generation. Other objects in the FOV volume will provide less than 7 feature information when evaluating variables for emotion generation.



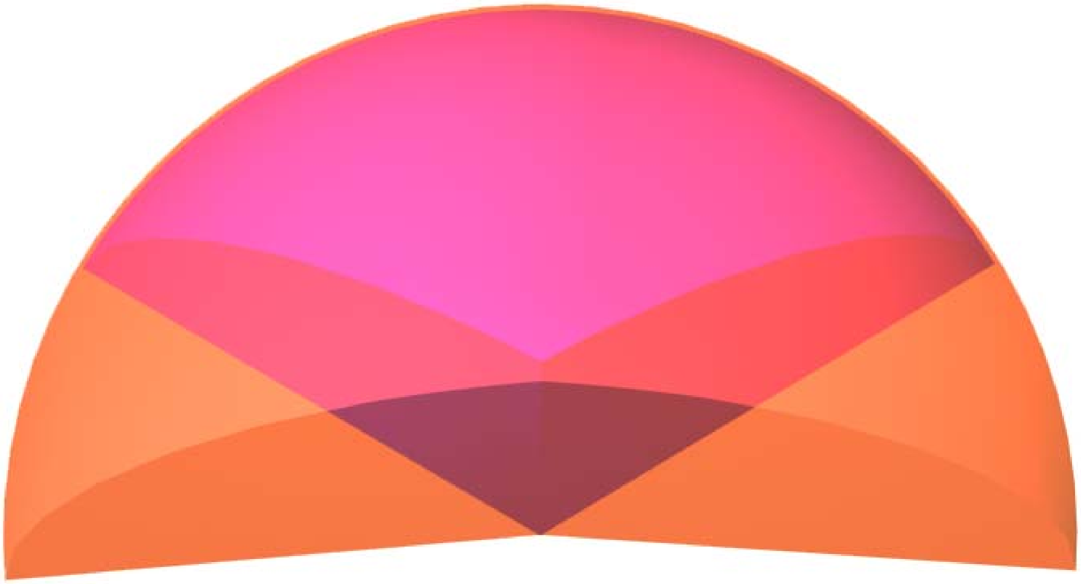


Figure 5-23 Visual Acuity Volume

The visual sensibility test has been indicated in **Section 5.1.1.4**, which decides how small an object can be seen. Considering the brightness of the environment, movement state of both human and objects, and some other reasonable factors in the real world that might affect a human's visual sensibility, the executing value of the minimum visible angle in the synthetic vision module is higher than the value of this range. In this virtual human system, cotangent of five minutes of arc is chosen as the standard value for synthetic vision system:

$$\frac{distance(obj_i)}{size(obj_i)} > cot(5')$$

5.4.4 Case 4: Blinking, a review and update mechanism

After several tests, it is realised that there is a bug in this synthetic vision system. Since the synthetic vision approach is collision-based, it cannot detect the changes inside the FOV volume. For example, an object that suddenly starts firing in a virtual character's FOV volume. The virtual character cannot detect this kind of change functionally. Therefore, the collision-based approach has to be modified for providing a synthetic vision function more like that of a real human.

The method introduced here is to endow the virtual character with the capability of blinking. When the virtual character blinks, the FOV volume firstly shrinks into a small volume (V'_{for}), and then expands to the initial size (V_{for}). The small volume should be small enough to be ignored, such as: $V'_{for} : V_{for} \leq 1:100$ in the majority of cases. The FOV volume will collide with all objects in the area in quite a short time as fast as a real human can blink. This function is expected to help the virtual character recognise dynamic events in a more natural way. However, the purpose of implement such function is not trying to simulate the physiological function of blinking. The blinking process is captured in pictures as shown in **Figure 5-24**.

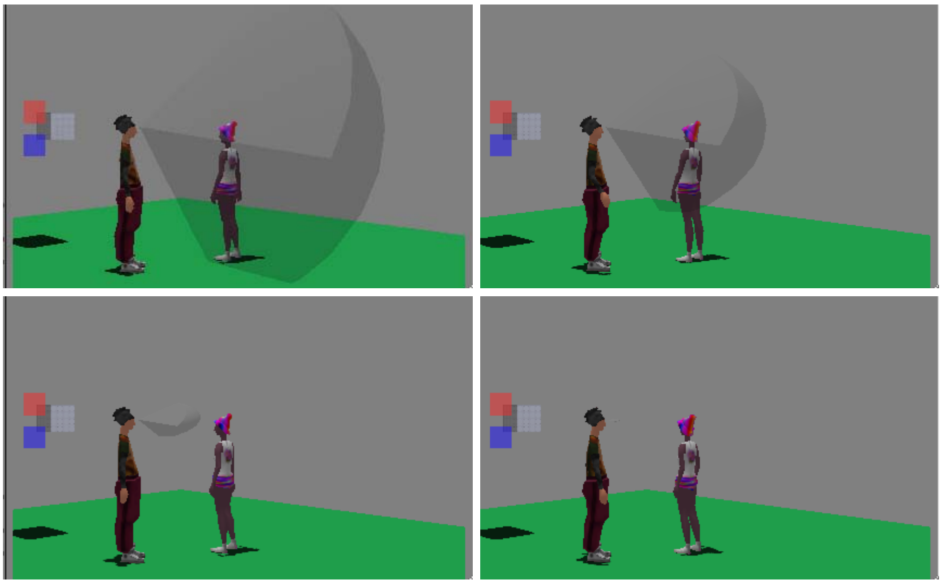


Fig 5-24 the blinking process and the snapshots of FOV volume changes

5.4.5 Case 5: Test the synthetic vision system in a group of people

The approach can also be used for crowds. In **Figure 5-25**, one of the simulations, six virtual characters walked in a virtual environment based on their synthetic vision without colliding into each other, avoiding obstacles and fires.

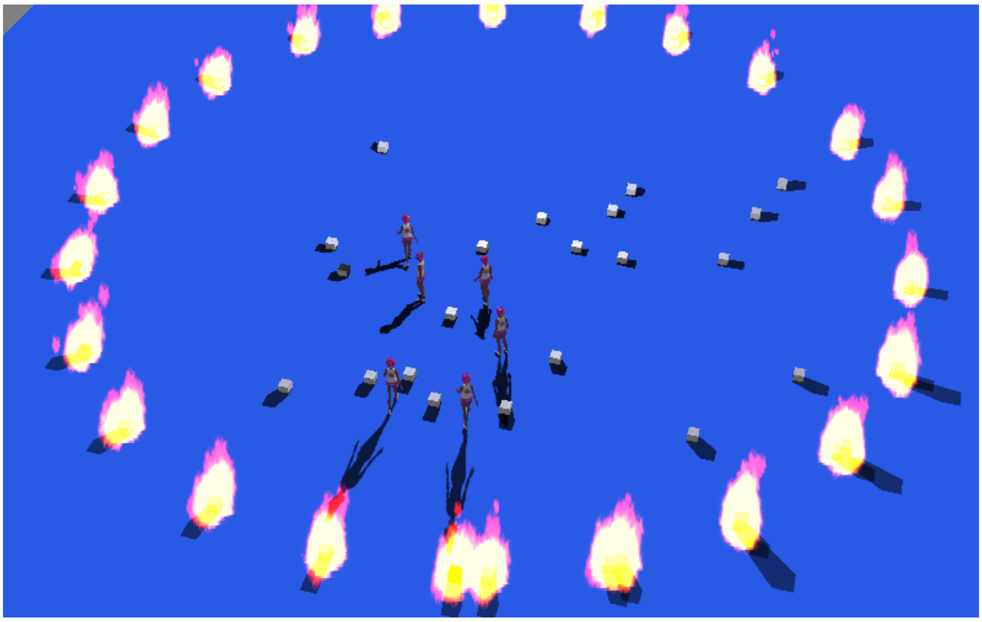


Figure 5-25 A simulation of a crowd in a virtual environment. Each virtual character is trying to avoid collision with others based on their onboard synthetic vision system and virtual memory. They can also avoid static or dynamic obstacles in the virtual environment.

5.5 Discussion

The models presented in this chapter are integrated into the improved virtual human model and virtual human model with emotion capabilities. All the simulation is executed in Virtools™. The target of modelling such a synthetic vision and virtual memory model is to help increase the autonomy of virtual humans and provide a unified interface of information that can be used to generate emotions in virtual humans. The synthetic vision system is made to simulate a general vision processing of human beings. It avoids to struggle with those individual differences, such as oxyblepsia (oxyopia), achromatopsia, partial tritanopia, etc. There is a more complex cognitive structure behind these individual differences, rather than only vision processing. Last but not least, the synthetic vision system is about identifying visual objects and changes within relatively short distance in virtual environments as a peripheral vision detector.

Compared with the methods which analyse pixels of a rendered image from a virtual character's point of view, the collision-based synthetic vision model proposed here is biologically more faithful to the view of a real human. Compared with the computing visibility method (Tu 1994; Pursel 2004), the collision-based synthetic vision model proposed here is simpler and easier to execute. It provides more reasonable and accurate synthetic vision for a virtual human in a virtual environment, especially for indoor and short distance vision detection.

The main disadvantage of this collision-based approach appears to be how it works during normal viewing conditions when there is a need to test a long distance visibility. For example, the testing of far away objects is prohibitive as the FOV volume would not be enlarged into an unreasonable scale. This problem is not discussed in this work, as objects or events occurred in long distances are less important to affect human's emotion state and decision making than surrounding objects. The problem is also beyond the scope of the virtual human modelling.

5.6 Conclusions

In this chapter, a novel collision-based synthetic vision system and vision based short-term virtual memory structure have been modelled and executed in a series of 3D virtual indoor environments which have been built in Virtools™. This approach is a simple and more reliable information channel between the virtual environment and virtual humans. It is sufficient to support information for the emotion calculation and decision making processes of the virtual humans in this work.

The synthetic vision system detects whether a virtual object was in a virtual character's field of vision only by checking the collision times between the object and the surface of the FOV volume. It does not follow the traditional method, which decides the visibility of an object through calculating the distance from the observer to each vertex of object. This feature also makes the approach quite suitable for an interactive system.

On the other hand, this approach still has aspects which need to be improved. As luminance is not considered in this approach, the virtual character could not ‘see’ the changes of brightness in the virtual environment. Also, the synthetic vision in this approach is still not suitable for long distance visibility detection. That makes it quite suitable for the indoor environment but not in outdoor scenarios. This is because it is quite hard to define the effective radius in different outdoor environments. Extra information is still required for virtual characters to realise big and far away objects, which is normally called background objects. All these issues will be the questions for future research.

Chapter 6
Emotion Modelling

6.1 Introduction

Emotion is now being considered by more and more researchers as playing an important role in guiding and regulating choice behaviour (Lyons 1978; Bower 1982; Araujo 1993; Antonio 2001; Freitas 2005; Garcia-Rojas 2006; Hudlicka 2007). It is necessary to design some practical structures for emotion as building blocks, which can easily be integrated with virtual human modelling.

In **Chapter 5**, a collision-based peripheral synthetic vision was presented and implemented. This synthetic vision model builds a bridge between the virtual human and its surrounding virtual environments. It helps virtual humans acquire necessary information for emotion generation and decision making. A short-term memory has also been integrated with synthetic vision to help virtual humans remember visible information in virtual environments. This 'synthetic vision and short-term memory' structure provides virtual humans with a realistic decision making environment.

In this chapter, the emotion generation module is introduced with the emotion capability is proposed as an important part to improve the reality of the virtual humans. Emotions can change ones behaviour and decision-making consciously or unconsciously. The notion of emotion is a macroscopic concept. Ortony et al. proposed to construct a cognitive theory concerning the development of the emotions during a person's lifespan (Ortony 1988; Ortony 2007). He also discussed the variables affecting the intensity of emotions, and proposed concepts about variable-values, variable-weights, and emotion thresholds. This actually gives a possible way to model emotion in computer programming.

A method of how to integrate emotion processing with virtual human modelling is proposed in this chapter, which includes how emotion changes along with visual stimuli (**Section 6.2**); how to form emotion equations based on psychological tests (**Section 6.3**). A creative emotion calculation approach is proposed based on the theory of hierarchical cognitive structure of emotion (**Section 6.4**). The structure is an appropriate approach to integrate the emotion process with computers. It helps virtual humans generate their own emotion states according to synthetic perception and short-term memory information, and provides basic emotion parameters for reactive behaviours and decision-makings.

Case studies of how individual objects would affect virtual human's emotion and variables that are contributing to the intensity of certain emotions are given in **Section 6.5**. Some modelling results and discussions are given in **Section 6.6**. **Section 6.7** concludes this chapter.

6.2 Emotion measurement

The first problem of modelling emotion capability for virtual humans is how the intensity of emotion would change and how to simulate the change of emotion in computers. Several informal subject evaluations have been conducted to assess how emotion changes in intensity along with vision signals using psychophysiologcal measures. Some basic principles of emotion changes are suspected to be found by analysing these test results.

Psychological tests are introduced to identify the feature of how emotion changes in intensity along with visual stimuli. The result of these tests has been studied and the evaluated results are modified to create basic principles for plausible emotion generation. In this emotion generation system, an emotion calculation model and a maintenance mechanism are established to allow virtual human to have its own emotion state. It generates a general principle of how emotion could affect virtual humans' behaviour and decision making.

6.2.1. SCR tests

As mentioned in **Section 3.1.2**, SCR sensors can be used to record the skins conductance over a small area. It is known that sweat glands (eccrine glands) present in the hands and feet show a galvanic effect. This effect is triggered not by thermoregulation, but by signals present in the sympatric nervous system. These emotional signals such as arousal, are shown to cause near instant changes in the level of sweat in these glands, in turn affecting the skins conductivity in the area the glands are present. SCR measurements are generally identified as the most reliable indicators of a subject's arousal. Therefore a SCR reading indicates the subjects level of arousal, on a scale from calm, agitated, to outright frustration and anger (Morrissey 2006).

SCR, as an affective signal which can be used to describe emotion, is used extensively by researchers in psychology. The actual sensors are generally fixed about two inches apart, either to the top and bottom of the middle finger or on the base of two adjacent fingers. This arrangement is quite comfortable and unobtrusive, however, it does not bode well when washing ones hands. On the down side, conductance readings are known to vary due to external factors such as ambient temperature and humidity, necessitating the addition of extra temperature and humidity sensors on the subject, used to negate these changes.

The SCR is highly sensitive to emotions in some people (Bauer 1998). Based on the electrical resistance of the skin, it is possible to determine how long it would take for a human to have a distinctive emotional reaction, how rapid in intensity of emotional reactions can be changed, and how long they can persist.

10 different subjects, who vary in age, culture and educational backgrounds, were involved in these tests: 5 undergraduates (two third year students, two first year students), 4 postgraduates (two British students, three Mandarin students), 1 teacher (lecturer from social science). Results of the SCR tests are listed in **Appendix E**. A

case study is shown below to investigate how it works.

In a testing group, 20 pictures were shown to each subject, which included 8 pictures of snakes and some pictures of kitchenware (which are considered as pictures not related to "fear" emotion). The pictures are arranged in a random sequence. Each picture is shown to the subject for 4 seconds and a 4 seconds break is given in-between two pictures.

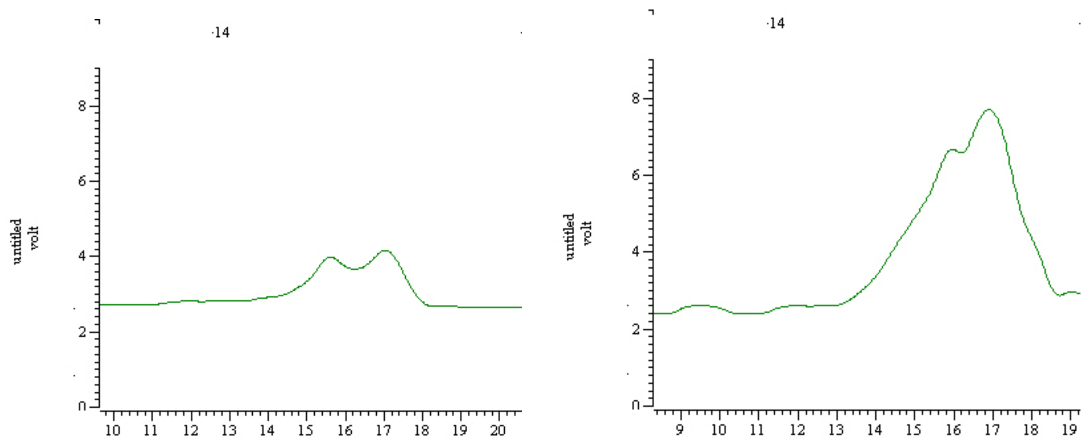


Figure 6-1 Samples of SCR data: emotional reactions to snake

Samples of the SCR results are measured against how long it will take for the subject to have an emotional reaction and how rapid this reaction can change.

6.2.2 Data analysis for fear related emotion

This case shows how equations of fear emotion are identified for a testing subject. Subjects for SCR testing are required to calm down for 10mins before doing each test. Two tracks of fear reacting tests have been taken for each subject. The result curves have been compared to remove noise in the recording during the test. Then a typical emotion curve responses to fear stimulus has been identified.

Figure 6-2 shows an original curve cutting from SCR test result. It indicates a testing subject's emotion state when they were shown a scary picture of a cobra. The red bar on the timeline shows the period of displaying the picture. Normally, the period of displaying the picture is 4 second.

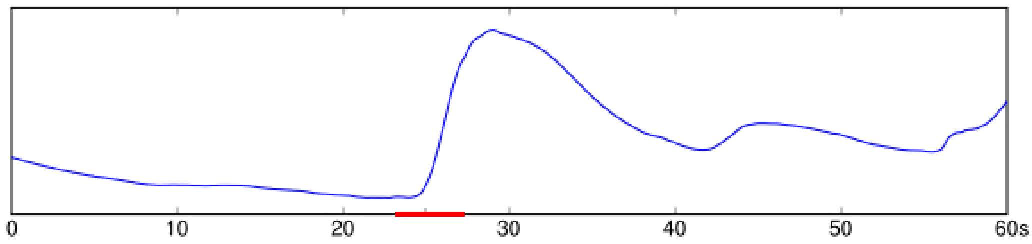


Figure 6-2 Example of SCR testing for fear reactions

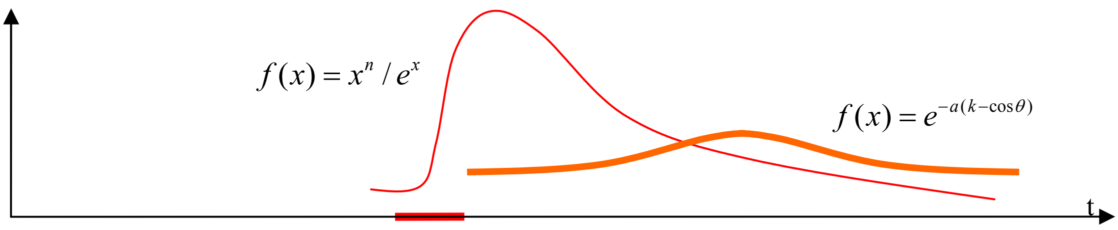


Figure 6-3 Illustration of simulating emotion equations

After identifying the fear reaction curve, a group of equations could be formed. Two typical emotion equations for fear have been introduced in **Figure 6-3**. It shows how single stimulus could affect a human's emotion level. In this simple testing case, the emotion curve is assumed only affected by the latest picture which had been shown to the subject. In other words, the subject is assumed not to remember previous pictures that have been displayed. This is also the simplest case in the emotion arousal process. Further discussions of how to form emotion equations are identified in the next section.

6.3 Emotion synthetic equations

For over a hundred years psychologists have believed that the general function relating to various quantitative aspects of stimuli and the affective reaction to them could be represented as an inverted U-Shape (Wundt 1874; Berlyne 1960), which can be used to explain the general experience of how one might be too happy to smile, or shocked to have an expression, etc. However, this is not the case for this hierarchical emotion model structure. There are at least two reasons for this:

Firstly, the emotion level does not always decrease after reaching certain thresholds (Berlyne 1960; Plutchik 1980; Ortony 1988). One can be too happy to smile, however the feeling of being happy still exists and remains at a quite high level. It might not be able to increase in intensity because of biological limitation, but that does not mean it will decrease reversely.

Secondly, emotions are not independent with each other (Plutchik 1960; Averill 1975; Ortony 1988). Some emotion could be the cause and consequences for other emotions. If the affective reactions decrease after the quantitative stimuli have reached to a certain point, it might affect the related emotions as well.

6.3.1 Equations of increasing emotion intensity

After analysing the results gathered by SCR method, it is realised that a typical curve for emotional reaction could be described as follow: at the beginning of such a curve, the intensity of emotion increases rapidly with the rise of the independent stimuli variable. Ultimately, some optimal level is reached, where the independent stimuli variable is held to give rise to a slower growth in the intensity of emotion.

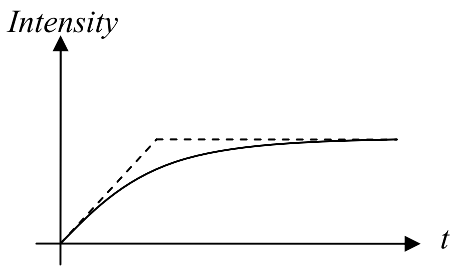


Figure 6-4 General relationship between intensity of stimuli and an emotion

Thus, up to a point, "increase in direct proportion," after which, "one can feel too much to feel more." The contributions of the majority stimuli variables to momentary basic-emotions are similar to this kind. Therefore general functions relating to various quantitative aspects of stimuli and the affective reaction to them is proposed as a curve which is very close in resemblance to the logarithmic function (**Figure 6-4**).

A formula for basic emotion calculation is derived based on Tang's emotion equations (Tang 2001) as mention in **Chapter 4**:

$$E = A \cdot log(ax + b) + c \qquad \text{(eq. 6-1)}$$

The emotion value is in [0, 1]. If the stimuli variable is below some threshold, there is no emotional experience at all (**Figure 6-5**). This also explains why some emotion experience does not appear linear but suddenly experienced from a relatively strong intensity. The threshold values for different emotions are affected by personality. Different people might have different thresholds as certain emotion is aroused (Ortony 2007).

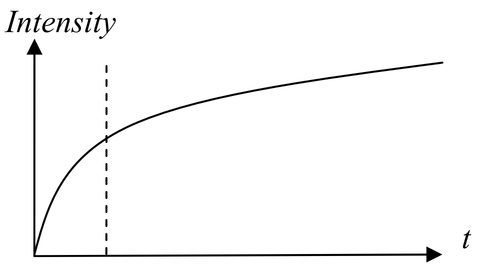


Figure 6-5 Emotion threshold

The consequent expression is modified as follows:

$$E = \begin{cases} a \cdot \log(a \cdot \Delta x + 1) + b & (x > x') \\ 0 & (x < x') \end{cases} \qquad \text{(eq. 6-2)}$$

$\triangle x$ means the value difference between the stimulus and its reference. Also known as $\triangle x = (x - x_r)/x_r$. x_r is the reference value of stimulus.

Based on the results gathered by SCR testing, the main outcome of how emotion changes along with visual stimuli can be described as in the following:

Lemma1: object-based emotions will not decrease when the object is in FOV. This explained why the emotion curves does not debilitate as the emotion stimulus decreased. As long as the object is still in one's FOV, the emotion will not decrease in intensity. On the contrary, event-based emotions can decrease when the stimulus decreased. This is because the affecting variables related to the events are different to object-based emotions.

Lemma2: When out of FOV, the object-based emotions debilitate with different decreasing strategies;

During the SCR tests, it is also realised that different stimuli variables might have various capabilities to affect the intensities of corresponding emotions (as shown in **Figure 6-6**). This variety means the relation between the stimuli variables to certain emotion can be independent. The weights of different stimuli to emotion are various.

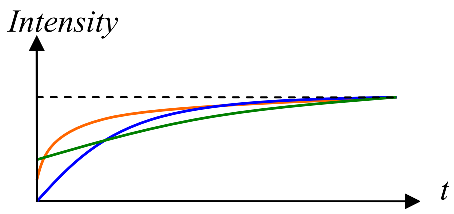


Figure 6-6 Comparison between different stimuli to emotion

The general relationship between stimuli and emotion could be represented as in the following equation:

$$E = \begin{cases} \sum_{i=1}^{n} \alpha_i e_i & (e > e') \\ 0 & (e < e') \end{cases}$$

(eq. 6-3)

a_i is the weight index of the corresponding stimulus, and e_i is eliciting emotion value of corresponding stimulus. Those factors will mathematically decide the shape of an emotion curve.

6.3.2 Equations of decreasing emotion intensity

Based on the results gathered by SCR method, the equations for decreasing emotion curves could be very different. Emotion will fade out when all stimuli disappeared. However, very rare papers on the emotion calculation modelling research could be found in the literature (Mera 2003).

First, it is interesting to investigate how the emotion decreases when only one stimulus is reduced while keeping other factors unchanged. It is assumed that the general decreasing equation could be represented as in the following:

$$E_i = f(x_i) \qquad \text{(eq. 6-4)}$$

Where x_i is the value of a stimulus that can affect the intensity of the emotion E_i, $\vartriangle x_i = x_n - x_{n-1}$, $\vartriangle x_i < 0$ means the stimulus is decreasing.

Ideally, the intensity of emotion can be reduced linearly after the stimulus has decreased. For some personality, the decreasing of emotion intensity is likely to be a straight line (**Figure 6-7**). Typical synthetic equation is $E(x_i) = -k \bullet t$, when $\vartriangle x_i < 0$.

Where $\vartriangle x_i < 0$, $f'(x_i) = c < 0$.

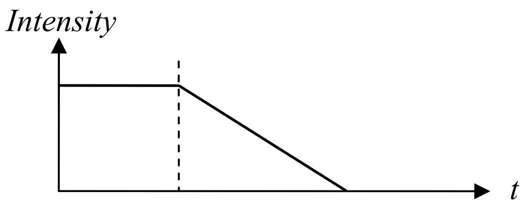


Figure 6-7 A decreasing curve of emotion intensity

However, most SCR tests have indicated the intensity of an emotion decreases nonlinearly. For example, after suddenly encountering with a feral dog, female might need more time to calm down from fear than male. This may due to the likelihood of the dog, also known as the threat of the dog still exists. This can also be explained as the lady still recalls the image of the feral dog continuously. Her memory keeps on refreshing the impact of the dangerous dog. So the decrease of the emotion fear could be slower than others in this case and even unstable (**Figure 6-8**). Typical synthetic equation is $E(t) = -k \bullet t^2 - m \bullet t - n$, when $\triangle x_i < 0$, $f'(x_i) < 0$, $f''(x_i) > 0$.

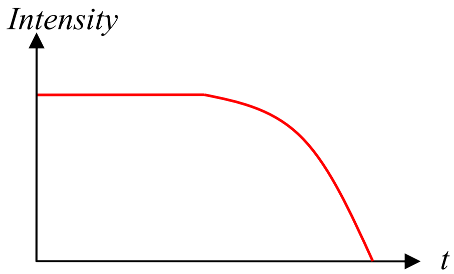


Figure 6-8 A decreasing curve of emotion intensity with accelerated feature

On the contrary, if the same situation is applied to a dog lover. He might be surprised and shocked for a little while and calm down rapidly. Because he thought he could easily handle the dog, or he could have realised the dog was not that big. One way or another, he can ignore the threat of dog and forget the negative impact (**Figure 6-9**). Typical synthetic equation is $E(t) = E_0 \bullet e^{d_t \bullet T}$, when $\triangle x_i < 0$, $f'(x_i) < 0$, $f''(x_i) < 0$. d_t is the declining index for the duration of emotion *T*.

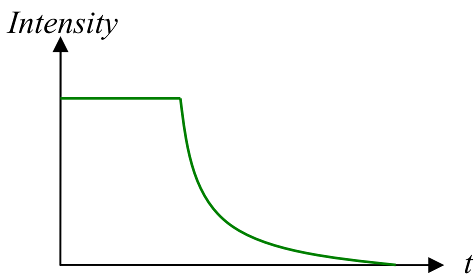


Figure 6-9 A decreasing curve of emotion intensity with decelerated feature

There are some even more complex situations, in which SCR results are capricious. The intensity of emotion fluctuates (**Figure 6-10**). This can be caused by other cognitive processes or memory. It is elicited from more fundamental level, such as physical handicap or neuropathy. This topic is not in the scope of this thesis. However, it is interesting to know the research as it may be important to build realistic emotion generation models.

$$\triangle x_i < 0 \ \ or > 0$$

$$f'(x_i) < 0 \ \ or > 0$$

$$f''(x_i) > 0 \ \ or < 0$$

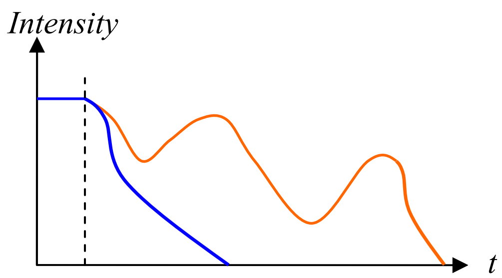


Figure 6-10 A decreasing curve of emotion intensity with unstable feature

Now, all the possible decreasing curves of emotion have been introduced (**Figure 6-11**). The emotion curves are different according to gender, age, personal experience, etc. however, overall, the curve mainly depends on one's personality.

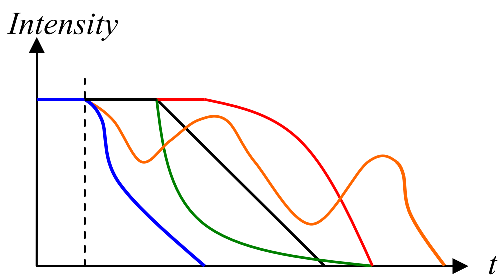


Figure 6-11 All possible decreasing curves of emotion intensity

6.3.3 Emotion acuity

One of the main purposes of the current emotion calculation model is to predict virtual human's emotion through synthetic vision. The strongest possible intensity of certain emotion which could arise from visible objects is concerned. As inspired from visible acuity, the emotion acuity is proposed as a term to describe the upper limit of emotions.

By definition, emotion acuity is the capacity to discriminate the difference in intensity of an emotion-stimulus variable. In another words, emotion acuity is the sensibility of emotion, the capability of eliciting an emotion. Emotion acuity decides the maximum possible intensity of an emotion aroused from single object. Emotion acuity could depend on many factors, including: gender, experiences, and age, but most relevant to overall reactive behaviour is its inverse dependence on the visual acuity and memory definition.

As mentioned earlier, proximity is a global variable that affects the intensity of emotion, and one's vision is an important sense of perception to raise emotions. The details one could get through vision will affect the value of the stimuli. The stimuli would affect the intensities of emotions. Essentially, this is because majority of stimuli to emotion are incepted on the bases of human vision, especially on those object-based emotions.

In this project, emotion acuity is dominated by the visual acuity of objects in one's field of vision and short-term memory. Visual acuity, the clearness of vision depends primarily on the sharpness of the focus, and on age, luminance, distance as well. But mostly, it depends on angular distance from the eye fovea. This is because the density of cone photoreceptors in the retina decreases with distance from the fovea. Therefore, as a visual target moves further from the fovea, visual acuity (the clarity of the viewed object) drops until it reaches zero when the target is outside one's field of vision.

The memory definition for short-term memory (or flash memory) depends on how long the target is out of one's field of vision. It is assumed that the fine details of the viewed object will be fading out after it is outside one's field of peripheral vision in one's short-term memory. As I believe, time always blurs the short-term memory. Therefore, in a short period of time, the memory definition drops until it reaches zero after the target moved out of the field of vision. The long-term memory is not discussed here, simply because it is more complex to discuss the effect of long-term memory to emotion than the affection of short-term memory. The key point that distinguishes long-term memory from short-term memory is the recall of memory. Long-term memory recalls and refreshes corresponding anamnesis (a recalling to memory, recollection); short-term memory does not recall any anamnesis. A long-term memory is sometimes evolved to an experience or even a conscious reaction to certain stimulus. It is believed as an interesting topic in the future work.

Consequently, one generally strives to minimise the angular distance between the line of site and a visible target in FOV. This aspect of emotion acuity, which drives one's view to align with a target in order to increase emotion clarity, is called relative emotion acuity. In order to model relative emotion acuity, the angular distance is represented with a site angle. A site angle is the angle between the vector from the eye to the target (eye-to-target vector), and the vision vector, which emanates from the eye perpendicular to the face. Relative to the site angle, visual acuity has a maximum value of one when the angle is approximately zero, and it decreases exponentially as the site angle increases.

Kim et al (Abdel-Malek 2006) derived the following formula for relative visual acuity by interpolating published data from W. Blanke and C. Bajaj (Blank 2002).

$$emotion\ acuity = e^{-7(\theta)} \qquad \text{(eq. 6-5)}$$

When the target is in the FOV, the emotion acuity curve is like this:

$$emotion\ acuity_1 = e^{-a(1-cos\theta)} \qquad \text{(eq. 6-6)}$$

θ is the site angle. It is the angle between the vision vector and the eye-on-target vector. In **Figure 6-12**, two possible emotion acuity curves are marked with blue and red colours. The shape of the curves can be modified by changing value of the variable a in the equation.

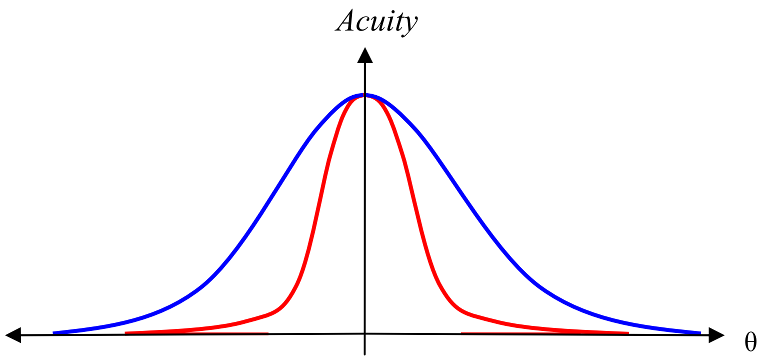


Figure 6-12 Two possible emotion acuity curves

The above equation is used to simulate the emotion acuity in this emotion generation model. Because of the arc cosine term, the gradient is undefined when the dot product is one (when θ = 0), which causes the acuity curve to be discontinuous. Such discontinuities may not be suitable for representing emotion acuity, as to the cognitive process of emotion is not linearly corresponding to visual stimuli. To avoid these discontinuities, the following formula for relative emotion acuity is derived:

$$emotion\ \ acuity = \begin{cases} f(age)\cdot f(luminance)\cdot f(distance)\cdot e^{\frac{-a\cdot(1-\cos\theta)}{size}} & (inside\ \ FOV) \\ \log a\cdot t_1(t-t_0) & (outside\ \ FOV) \end{cases}$$

(eq. 6-7)

In which, a>1. $f(age)$ and $f(luminance)$ are functions for age and light. In this thesis, $f(age) \bullet f(luminance) = 1$.

Relationship between visual acuity and observation distance is normally called Distance Vision Acuity in ophthalmology (Heron 1995; Sakamoto 2008). Some related work in ophthalmic has been reviewed and the relationship is represented in a mathematic equation. In this chapter, the distance vision acuity equation is derived from the research of Sakamoto *et al* and some other similar findings (**Figure 6-13**).

$f(distance) = x^n / e^x$, normally n=2;

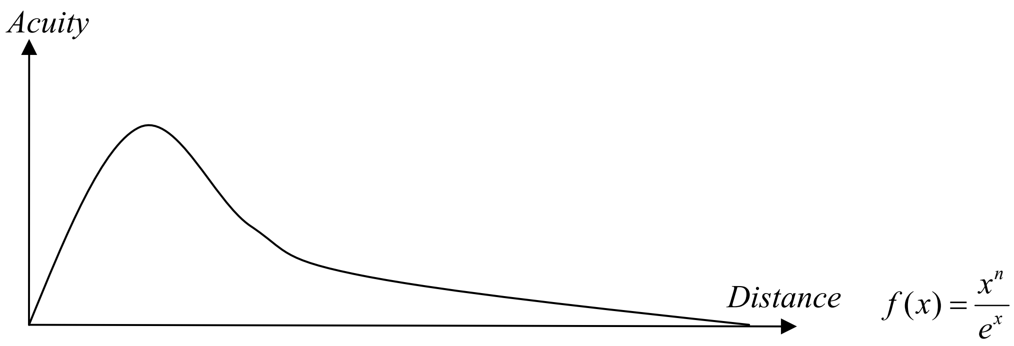


Figure 6-13 Relationship between distance and vision acuity

So far, equations that are appropriate to be applied in emotion synthetic systems have been introduced. From the next section, the details of emotion generation processing in the virtual human system will be investigated.

6.4 Hierarchical emotion calculation model

6.4.1 Dimension of emotions

Classified by the number of affecting local variables, emotions vary with different dimensions.

One dimensional emotion: Joy

Joy is a kind of well-being emotion, which is considered as one of the most basic emotions. The intensity of joy and distress are affected by the simplest control factor desirability among all the emotions. I proposed a structure for well-being emotion in **Figure 6-14**, which can be treated as a programming flow chart showing the emotion joy. The intensity of joy is set as a value between 0 and 1.

The intensity of joy is only affected by one local variable, the degree of desirability, so it is called one dimension emotion. Inside the emotion block, there are also some other factors that need to be considered which affect the intensity of joy. First factor is the time (t). It is believed that, as time goes on, the intensity of majority emotions will decrease (i. e., joy). The other factors are global variables, which could affect all emotions, and personality (p), which is a group of factor-weight settings to different emotions, and also the threshold of the emotion.

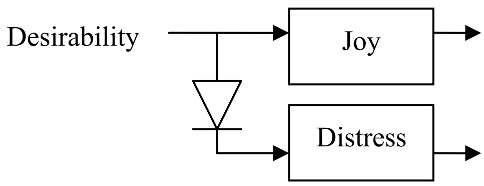


Figure 6-14 Programming flow chart of "Joy"

Multi-dimensional emotion:

Majority of emotions are affected by more than one input factors. It is more complex to define and calculate the values of them than one-dimensional emotions. Hope is prospect-based and a kind of emotion reaction to events. The intensity of hope is affected by two local variables as shown in **Figure 6-15**. There are two factors affecting the intensity of hope, so hope is called a two-dimensional emotion.

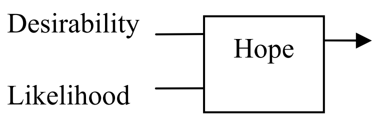


Figure 6-15 Programming flow chart of "Hope"

Table 6-1 Summary of dimensions and local affect variables on 22 basic emotions

Dimension	Emotions	Local variables
1	Joy_1, $Distress_2$	$Desirability(3)_{1,2}$
2	$Liking_3$, $Disliking_4$, $Hope_5$, $Fear_6$, $Admiration_7$, $Reproach_8$	$Familiarity_{3,4}$, $Appealingness_{3,4}$, $Likelihood_{5,6}$, $Desirability(3)_{5,6}$, $Praiseworthiness_{7,8}$, $Expectation\text{-}deviation_{7,8}$
3	$Pride_9$, $Shame_{10}$, $Gratitude_{11}$, $Anger_{12}$	Strength of cognitive $unit_{9,10}$, $Expectation\text{-}deviation_{9,10,11,12}$, $Praiseworthiness_{9,10,11,12}$, $Desirability(3)_{11,12}$
4	$Gratification_{13}$, $Remorse_{14}$, $Satisfaction_{15}$, $Disappointment_{16}$, $Fear\text{-}confirmed_{17}$, $Relief_{18}$, $Happy\text{-}for_{19}$, $Sorry\text{-}for_{20}$, $Resentment_{21}$, $Gloating_{22}$	$Likelihood_{15,16,17,18}$, $Desirability(3)_{13,14,15,16,17,18}$, $Effort_{15,16,17,18}$, $Realization_{15,16,17,18}$, Strength of cognitive $unit_{13,14}$, $Expectation\text{-}deviation_{13,14}$, $Praiseworthiness_{13,14}$, $Desirability(1)_{19}$, $Desirability(2)_{20}$, $Presupposition_{19,20,21,22}$, $Likesome_{19,20,21,22}$, $Deserving_{19,20,21,22}$

Table 6-1 is the summary of dimensions and input factors of the OCC model's 22 basic emotions. Where Desirability (1) means the degree of desire about desirable event for the others; Desirability (2) means the desire about undesirable event for the others; Desirability (3) means the desire about event for oneself. Each emotion in **Table 6-1** has a unique subscript to designate that emotion, and each input factor has a few subscripts to represent that this input is for those emotions with the same

subscript. For example, input factor $\text{Familarity}_{3,4}$ affects emotions Liking3 and Disliking_4.

Beside the multi-dimensional emotion mentioned above, hierarchical multi-dimensional emotion is contributed by variables that affecting emotions and other emotions from a lower hierarchical level. For example, in **Figure 6-16**, "*Satisfaction*" is affected by three input factors: *Realisation*, *Effort* and the "*Hope*". The emotion "*Hope*" is actually affected by other two input factors: *Likelihood* and *Desirable III*. Therefore, "satisfaction" is called a four-dimensional emotion, which is affected directly by two variables (*Realisation*, *Effort*) and is also affected indirectly by other two variables (*Likelihood*, *Desirable III*).

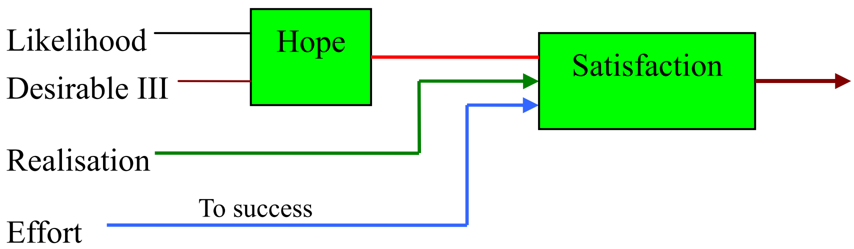


Figure 6-16 Programming Flow Chart of "Satisfaction", a hierarchical multi-dimensional emotion.

6.4.2 Emotion function

6.4.2.1 Intensity

As mentioned above, the majority of emotions are affected by multi-factors. The degree of each factor is defined by a value between 0 and 1. The presentation of a four-dimensional emotion in its emotional space is $E_1(a_1, b_1, c_1, d_1)$. The intensity of E_1 can be represented as follows:

$$Intensity(E_1) = Magnitude(E_1) = \sqrt{\alpha a_1^2 + \beta b_1^2 + \eta c_1^2 + \tau d_1^2} - threshold(E_1) = rE_1$$

(eq. 6-8)

The notations α, β, η, λ are the coefficients (weights) for factors a_1, b_1, c_1, d_1,

For an n-dimensional emotion E_n

$$E_n = \sqrt{\alpha_1 d_1^2 + \cdots + \alpha_i d_i^2 + \cdots + \alpha_j d_j^2 + \cdots + \alpha d_n^2} \leq 1 \qquad \text{(eq. 6-9)}$$

Where α_i is the coefficient (weight) for input factor d_i.

$$MAX(rE_n) = 1 \qquad \text{(eq. 6-10)}$$

The structures of different emotions are considered individually here. For each virtual human, the value of 'likelihood of the event' and 'desirability of the event' will determine the intensity of the emotion 'fear' through the emotion function for fear with different coefficients.

6.4.2.2 Threshold

There are threshold for emotions and reactive behaviour. One might not be able to experience emotions if the stimuli is below some threshold, and one might not be able to express one's emotion if the emotion is over a limit (shock) or controlled by ration. For example, the intensity of joy could be expressed as follows:

$$Intensity\ of\ Joy = Potential\ of\ Joy - Threshold\ of\ Joy \qquad \text{(eq. 6-11)}$$

Emotions on a different hierarchical level are not always changing within unified proportion and do not have the same threshold.

6.4.3 Hierarchical emotion structure

A hierarchical emotion eliciting structure is proposed in order to find a possible way to programme the emotion process, based on understanding of OCC's emotion model.

Figure 6-17 shows part of this hierarchical emotion generation structure. (A detailed hierarchical emotion structure for emotion generation is presented in **Appendix D**)

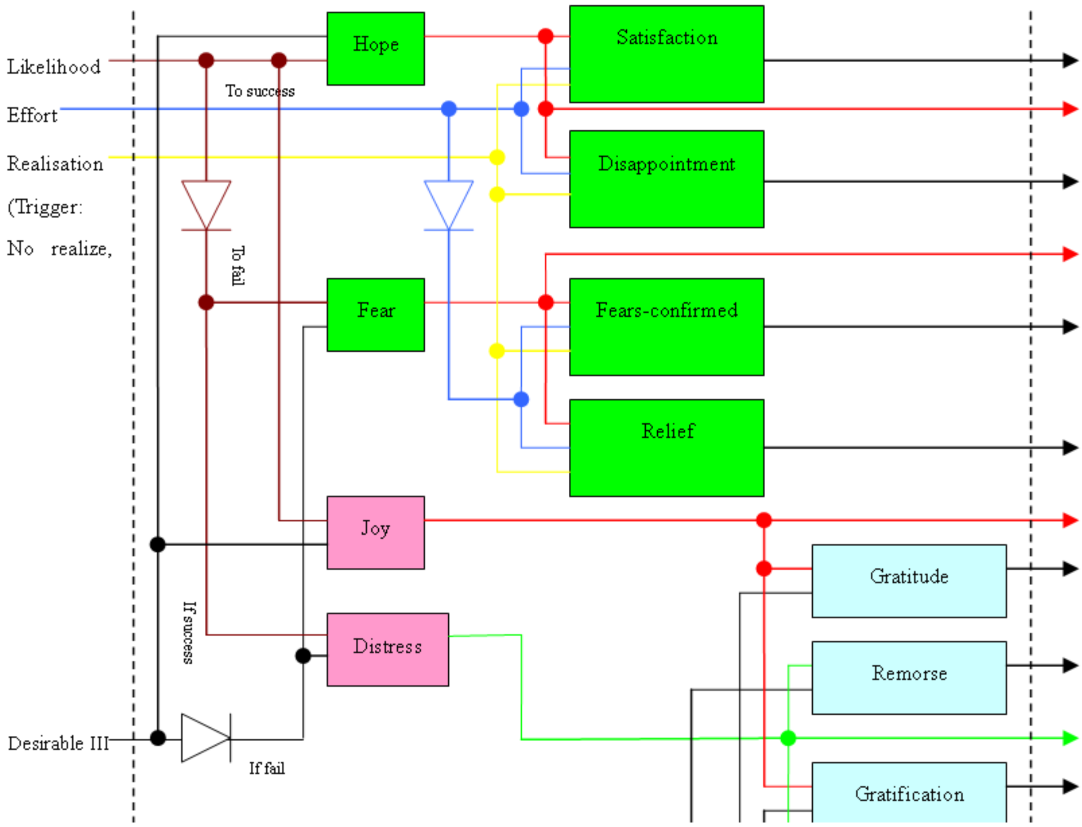


Figure 6-17 A glance of hierarchical structure for emotion generation

The hierarchical structure at least explains three issues:

1. More than one emotion can coexist at the same time;

2. Factors affecting different emotions in different weights;

3. There are different sub-groups in hierarchical emotion structure.

For example: the emotion fear is affected by two variables in this hierarchical emotion structure: Likelihood and Desirable 3. Here likelihood means the subjective likelihood of the prospective event occurring. Desirable III means the degree to which the event is desirable.

6.5 Model implement and case study

In this section, the simulation of emotion is elaborated from the simplest type: object-based emotion. The evaluation of object-based emotion is based on a person's attitude on certain objects (Ortony 1988).

A testing environment was created in Virtools™ for the virtual human model with emotion capability with the use of the emotion equation (1). The interface shows as **Figure 6-18**. The coronary shape is the field of vision (FOV) for the testing synthetic vision model. The body of virtual human has been deleted in this interface for a better view of the scenario. The testing system could instantly give feedback regarding the distance from the virtual human subject to objects in FOV, the site angle, visibility of the object, etc. on the screen to testify the performance of the emotion acuity function for the virtual human.

$$E = f(lumminance) \cdot f(age) \cdot \frac{x^2}{e^x} \cdot e^{\frac{-a(1-\cos\theta)}{size}}$$
(eq. 6-12)

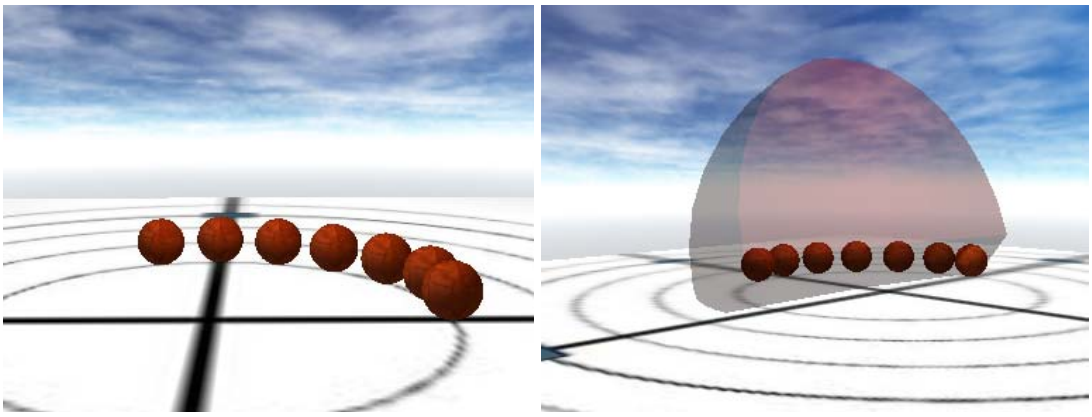


Figure 6-18 Perspective views of the testing environment and field of vision

6.5.1 Case 1: emotion acuity based on site angle

If an object is placed at the central front of one's FOV rather than on the side of one's FOV, it could elicit a stronger emotion consequence based on the emotion acuity theory. Assuming the distance to object is fixed, the process is programmed in virtools™ as follows.

In this case, a scenario is designed with a ball moving around in virtual human's FOV volume. The distance from observer to the ball, the site angle, the emotion acuity index and the intensity of emotion like is recorded. The position of the rolling ball is recorded each second during the test.

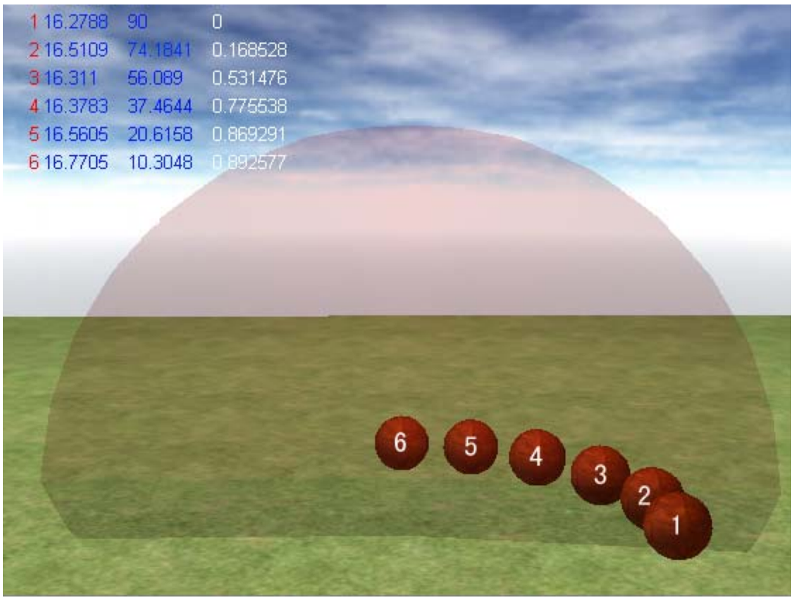


Figure 6-19 emotion acuity value based on distance and site angle

In the **Figure 6-19**, the distance between the object and the observer is displayed in the first column on the top left corner of screen. The site angle is shown in the second column. The third column displays the emotion acuity index for emotion calculation. As suspected, emotion acuity index decreases exponentially as the site angle increases.

In this scenario, the distance between virtual human and the rolling ball is approximately fixed (Standard deviation of distance is $\sigma = 0.1724$). The emotion acuity index increases as the ball moves towards the centre of the vision. The possible intensity of related emotion also increases with the change of the emotion acuity. Where, in this test, a=4, $f(age) \bullet f(luminance) \bullet x^2 / e^x = 1$, the size index of object is 1, then the formula of emotion acuity will be derived as follow: $E' = e^{-5\bullet(1-cos\theta)}$

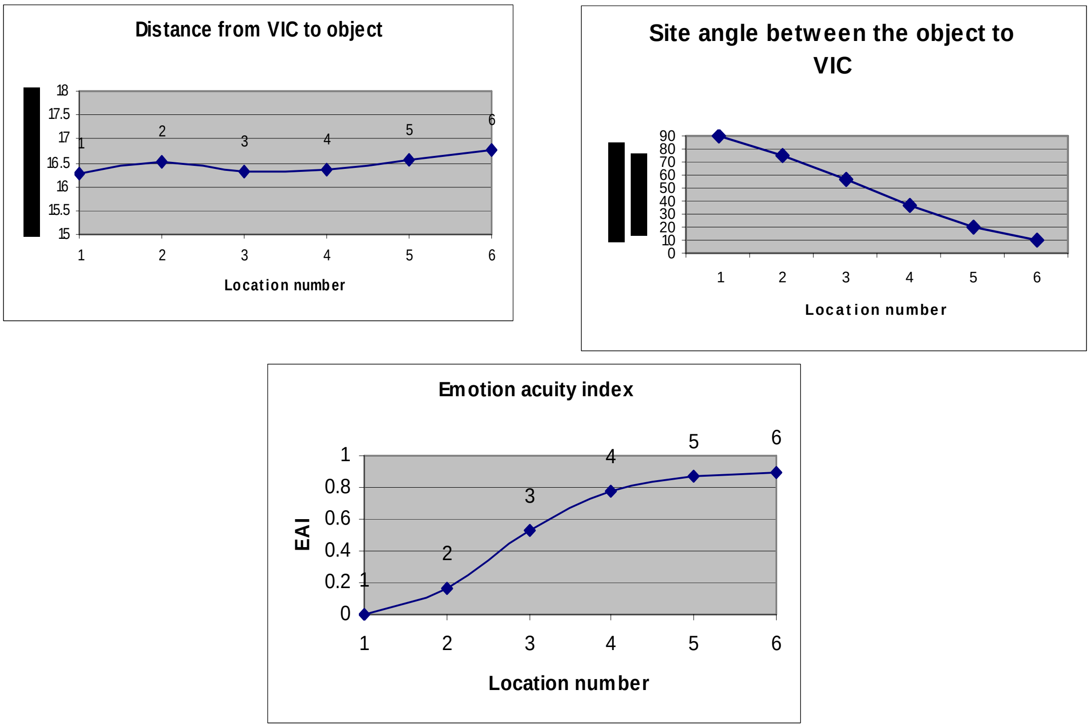


Figure 6-20. Distance, site angle, emotion acuity index

6.5.2 Case 2: The emotion curve of object-based emotion

In this case, a scenario is designed with a fire source suddenly appearing in centre of the FOV volume (**Figure 6-21**). The "fear" emotion in this emotion generation model is chosen to be tested in this scenario. The distance from the observer to the ball, the site angle, the emotion acuity index and the intensity of emotion fear is record. Where the formula of emotion acuity in this scenario is derived as: $E' = e^{-5\bullet(1-cos\theta)}$

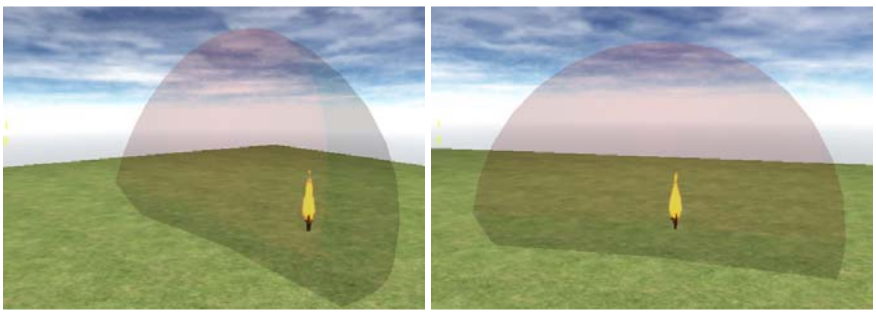


Figure 6-21 A scenario to test the "fear" emotion based on a firing object in FOV

The calculated “fear” emotion curve is displayed as follows. The right hand side shows the calculated result (dash red line) in comparison with SCR result (blue line):

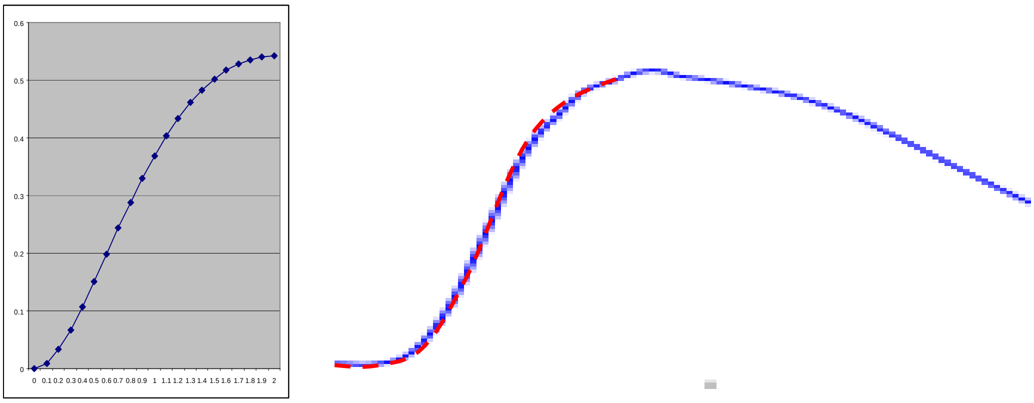


Figure 6-22 Comparison, SCR result and emotion calculation result (dash line)

One needs some time to react to the environment. Based on SCR testing, this reaction time Δt might be different from one another. Adjusting this reaction time is realised through adjusting the emotion generation equation. The adjusting of the reaction time would provide different personalities for virtual humans, such as, sluggish, dull, and stolid to adroit, smart, and dexterity.

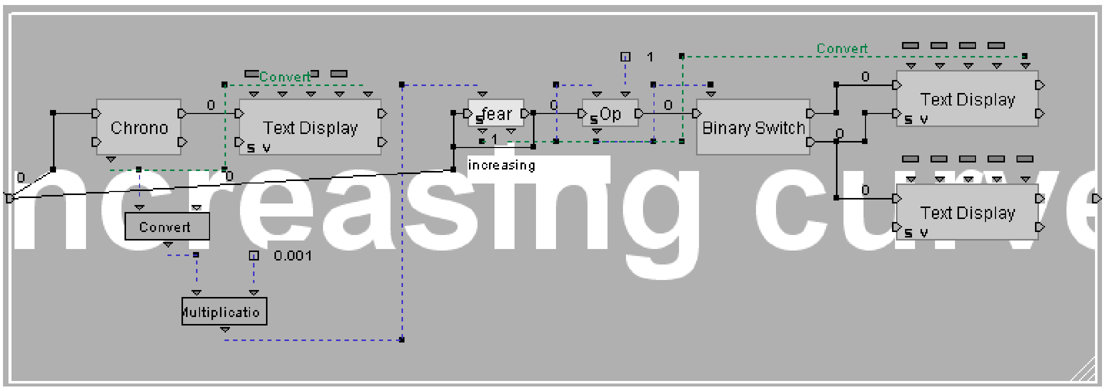


Figure 6-23 Programming realisation of the emotion curve in Virtools™

Same to the increasing curve, the decreasing curve of object-based emotion can also been simulated by the same method.

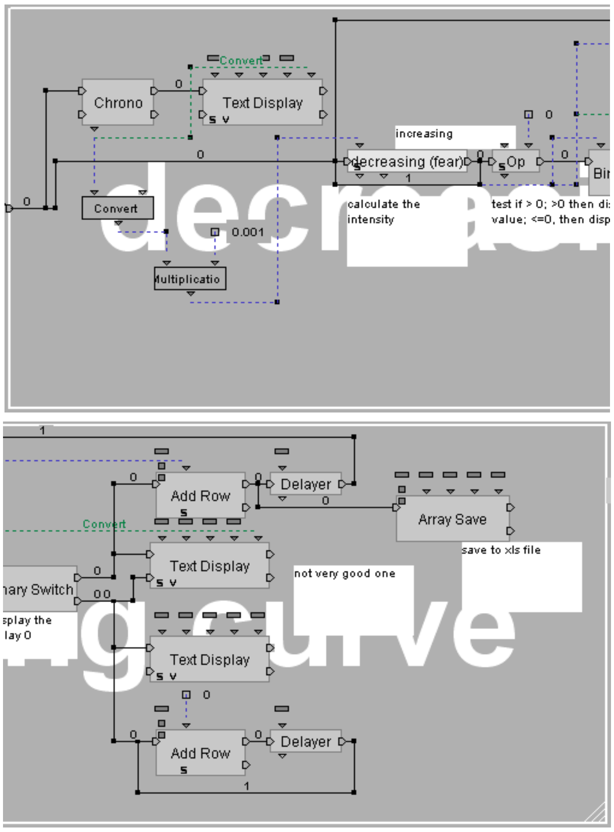


Figure 6-24 programming of the emotion decreasing function

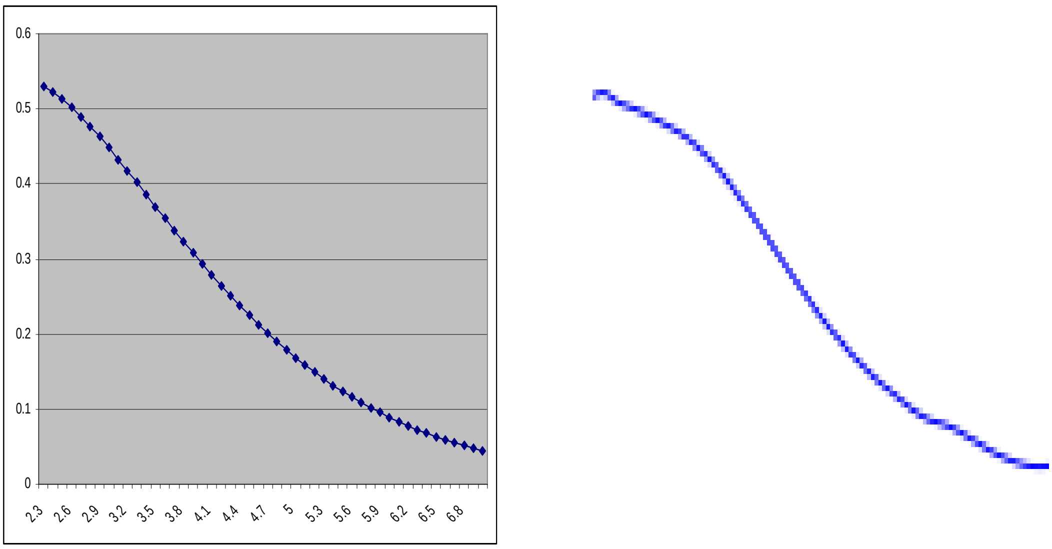


Figure 6-25 The simulated decreasing curve of "fear" compared with SCR result

6.6 Results and Discussion

A series of indoor environments have been designed for the testing virtual human modelling. Here a virtual environment based in lounge is introduced to simulate virtual human's emotion generation process (**Figure 6-26, Figure 6-27**).

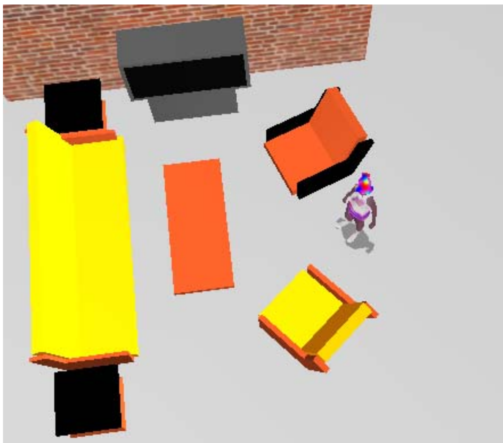


Figure 6-26 Top view of an indoor scenario

	0 : object list
0	LoungCha01
1	LoungChair
2	CofeeTable
3	HDTV
4	Couch
5	EndTable01
6	EndTable02
7	

	0 : event list
0	fire
1	blast
2	fire 2
3	fire 3

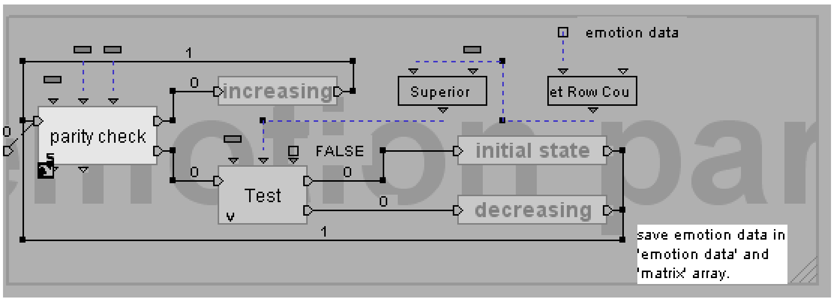
Figure 6-27 Object list and event list for the scenario

There is an evaluating matrix for all entities in this virtual environment (**Figure 6-28**). Evaluation value for event in this matrix could be dynamic with the time.

	0 : object list	1 : desirable III	2 : likelihood	3 : effort	4 : realization	5 : cognitive stength	6 : expectation deviation	7 : praiseworthiness
0	LoungCha01	0.5000	1.0000	0.0000	1.0000	0.0000	0.0000	0.0000
1	LoungChair	0.1000	1.0000	0.2000	1.0000	0.5000	0.0000	0.0000
2	CofeeTable	0.2000	1.0000	0.0000	1.0000	0.0000	0.0000	0.0000
3	HDTV	0.8000	1.0000	0.0000	1.0000	0.0000	0.0000	0.0000
4	Couch	0.7000	1.0000	0.0000	1.0000	0.0000	0.0000	0.0000
5	EndTable01	0.0000	1.0000	0.0000	1.0000	0.0000	0.0000	0.0000
6	EndTable02	0.0000	1.0000	0.0000	1.0000	0.0000	0.0000	0.0000
7		0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000

Figure 6-28 Example of evaluating matrix for objects in scenario

Emotion data for each entity is stored in real-time (per-second record in the **Figure 6-29**). Typical emotion data for an object is presented as in the following figures. This emotion records when virtual humans detect a fire in the living lounge. There is a slight delay on the changes of these emotion intensities, such as 'joy' and 'distress'. A longer delay is shown for higher level emotions changes, such as 'satisfaction'. This difference is mainly caused by the speed of different parity check loops as shown in the following figure.



1 : joy	2 : distress	3 : hope	4 : fear	5 : satisfaction
0.0000	0.0000	0.0000	0.0000	0.0000
0.0000	0.0000	0.0000	0.0000	0.0000
0.2788	0.9590	0.3711	0.7745	0.8002
0.2788	0.9590	0.3711	0.7745	0.8002
0.2788	0.9590	0.3711	0.7745	0.8002
0.2688	0.9490	0.3611	0.7645	0.7902
0.2588	0.9390	0.3511	0.7545	0.7802
0.2488	0.9290	0.3411	0.7445	0.7702
0.2388	0.9190	0.3311	0.7345	0.7602
0.2288	0.9090	0.3211	0.7245	0.7502
0.2188	0.8990	0.3111	0.7145	0.7402

Fig 6-29 possible emotion data for an object

The graphic scripts for emotion calculation in Virtools™ are presented as follows:

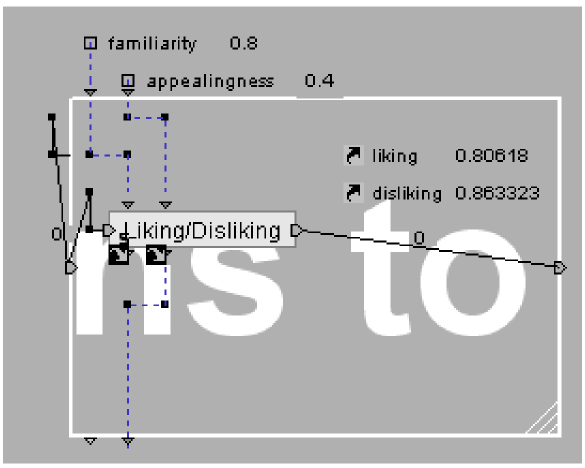


Figure 6-30 Emotions to objects

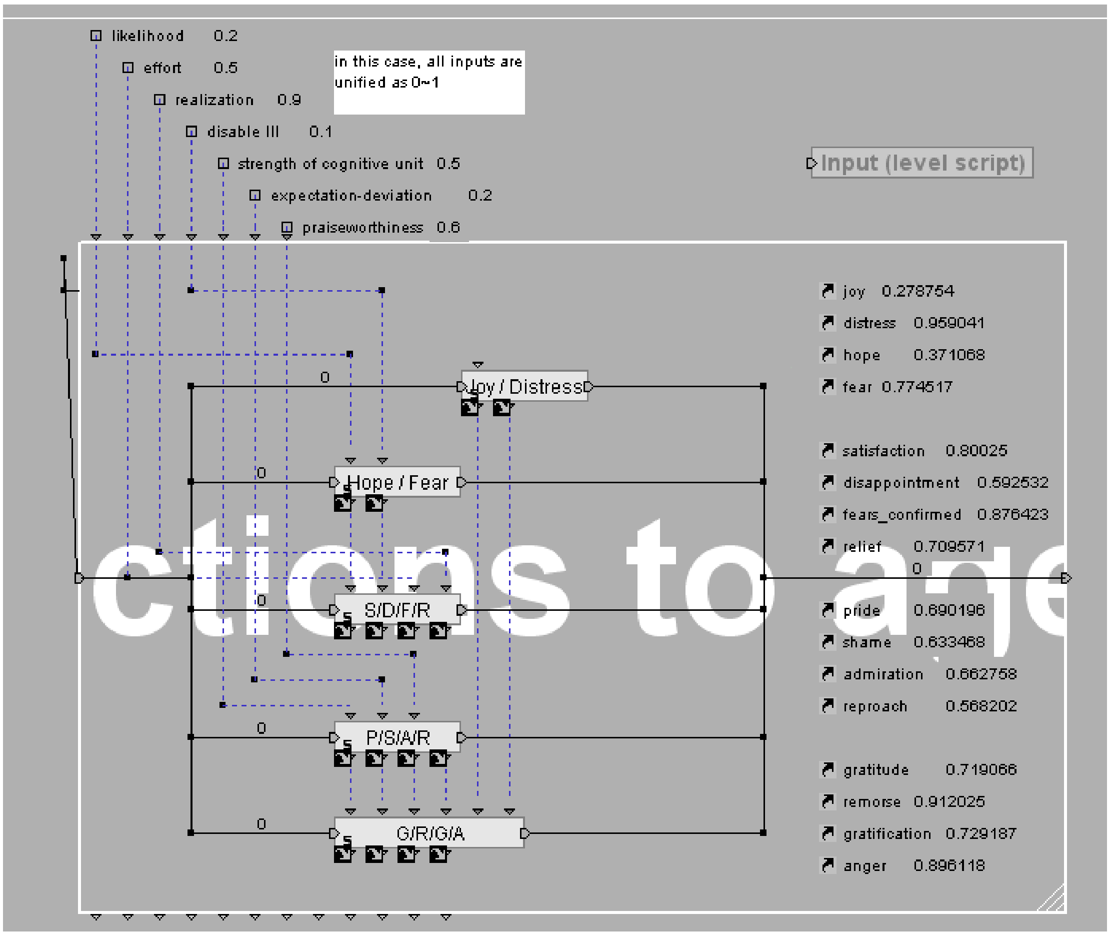


Figure 6-31 Emotions to agents

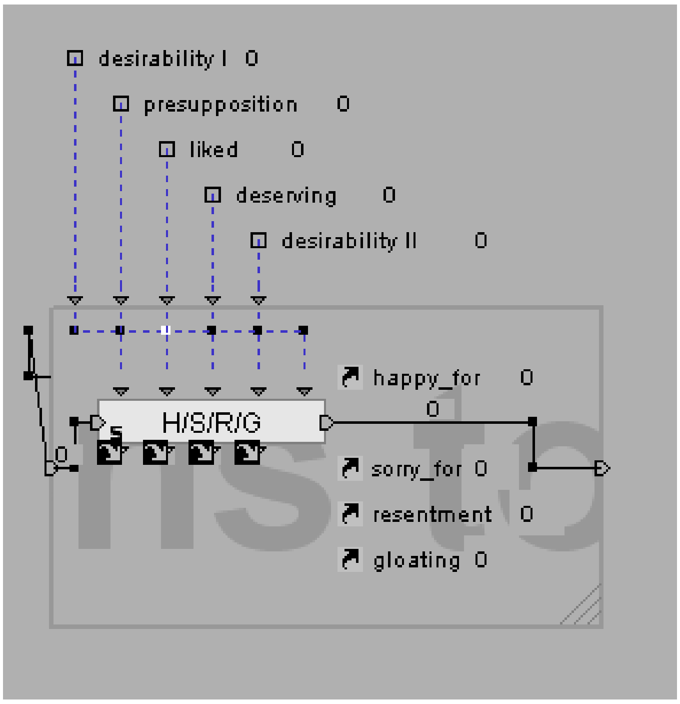


Figure 6-32 Emotions to events

6.7 Conclusions

This chapter presents the emotion measurement and simulation approaches of the virtual human emotion generation. The current interface implemented in Virtools™ could generate emotions for virtual humans based on its synthetic vision. The emotion states are recorded in real-time for the emotion affected decision making process.

The main advantages of this emotion calculation approach in computer simulation aspects are: (1) an intuitive hierarchical emotion generation structure, which indicates how emotions at different levels can be generated **(Section 5.4**); (2) a fast and easy method for realising different personalities. This approach provides a possible way to quantitatively describe personality as weight settings among variables which affect emotions. The different weight settings among inputs could affect the intensity of emotions directly.

The emotion calculation approach here is inspired from psychophysiologcal measures. This vision based emotion generation approach provides an alternative and more accessible means (normally, without psychology background) to create the simple and more realistic emotion affected decision making virtual agents. Moreover, this system can be utilised as a fast prototyping machine, where virtual characters can interact with human emotions. The methodology and framework can be implemented in commercial animation package, such as 3DS Max, Maya, to demonstrate powerful emotion generation functions.

This system can also be extended to generate a full range of emotions by people of different genders. The detection and simulation of the effect of long-term memory on emotions is another interesting point. Meanwhile, future work can further enhance system functionalities, through enabling the virtual human's facial expressions and an emotional phonic dialogue. Some results in this chapter have been also published in Zhao's work (Zhao 2006; Zhao 2007).

Chapter 7
Decision-Making and Behaviour Modelling

7.1 Introductions

A realistic virtual human model does not only concern with vivid representation, smart perception sensors, but is also significant for the extended humans' reaction behaviours. In **Chapter 5**, a novel collision based synthetic vision system has been studied to help virtual characters understand their surrounding environment. In **Chapter 6**, an emotion model has been studied to create emotion for a virtual character and how to update emotion state based on virtual character's location and changes in immersed virtual environment. From this chapter, how emotion states would affect virtual characters is investigated. This chapter focuses on the application of the emotion model on the virtual humans through decision-making. The implementation of the ways in which the virtual humans make their own decisions when interacting with virtual environments is also included. How those previous emotion states affect the virtual humans' decision making are also tested.

7.2 heuristics decision making

In Gerd's simple heuristic theory, there are four major classes of heuristics: ignorance-based decision making, one reason decision making, elimination heuristic, and satisfacing (Gigerenzer 1999). These four heuristics will be introduced one by one in this section. How they could be applied in the virtual humans' decision making modelling will also be investigated.

7.2.1 Ignorance-based decision making

There are situations of limited knowledge in which a person depends on only one piece of information, and could make faster and easier decisions with more accurate inferences than a considerable amount of knowledge can achieve. The decision is consequently based on only one piece of information and recognition. A lack of recognition is essential for enabling a decision, which is called ignorance-based Decision Making.

The simplest example in this class is the recognition heuristic: if one of two objects is recognised and the other is not, then it is inferred that the recognised object has the higher evaluation value in decision making. It could lead to a surprising prediction: a person who knows less than another can make systematically more accurate inferences. This is called “less-is-more” effect (Gigerenzer 1999). The recognition heuristic is adaptive because there is little else one can do under situations with limited knowledge. It can only be applied when one of two options is not recognised, that is, under partial ignorance.

The ignorance-based heuristics search recognisable objects in the memory stack when the objects come into the memory stack. Once the first recognised object is found, then it stops searching and considers this object with a higher value in reaction strategy. If no object has been found before a decision has to be made, it randomly guesses one object from the memory-stack and considers it with a higher value in reaction strategy. For example, one attends a ball. One chooses to talk with the first recognised friend and stop looking for others.

7.2.2 One-reason decision making

When there is more information available, recognition heuristic is not suitable anymore. In most cases, more than one object could be recognised as candidates for decision making. One-reason decision making is using only a single piece of information, cue, to make a decision. The cue search is stopped as soon as the first cue is found, which allows a decision to be made.

There are 3 types of one-reason decision making heuristics based on Gigerenzer’s work. The first one is called "minimalist" strategy, the second one is called "take the best" strategy, and the third one is called "take the last". These heuristics are distinguished by their different cue searching strategies. Those three types of heuristics could lead to different personalised reactions when making decisions.

Minimalist heuristic: randomly searches a cue for decision making based on the options being considered.

1. Use recognise heuristic: only one object is recognised, predict the object has a higher value on decision making. If the object is not recognised, then guess and check randomly. If more than one is recognised, go step 2;

2. Random search: draw a cue (potentiality) randomly. And check the cue value of the two objects;

3. If one object cue value is 1, the other is 0 or unknown. Then goto step 4; otherwise go back to step 2, find another cue, if no other cue is available then guess;

4. Decision rule: predict the object with the cue value as 1 has a higher value on decision making.

For example, stop search cue, once a cue which could give only one object with a positive cue value has been found, the search will be stopped. A positive cue for minimalist heuristic can be set as "most entrance strategy" (the virtual human will chose the path with most doors), most closed entrance, the entrance with bigger size,…

The programming code for Minimalist Heuristic can be described as general in the following format:

Step 1

If Recognition(door) = True && Recognition(the rest objects) = False then

Save door in priority stack // draw one's attention

```
    Go recognition heuristic
  elseif Recognition(all objects) = False then
    object 1 = Random Search(visible stack)
    go Step 4
    // pick one object and give it a higher cue value for decision making
  elseif Recognition(door) = True && Recognition(window) = True then
 Go Step2
  Endif
Step 2
Random Search(cue)
// search in a cue set, get cue_i which has not been used before.
Get cue_i
   cue_i (window) = Boolean   // check the value of cue_i on window
   cue_i (door) = Boolean   // check the value of cue1 on door
if no cue has been found then
   object 1 = Random Search(visible stack)
   go Step 4  // if no more cues are available then guess one object from alternatives
end if  // pick one object and give it a higher cue value for decision making
Step 3
If {cue_i (window) =true && cue_i (door) = false} or {cue_i (window) = false &&
cue_i (door) = true} then
   Go Step4
Else
   Go back to Step2
Endif
Step 4
   Decision making based on the object has been chosen
   Predict the object | cue_i(object) =true is the goal position.
```

Take the best

In some situations, some cues are better than others based on the personality of different virtual humans. Different to minimalist heuristics, cue is not randomly searched for picking up best candidates. An order of cues could be prepared for virtual humans. Different cue sequences would show different personalities during reactions.

1. Use recognised heuristic: only one object is recognised, predict the object has higher value on decision making. If the object is not recognised, then guess and check randomly. If more than one is recognised, go to step 2;
2. Ordered search: choose the cue with the highest validity that has not yet been tried for this chosen task. Then check the cue value of the two objects; the order of the cue set could be various, such as: order of size, order of distance, order of from dangerous to not so dangerous;
3. If one object cue value is 1, the other is 0 or unknown. Then goto step 4; otherwise go back to step 2, find another cue, if no other is cue available then guess;
4. Decision rule: predict the object with the cue value as it has the highest value on decision making.

In which, the "order search" of cues is the function that distinguish this simple heuristic strategy from the others. In a "take the base" one-reason decision-making, cue set is arranged in a specific personalised order. This is based on some cue that is more important than others when people make decisions. For some individuals, reliability is more important than safety, so they may choose to walk rather than running when under a fire escaping scenario.

Take the last (customary thought)

Different to minimalist and "take the best heuristics", "take the last heuristics" normally have been adopted after some decisions have been made. One would like to make the next decision based on the previous cue. This kind of customary thought effect helps one to make a quicker decision based on experience and validity cue.

1. Use recognised heuristic: only one object is recognised, predict the object has higher value on decision making. If no object is recognised, then guess, randomly check. If more than one is recognised, go to step 2;
2. Einstellung search: need memory of past discriminated cues. If there is a record of which cues stopped previous search, choose the cue that stopped search on the last problem and has not been tried in this problem. Check the values of the two objects. Or guess a cue and make it as a record.
3. If one object cue value is 1, the other is 0 or unknown. Then goto step 4; otherwise go back to step 2, find another cue, if no other cues are available then guess;
4. Decision rule: predict that the object with the cue value as it has the highest value on decision making.

For example, a cue for "take the last" decision-making can be set to repeat the same strategy: "the least fire (dangerous)" strategy, where virtual humans always try to move to a place with less fire flame based on their successful experience before.

7.2.3 Elimination heuristics

One decision is made through choices of several possibilities. The possible candidates are normally more than just two or three in those situations. Normally, reaction must be performed quickly but validity cues take time to search for. In those situations, one could make fast and frugal decisions by eliminating negative reactions rather than choosing the correct strategies. The class of eliminating heuristics uses cues one by one to filter the set of remaining possible choices, stopping as soon as only a single category remains.

The heuristics help one subject narrow down its possible choices rapidly. Reaction occurs as soon as only one choice remains. The decision initially avoids negative consequences rather than getting optimal result. As in multi-choice decision making optimisation might take longer time to find. Therefore, this decision-making strategy is also called the "Quikest heuristic".

Quickest heuristic:

> ...
>
> *2.negative bias search: search is terminated when the first cue is found that the object does not have. If more than one objects has all cues in list, then guess an object for decision making.*
>
> ...

7.2.4 Satisficing

This heuristics structure is needed when it takes time to find alternatives, appearing sequentially over an extended period. This strategy searches information about each alternative, and also searches for alternatives. For example, sequential mate search. This kind of heuristic is not in the scope of in this thesis, as it's not quite related to the real-time decision making category.

7.3 General processing of emotion affected decision making

Rational rules are normally used as cues in simple heuristics theory. For example, doors are normally a safer and familiar escaping route than windows. In those cases, cue_m: which (object) is more reliable; cue_n: which (object) is more familiar to the subject; and can be used as cues in simple heuristics. However, this normally works effectively when there are only a few options available for decision making. When the number of options increased, and time is still limited for decision making, rational cues are not realistic anymore. Within limit time, a virtual character may not be able to estimate the cue values for all options. The virtual character has to interrupt current estimating process, and the decision making will become irrational. If it is still not enough to generate emotional behaviours, more advanced cues, which directly relate to emotions, should be introduced to exaggerate the emotion feature of behaviours.

Emotion can be used as a cue for decision making directly. For example, the door could lead to a more positive emotion state than the window. In this case, the cues for decision making can be described as: cue_1: which (object) can lead to higher relief; cue_2: which (object) can lead to joy; etc.

Meanwhile, reaction motions have to be chosen from an emotional motion database. As the intensity of certain emotion decides the activity of a certain group of emotional motion patterns, virtual character's decisions can only be performed by those active motion patterns, which can help virtual characters to display their internal emotion states.

After the emotion calculation processing, the emotion states of a virtual character are evaluated and updated. The emotion states are saved in an array with emotion values between 0 and 1. An example of this emotion array is shown in **Figure 7-1**.

Figure 7-1 Example of state of emotion Array

Emotion	joy	distress	hope	fear	satisfaction	…	gloating
Record 1	0.12	0.41	0.49	0.1	0.28	…	0
Record 2	0.22	0.41	0.44	0.1	0.31		0.1
Record 3	0.17	0.46	0.41	0.1	0.3		0.1
Record 4	0.12	0.41	0.46	0.2	0.22		0.1
Record 4	0.07	0.46	0.32	0.4	0.14		0.1

The decision making unit of the virtual character uses simple heuristics to generate reaction strategies for the virtual environment. The adopted reaction behaviour is contributed by a sequence of emotional motion patterns, including walking, running, sprawl etc. When expressing a whole body gesture, the virtual human selects appropriate gestures which matched with the character's personality and current emotion states. The emotion model and motion database can help virtual humans to determine which motion patterns are preferred to be carried out. Therefore the virtual humans are unlikely to do anything irrational.

More than one pattern has been captured for each emotional motion type to increase the diversity of reactions, such as fear walking. Each motion pattern has a different weight to different emotions, which means it has different percentage possibilities when being chosen to accomplish corresponding behaviours. Necessary constraints are also added to make sure the motion sequences could be transformed smoothly and realistically. For example, virtual humans need to start and end each motion pattern at the same posture (initial pose); some motion patterns can or can not be the next sequence of some other motion patterns.

All these emotional motion patterns are classified by emotion types and saved in a dynamic motion database. If certain motion patterns reach their thresholds for certain emotions, the corresponding subset in the motion database becomes active. The emotion states of the virtual character changes depending on its own short-term memory stack. The available motions in the motion database are also dynamically changing along with the virtual character's emotion states. For example, case as shown in **Figure 7-1**, the latest emotion states of a virtual character is presented in the fifth row, record 4. As in the record 4, the emotion value of joy is 0.07, which means only those motion patterns with threshold of joy lower than 0.07 will be triggered as active. Meanwhile, those motion patterns with threshold of distress lower than 0.46 are also active. In other words, more distress motion patterns than joy motion patterns will be triggered in this case. Therefore, the virtual human is more likely to choose motion patterns with distress features than motion patterns with joy features when choosing reactions from its dynamic motion database.

7.4 Case study: decision making using different heuristics

7.4.1 Ignorance-based decision making

The ignorance-based heuristics is the simplest heuristic decision-making strategy. It can be easily realized in a virtual human system. A flow chart of the ignorance-based heuristic decision-making which is used in the virtual humans is presented in **Figure 7-2**.

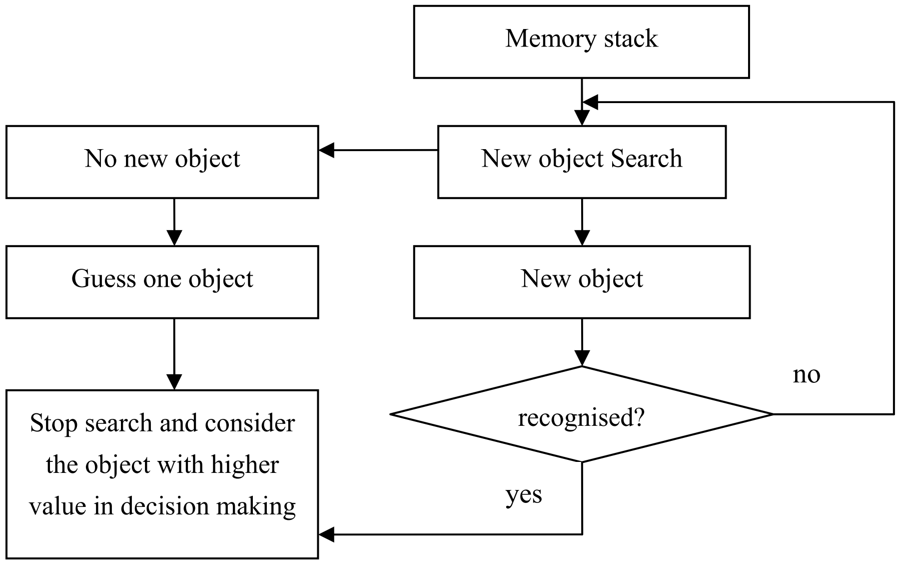


Figure 7-2 The structure of ignorance-based decision making

7.4.2 One-reason decision making

Minimalist heuristics

Emotion intensity can be used as a cue in "Minimalist" strategy of one-reason decision making. For example, a virtual character has to choose an escaping route between two doors on different directions when evacuate from a lounge on fire. The virtual character can draw a cue as follows: check which door can generate more satisfaction, then move to the door which can meet higher evaluation value of this cue.

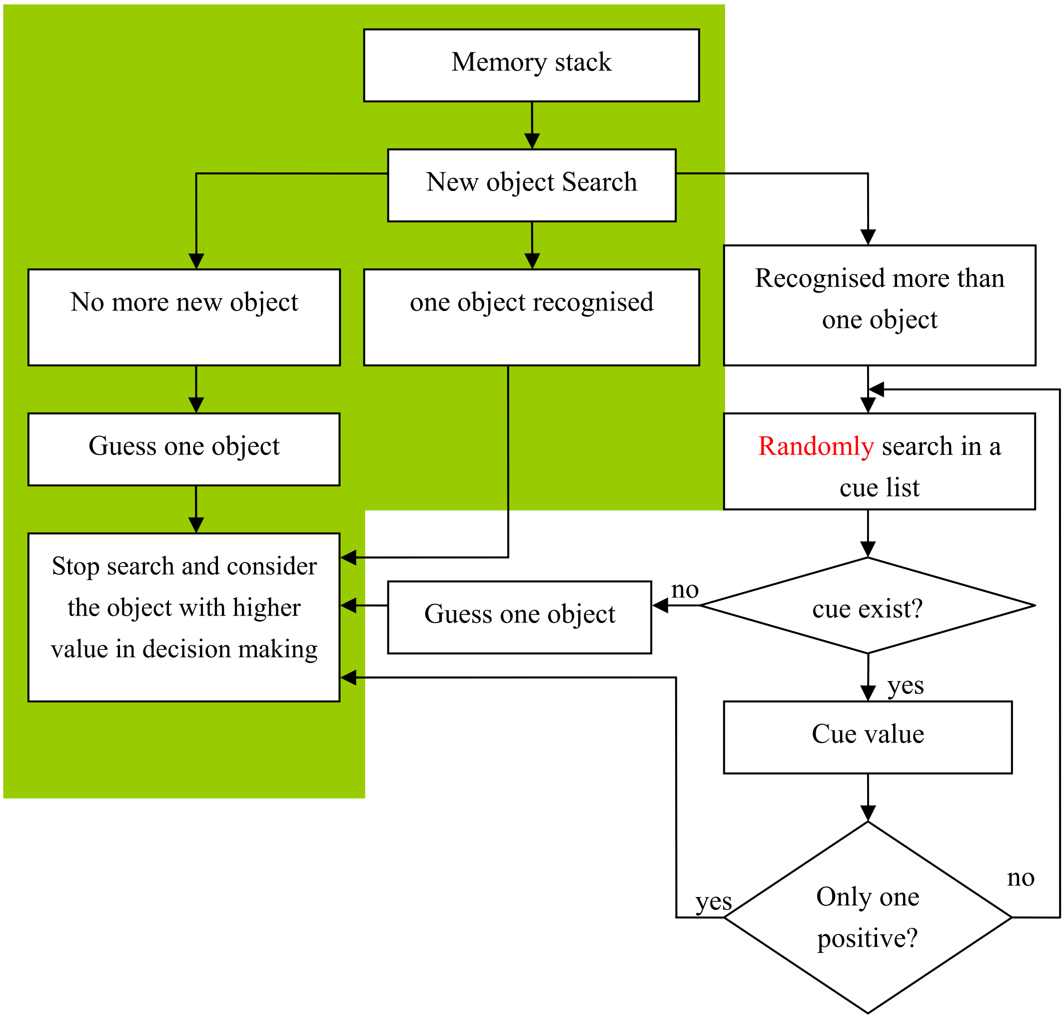


Figure 7-3 Flow chart of "Minimalist" Heuristics

Take The Best

An order of different cues has to be set down in the "take the best" strategy. For example, there are two cues available for virtual characters. The first cue judges the options that can arouse a higher satisfaction value; the second cue judges the options that can arouse higher hope value. The second cue is defined with higher priority than the first cue in the cue's ranking list. This is because hope is more basic emotion than satisfaction in the whole hierarchical emotion calculation structure. Then the reactions of virtual characters are shown as tend to increase their hope rather than meet their satisfaction.

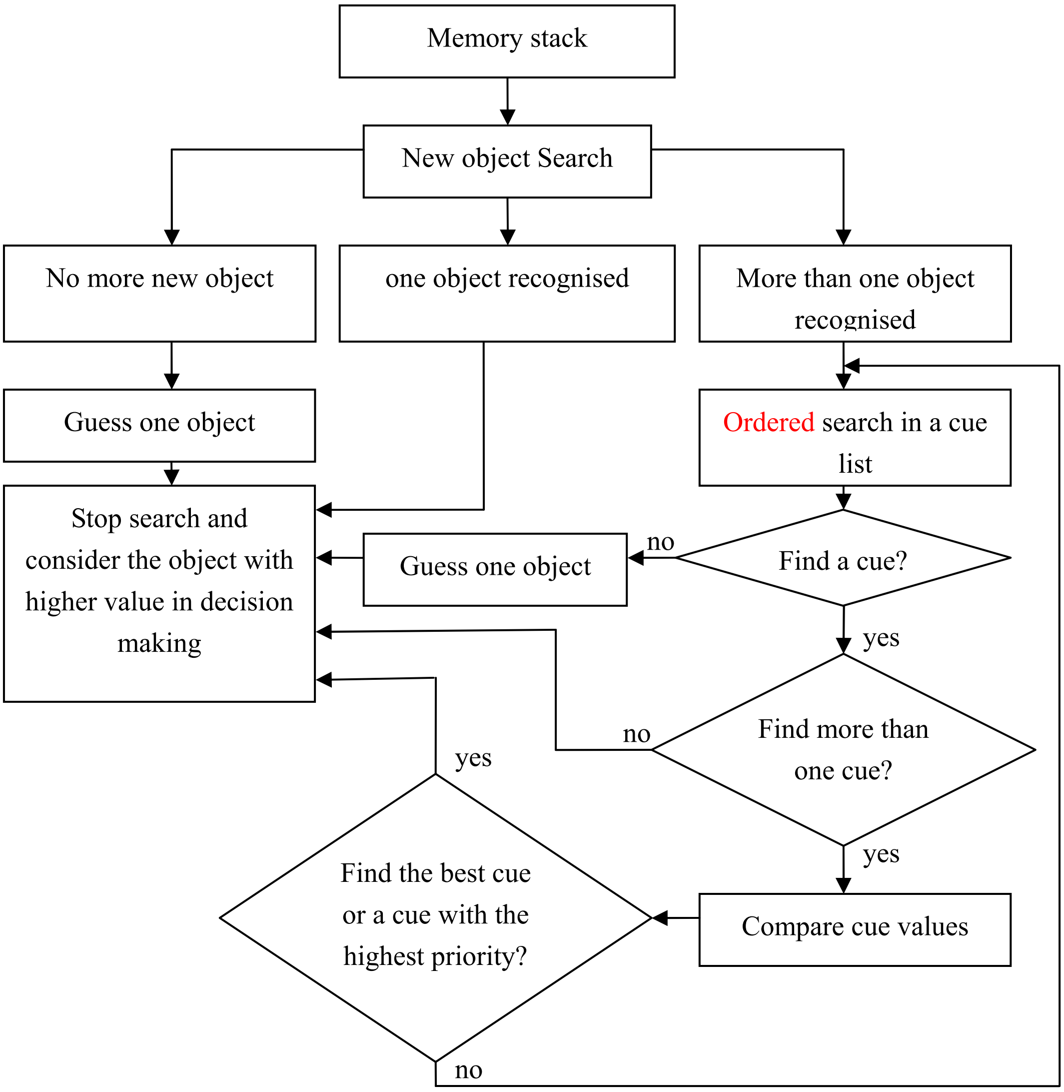


Figure 7-4 Flow chart of "Take The Best" Heuristics

Take The Last

A virtual character will draw the cue which has been successfully implemented in the last decision making process in the "take the last" strategy. If virtual characters have successfully used a cue which can arouse more hope emotion in previous decision making, they will also prefer to adopt the same cue in the current decision making customarily. This strategy gives virtual characters a feature of emotional customary thinking.

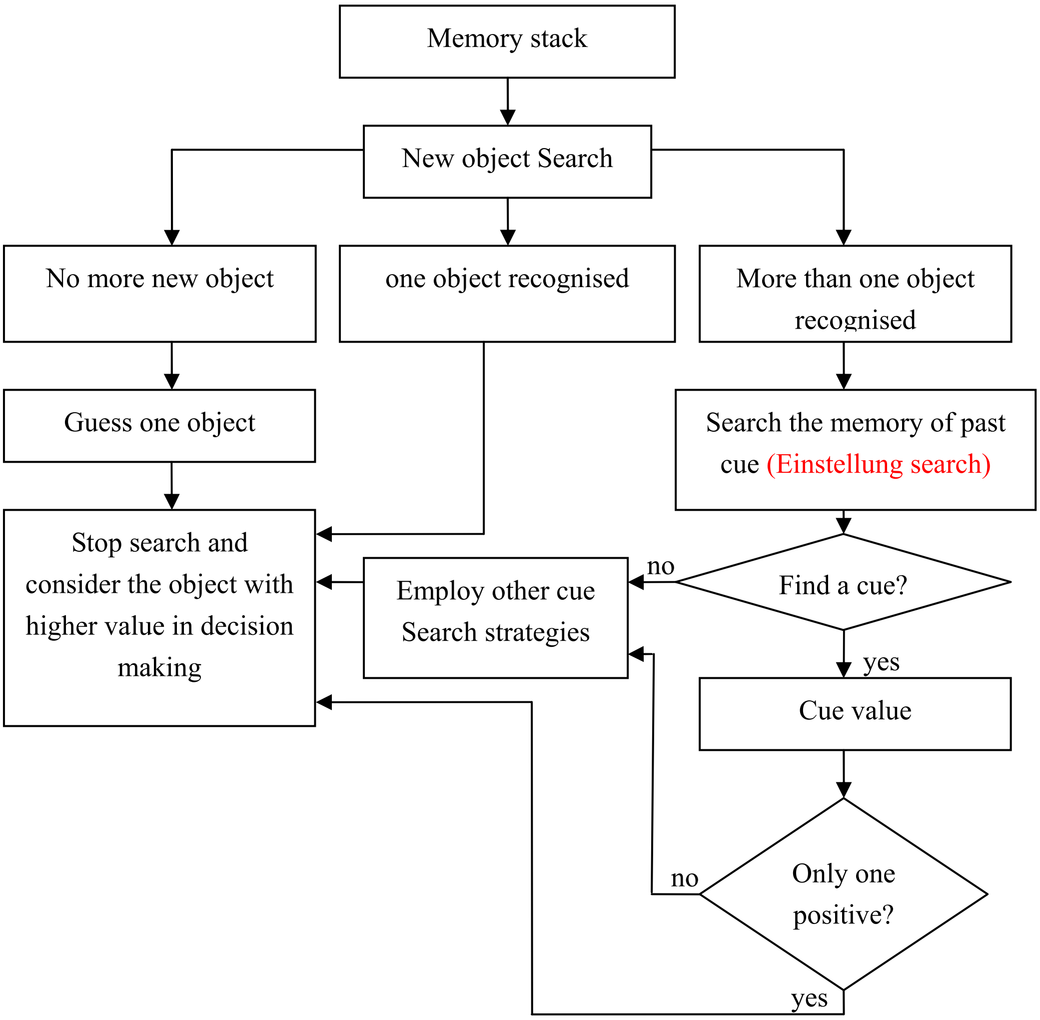


Figure 7-5 Flow chart of "Take The Last" Heuristics

7.4.3 Elimination heuristics

A virtual character has to narrow down the range of choices as soon as possible in elimination heuristic. Therefore, virtual characters may try to eliminate their choices which lead to negative emotion. For example, virtual characters will draw a cue of judging which options can arouse a lower fear value. Then they will rapidly eliminate the options which can arouse a high value of fear, and choose the option which arouses the lowest fear as the final choice.

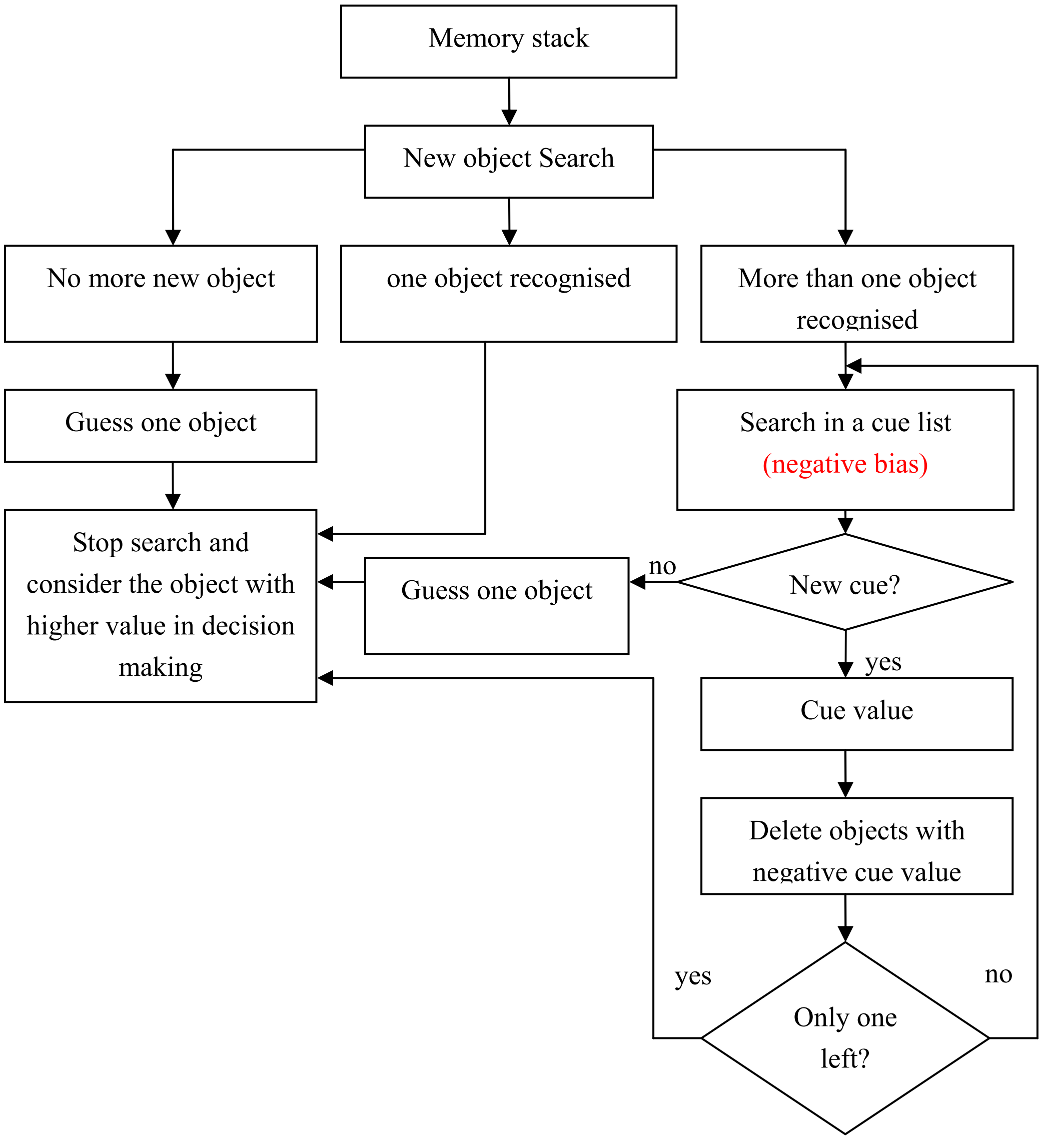


Figure 7-6 Flow chart of “Elimination” heuristics

7.5 Conclusions

In this chapter, different strategies of simple heuristic decision making have been presented and compared. How emotions affect behaviours through the simple heuristic decision making processes has been discussed individually. The flow charts of different heuristic strategies have presented various emotional decision-making.

The method presented here also has its disadvantages. For example, how to define the emotion related cues, how to set the priority ranking appropriately, which heuristic strategy should be applied and when it should be applied. Some of these questions actually departure the main topic of this thesis. For example, the third question mentioned above requires developing strategy selection principles for heuristic decision making structure. However, these questions can be interesting topics for related researchers for future work.

Chapter 8
System Implementation and Case Studies

A visualisation platform has been designed in Virtools™ to provide an interactive system with simple functionalities for the virtual humans' simulation. The aim of this work is to show that virtual humans can live their own lives according to their emotion states. They also have to adapt to their environments, which initiate unexpected or opportunistic situations. With this model configuration, the robustness of the emotional decision-making system was directly tested as the reaction performance was implemented in real-time. The decision-making is influenced by changes of the emotion states and updates of what they perceive. The decision-making system has to meet all the changes and needs to work properly when different emotion variables of a virtual human are high at the same time. At the beginning of the simulation, some of the emotion intensities may increase to the threshold values simultaneously.

8.1 Interface

A simulation platform (including an adaptable virtual environment toolkit) with a series of virtual environment scenarios have been designed for case studies.

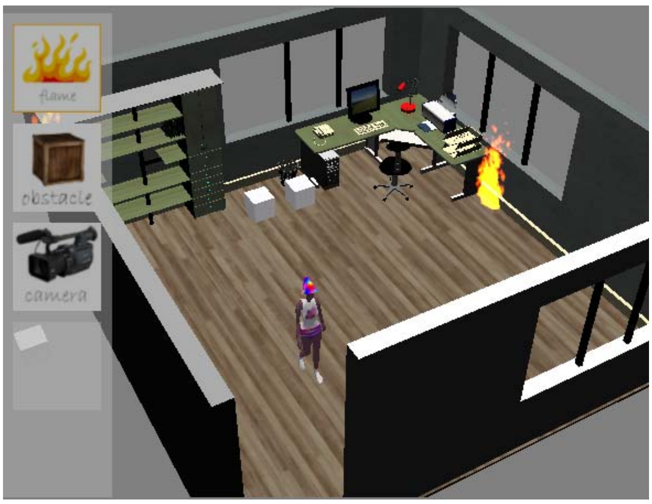


Figure 8-1 Virtual platform: office scenario

Figure 8-1 depicts one scenario of this simulation platform. In this simple 3D office, the virtual human can "live" autonomously by perceiving his environment and satisfying different emotions caused by specific objects or events. The office has all the necessary conditions to test emotional decision-making model for virtual humans in persistent worlds.

Fire tools and obstacle tools created in the platform of this scenario allow users to setup complex fire events and build obstacles in real-time. The camera tool created in the platform provides the user with a changeable viewpoint to the scenario.

 fire tools, users can choose different types of fire events, from a little flame to a blast, and left-click anywhere in the scenario to set an unpredictable fire event for virtual characters. 

Obstacle tools present a set of basic palette modules to represent different types of possible obstacles. 

Camera tool authorises the platform to integrate camera functionalities in Virtools™.

Figure 8-2 Setup a fire event by mouse click

8.1.1 Interface control

1 Button Control

These self-designed blocks (**Figure 8-3**) enable the control of function buttons to be activated in the control panel when it has been left-clicked and to make all other buttons inactive at the same time. The following figure shows an example of how to enable such a function among three buttons.

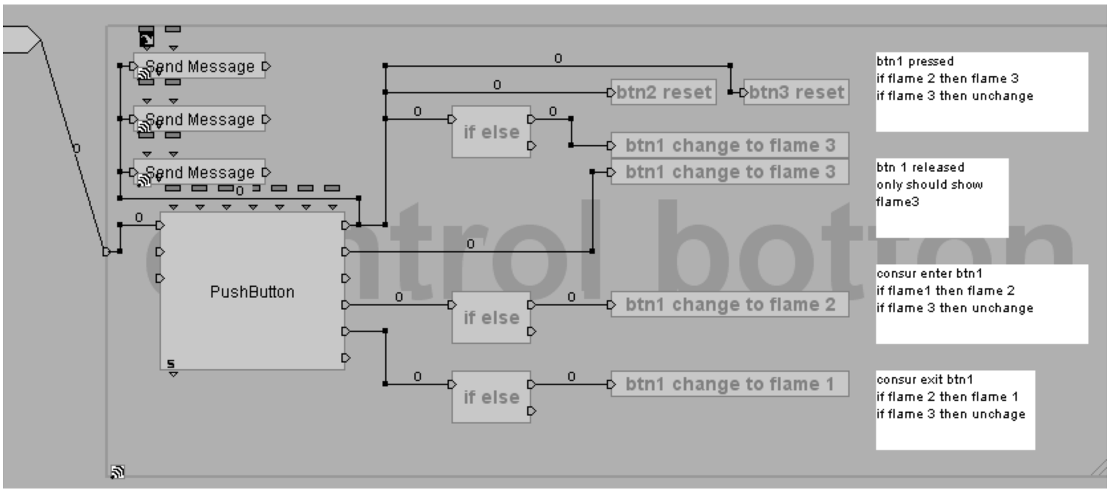
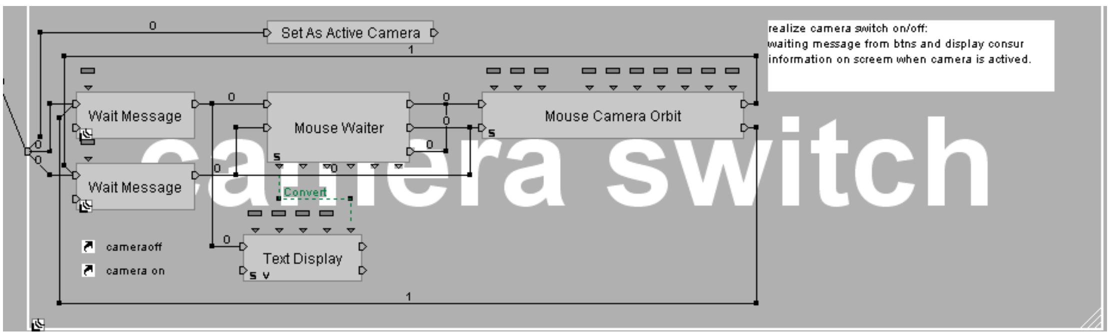


Figure 8-3 Example of button control (among three buttons)

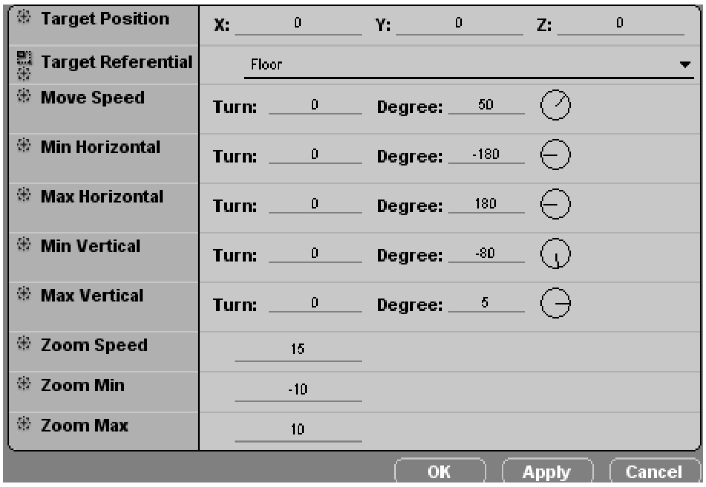
2 Camera Orbit

This block realises the control of the camera function and changes the viewpoint horizontally when holding left-click the mouse and dragging; zoom-in or zoom-out when rolling the middle mouse.



8-4 Scripts on camera control

The details of control parameters of camera are presented as follows:



8-5 Parameter for camera control

Beside these functions, Virtools also provides powerful function tools for fire flame control and duration of dynamic events (such as fire, blast). Users can easily change the range and duration of the fire and other events depending on different purposes of simulation.

8.1.2 Scenarios

Two main scenarios have been adopted to test the robustness of the model: a 3D lounge and a 3D office. The virtual humans can 'live' autonomously in these scenarios by perceiving their environment and initiating emotions as specific cues (see **Section 8.4**). In an indoor environment, the space is limited and several constraints have to be considered. When a simulation is launched, the virtual humans in such an environment will continually choose their reactions based on their own decision-making. Unexpected situations can also be set by users during the simulation. In an apartment, office or discotheque, the virtual humans can work, play, and satisfy their basic, essential, emotional needs and so on. Moreover, these emotional reactions and behaviours can be easily defined and recognised in such a relatively limited space. An indoor environment is not so complicated to design in 3D. This kind of environment has all the necessary conditions to test the emotion generation and decision making model for the virtual humans.

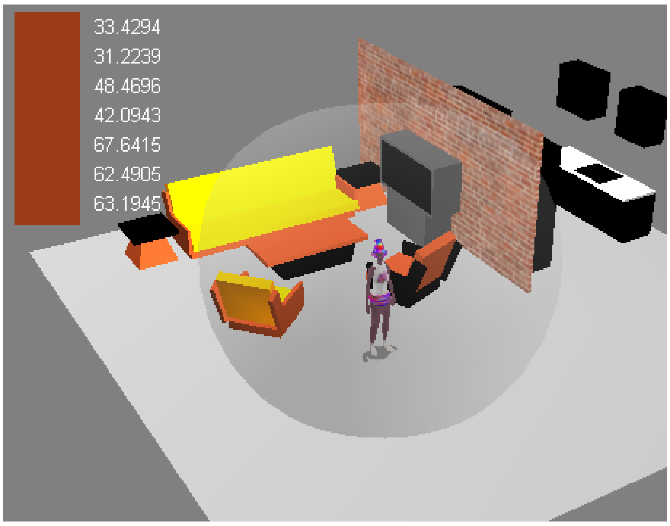


Figure 8-6 A scenario of 3D lounge

Figure 8-7 A scenario of 3D office

In the office and the lounge, the virtual characters detect the surrounding environment through their synthetic vision and remember the visible information in their minds to make decisions and react emotionally. Both scenarios also allow users to predefine or activate fire events in real time to simulate unexpected changes in the virtual environment. In the lounge scenario, the distance between the virtual character and each object is also shown on the screen. The aim is in order to show how the proximity of an object can affect virtual character's emotions (**Figure 8-6**). The office scenario allows users to setup obstacle functions (**Figure 8-7**) and fire events (**Figure 8-2**) in real time. These scenarios are complex enough to test all the functionalities of the synthetic vision, emotion generation and decision making models of distinctive autonomous virtual humans in virtual environments.

8.1.3 Summary

Three tools are developed on a simulation platform and two scenarios are created to test the capability of the virtual humans. Virtools™ is used for implementing and testing the model of emotion generation and decision making for the virtual humans. With a highly configurable graphical interface, the users can test all their ideas by adding events or objects as they want. The simulation platform can be easily modified through the graphical interface in Virtools™ before or during the simulation depending on the users' need and the goal of the simulation, which can create unexpected or opportunistic situations.

8.2 Case studies

8.2.1 Basic random wandering

Initially, the virtual humans in the system are set up to have no emotion. They begin by standing still and then start walking around randomly in a scenario (**Figure 8-8**).

Figure 8-8 A virtual character used in simulation

This building block module (**Figure 8-9**) realises random wandering of virtual characters. It can be applied to more than one virtual character at same time. At the beginning of simulation, the destinations of virtual characters are totally random before an unexpected emergency has been active. The aim of this work is to show that the virtual humans can live their own lives before making decisions according to their emotion states. They also have to adapt to their surrounding virtual environments with their own perception.

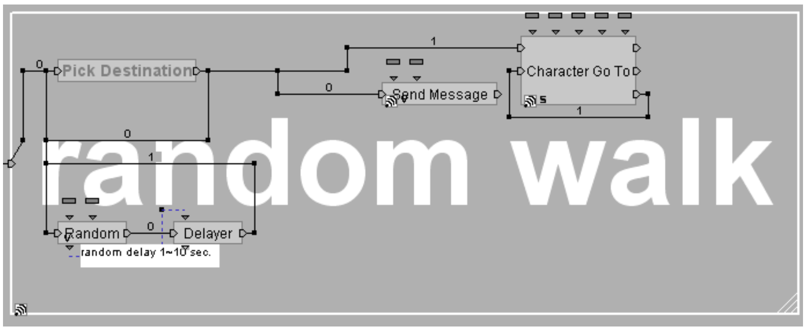


Figure 8-9 Random walk building blocks

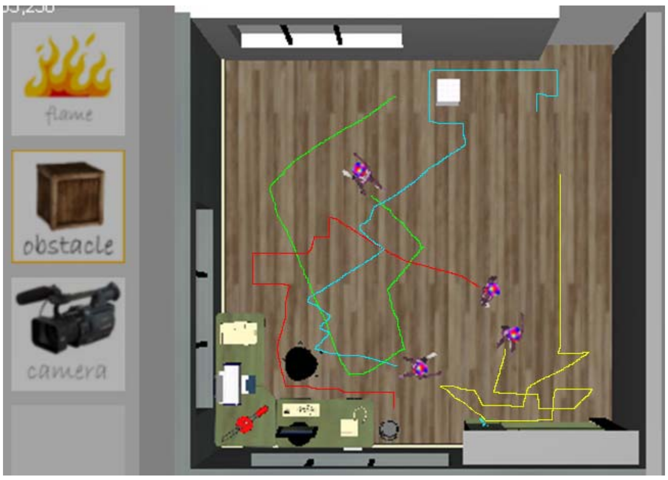


Figure 8-10 Snapshots of virtual character's random walking (every 4 minutes)

8.2.2 Flexible motion selection architecture

The 'emotional' virtual human model needs to take into account real-time information coming from the environment and adapt its decisions accordingly. This allows the virtual human to perform rational but not predictable behaviour. The virtual environment has to be sufficiently complex to provide opportunistic behaviours as well as behavioural interruptions. The virtual environment also has to be dynamic with variable quantity of resources and varied with many locations everywhere in the scenario for implementing the virtual human's reactions. The purpose of designing this group of visual scripts is implicated for testing whether virtual humans can adapt to appropriate motions in the initial model when passing through a path with unexpected obstacles in the way.

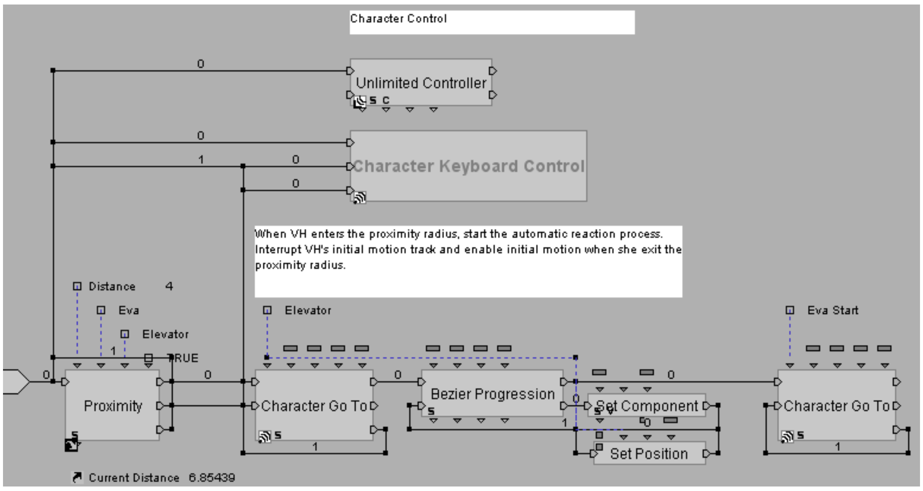


Figure 8-11 Motion selection building blocks

In the following case, the virtual character interrupted its initial motion track (walk) and jumped over an obstacle (the cube), after this, the virtual character continues its initial motion track (walk).

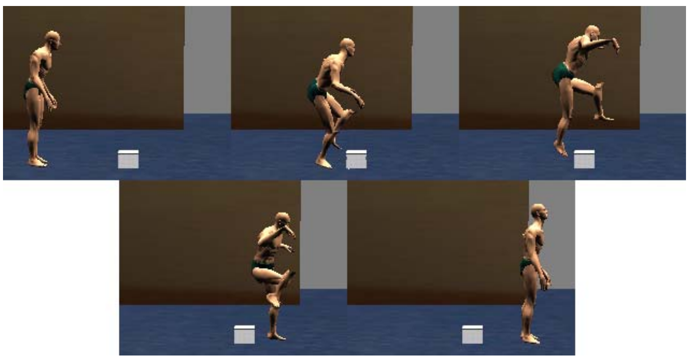


Figure 8-12 Case study of motion selection: virtual human interrupts and adopts appropriate motion when interactive with virtual environment.

It is necessary to mention that the motion selection mechanism can also be carried out by traditional AI methods, or by rule-based programming. The results might look exactly the same. However, the motion selection architecture here allows the virtual humans to select their own reactions based on their temporal emotion states. The reactions from the same virtual human to the same scenario can be different in one instance than in another. This diversity of the results shows that the virtual human is not based on rule-based programme but influenced by its dynamic emotion states. This difference allows the virtual humans to present emotional behaviour more like real humans. This difference also supports more trustworthy of virtual humans which can replacing real human to undertake simulation under some unpredictable situations.

8.2.3 Emotions of virtual character

The interruptions and opportunist behaviour (jump over object) illustrate certain personalities of a virtual human. For instance, if running motions is defined with a higher priority than walking motions, the virtual human will have a more active and panic-stricken behaviour. The virtual human will often run to the destinations and jump over some obstacles. This first step demonstrates and allows the virtual human to have a specific behaviour during the simulation. However, emotions are one way of illustrating individuality and personality. They influence the decision-making of the virtual human by taking into account the cues which evaluating the priority of choices based on the emotion state of the virtual human during the decision making. The emotional cues can be defined by users. For example, if the virtual human is in panic, he will have a strong preference to choose panic reaction over the others and perform it. In this system, the emotional motions can be defined in the rules at the initialisation, or with the graphical interface during the simulation.

As introduced in **Chapter 6**, emotion generation modules are composed in Virtools™ with Visual Scripting Language (VSL). Emotion state is recorded and saved once per second automatically to indicate the implementation of emotion modules. **Figure 8-13** gives an example table of 20 seconds for emotion state record for a virtual character. The first column displays the time of recording the emotion data. The second column records the changes on the intensity of emotion ‘joy’ per second. The third column records the intensity of the ‘distress’ emotion once per second.

	1 : joy	2 : distress	3 :
0	0.0000	0.0000	0.0
1	0.0000	0.0000	0.0
2	0.2788	0.9590	0.3
3	0.2788	0.9590	0.3
4	0.2788	0.9590	0.3
5	0.2788	0.9590	0.3
6	0.2788	0.9590	0.3
7	0.2788	0.9590	0.3
8	0.2788	0.9590	0.3
9	0.2788	0.9590	0.3
10	0.2688	0.9490	0.3
11	0.2588	0.9390	0.3
12	0.2488	0.9290	0.3
13	0.2388	0.9190	0.3
14	0.2288	0.9090	0.3
15	0.2188	0.8990	0.3
16	0.2088	0.8890	0.3
17	0.1988	0.8790	0.2
18	0.1888	0.8690	0.2
19	0.1788	0.8590	0.2
20	0.1688	0.8490	0.2

Figure 8-13 Examples of emotion state records in test

As the **Figure 8-13** presented, the initial values of emotions are all zero. Once an object or event has an affect on the virtual human’s emotion calculation module, the value of certain emotions increase rapidly, and it will affect virtual character’s behaviours once it reaches a certain threshold value. The value of emotion decreases when the object or event is out of virtual character’s vision. As shown in the Table, the intensities of ‘joy’ and ‘distress’ emotions decrease at the tenth second of recording. This means the object or event which was affecting the intensity of the virtual character since the third second has no longer existed in the virtual character’s virtual memory. The object or event can no longer affecting the intensity of the virtual character.

In the virtual human system, emotion capabilities of virtual humans can change in real-time. The rational personality of a virtual human can be changed into an emotional one by increasing the emotion thresholds for certain motions.

A chair-preference testing scenario has been designed to testing the emotional decision-making model of the virtual human (**Figure 8-14**). Initially, the virtual human is set to walk around randomly. It can perceive the surrounding virtual environment through on board synthetic vision system. There are two chairs in the virtual environment. One is an arm chair which is set to cause more positive emotions (such as 'joy'); the other is an office chair which is set to cause less positive emotions.

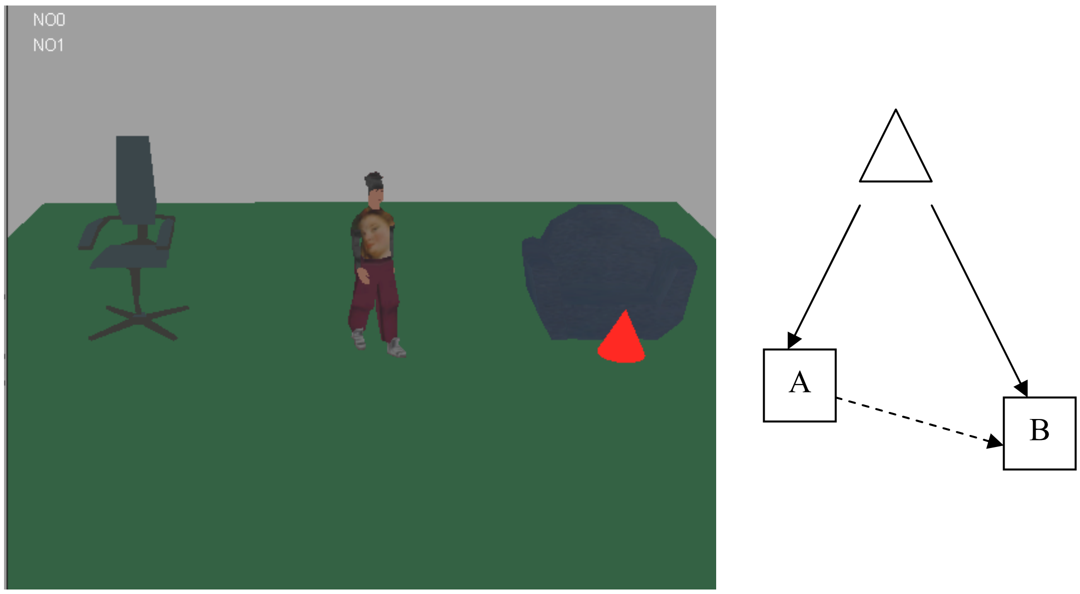


Figure 8-14 Chair-preference testing

The scenario is to test whether the emotion generation module can generate corresponding emotion states and influence the decision-making module of the virtual humans to react appropriately. For example, when a virtual human observes one chair, it will simply go to the chair with corresponding emotional motions, such as joy walk; when two chairs were observed, the virtual human would intend to go to the arm chair as it can elicit more emotion of 'joy' in intensity. In other words, go to the arm chair can satisfy more positive emotions, which is joy in this case.

Some interesting results were also simulated in this test: if the virtual human observed the arm chair when it was on the way to the office chair, it would intend to change its mind and turn to the arm chair as the arm chair eliciting more ‘joy’ than the office chair. However, if the virtual human perceived the office chair after the arm chair, it would not intend to change the current route. This test presents that the decision-making module of the system can show the emotional preference for the virtual human.

Figure 8-15 shows a matrix of variables that can affect the emotion of virtual humans and how the variables are set in Virtools™. In the matrix, the first cell in each row gives the name of an object in the scenario. From the second cell of each row, the table shows the values of variables within the object which can affect emotions and how much these variables can affect a virtual human’s emotion states. The variables are all set as value in [0,1]. All these values can be changed manually in Virtools™ depends on the need of users.

	0 : object list	1 : likelihood	2 : effort	3 : realization	4 : desirable III	5 : cognitive stength	6 : e
0	LoungCha01	1.0000	0.0000	1.0000	0.5000	0.2000	
1	LoungChair	1.0000	0.2000	1.0000	0.1000	0.5000	
2	CofeeTable	1.0000	0.0000	1.0000	0.2000	0.6000	
3	Couch	1.0000	0.0000	1.0000	0.7000	0.4000	
4	EndTable01	0.3000	0.0000	1.0000	0.1000	0.2000	
5	EndTable02	0.3000	0.0000	1.0000	0.1000	0.2000	

Figure 8-15 Initial setting Matrix of variables affecting object-based emotions

	0 : object list	0 : joy	1 : distress	2 : hope	3 : fear	4 : satisfactio
0	LoungCha01	0.7204	0.7204	0.8693	0.8693	0.8040
1	LoungChair	0.2588	0.9390	0.7546	0.9600	0.8203
2	CofeeTable	0.0000	0.0000	0.0000	0.0000	0.0000
3	Couch	0.0000	0.0000	0.0000	0.0000	0.0000

Figure 8-16 Example of object-based emotions caused by different objects

Figure 8-16 illustrates an example of their consequences on the intensity of object-based emotions that are caused by each object in real-time. For example, in the table, object “LoungCha01” (a lounge chair) generated “joy” emotion with intensity 0.7204 at a certain time (In this system, the intensity of emotion is a value between 0 and 1).

Object ‘‘LoungChair’’ (another lounge chair) generated ‘‘joy’’ emotion with intensity 0.2588 at the same time. The intensities of ‘‘joy’’ emotions caused by the two lounge chairs are different at one time, which means the “LoungChair01” caused more “joy” emotion than “LoungChair”. In this case, the virtual human prefers the “LoungChair01” emotionally when it has to make a decision, such as choosing a chair to sit down. In the third row of the table, the intensity of ‘‘joy’’ emotion generated by ‘‘Cofee Table’’ is zero, which means the object is not in the vision field of the virtual human. The value of variables in the initial setting matrix can be modified by users or designers of the virtual human (as shown in **Figure 8-15)**. In this way, the emotional preference of the virtual human which is caused by different objects can be adjusted and be visualised in **Figure 8-16**.

For now, the emotional decision making strategy in this model is very simple and only determines whether the virtual humans can satisfy their object-based and event-based emotions. However, the results give an idea on how this model could be enhanced with more complex emotions. The object-based and event-based emotions can be set randomly at initialisation and can be changed during the simulation.

The chair-preference test has been run 30 times. As expected the more positive the emotion is, the more the decision-making system chooses the associated emotional motions from emotional motion database. Conversely, the more one object can influence the virtual human’s decision-making, the stronger positive emotion the object can bring. In the chair-preference test, all the motion patterns which are above the corresponding emotion thresholds are set as active. These motion patterns are randomly chose by the virtual human. As shown in **Figure 8-17**, the difference between the choices is not huge. It means that emotion influence the decision-making but not dominate the decision-making.

Virtual human go to	Total: 30 times
Arm chair A (loungChair01)	22
Office chair B (loungChair)	8

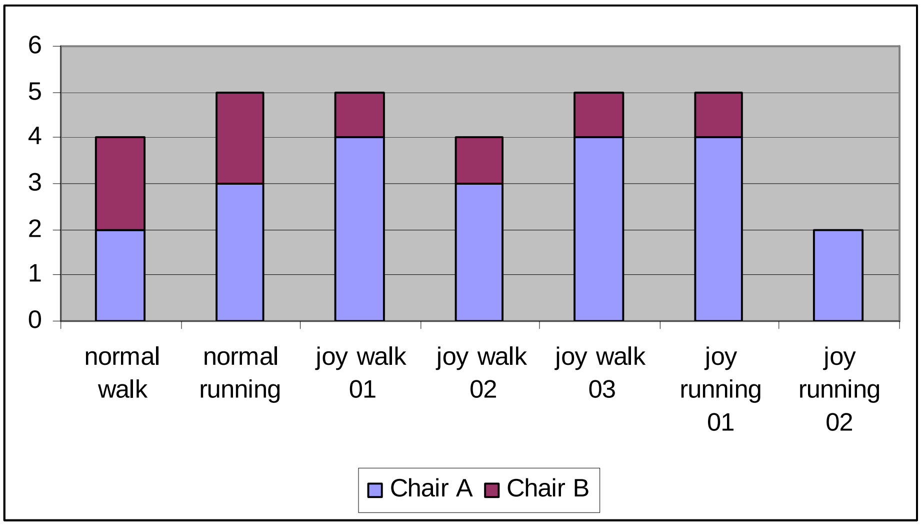


Figure 8-17 Number of times that each emotional motion is chosen by the virtual human during the 30 times interactions.

This strategy provides virtual humans the capability to make decisions with emotional preference. It also influences virtual humans to adopt emotional behaviours when implementing emotional decisions. The diversity of reaction is also generated randomly within the active emotional motion patterns.

The emotion states of virtual humans can be detected during the testing (**Figure 8-13**). This is to justify that the emotional behaviour of the virtual humans consist with their associated emotion states. In a rule-based system, the preference or intension of a virtual human's decision-making can be learnt and realised by some complex models, such as fuzzy logic, neural networks, etc. In this virtual human model, the decision-making module is implemented based on the heuristic decision-making strategy. The module also shows the influence of emotion on the virtual human's decision-making, which can not be easily realised in a rule-based system. The emotional decision-making strategy is more suitable to simulate real human's behaviour than a rule-based strategy. It is appropriate for more complex and advanced simulation.

8.3 Summary

Case studies show that the virtual human modelling can accomplish emotional decision-makings and have corresponding behaviours in persistent virtual worlds in real-time. The virtual humans can have their own emotions and behave emotionally according to their internal and external factors. The model also integrates some subjective evaluations of motion capture and decision-making to obtain more realistic and believable behaviours. Finally, some tests are made for demonstrating the generality of the model. The model shows its flexibility and robustness.

The system has some limitations which need to be addressed in the future to improve the modelling and simulation:

1. Despite the success of current systems, the hierarchical structure of emotion needs to be improved in the future. Since only one prototype of such virtual human model is created and employed at the current stage, a more generic emotion model with different weight coefficient settings is not implemented in the current system.
2. Due to the limitation of methods with emotion measurement. Some more advanced technologies are still in need to identify the intensity of certain emotions directly. A more precise implementation of the SCR method also needs to be developed.
3. The emotional motion database is a predefined database. The different motion tracks are connected through the standard initial pose. The smoothness of motion transform between different poses is limited in the current system.
4. The social interactions are not fully considered in this work. For example, there is no information exchange between the individual virtual humans. The social interactions of the virtual humans are related to psychological issues. Related social interaction models can be integrated into this virtual human system to improve the complexity of the simulation.

Chapter 9
Conclusions

Virtual human modelling and simulation is a new and fast developing research topic. The research focused on software to make the manipulation of a simulated human figure easy for a particular user population: human factors design engineers or ergonomics analysts. These people typically study, analyse, assess, and visualise human motor performance, fit, reach, view, and other physical tasks in a workplace environment (Badler 1993). Virtual human has broad applications in industry, military, biomedicine, education, public environment, etc. At the same time, virtual human modelling and simulation is also a widely accepted challenge of AI and a labour-intensive task, which involves extensive expertise, special equipment, professional software, and often various specialists and production teams (Thalmann 2005). However, emotion has rarely been considered as a significant part of creating a virtual human. For a quite long period, emotion was considered as an irrational factor of psychology and barely been considered to participate in any artificial intelligence processing. Although current psychological research has supported lots of practical theory and techniques for emotion measurement, modelling emotion features and integrating them into virtual intelligence of sophisticated virtual humans in a pure computer environment are still open challenges and have rarely been explored in the past.

9.1 Conclusions

This thesis consists of designing a virtual human model with emotion capabilities which presented new techniques for virtual humans to generate and perform multiple emotions. To have a base to compare the performance of the different model functionalities, the virtual human system has been modelled from an initial model and tested with only the basic functionalities. The initial model has then been improved step by step.

At the early stage of this work, a framework of dynamic emotional motion database is introduced in the improved virtual human model. In order to develop realistic virtual human behaviours, lots of subjects are motion captured when performing emotional motions with or without intent. The emotional motion patterns were endowed to virtual characters and implemented in different virtual scenarios to help evoke and verify design ideas, possible consequences of simulation (such as evacuation). This method provides a useful instantiation database for industrial design, ergonomics where emotional motions have rarely been considered in the past.

In the improved virtual human model, the field of vision (FOV) conception based on anthropometric data is also established. For developing a realistic vision system, a few collision-based field of vision volume models were created to verify the importance of field of vision in synthetic vision modelling. After that, a collision-based synthetic vision system was established. One of these FOV volume designs were utilised and implemented for the synthetic vision system in this improved virtual human model.

Beside a collision-based synthetic vision system, a novel virtual short-memory mechanism has been developed for the improved virtual human model. This virtual memory mechanism supports a more natural and reasonable virtual memory model and provides a "first-in-first-out" stack system for virtual humans to remember and forget environmental information resembling real humans. This mechanism can also be modified to simulate the diversity of memory between individuals by amending the size of the memory stack and span of time tolerance.

The subsequent virtual human model with emotion capability enables virtual humans to perform emotionally according to their internal and external factors in real-time with a novel hierarchical emotion structure. An emotion measurement approach in psychology, the SCR testing, has been introduced to analysis the change of human emotions. In this work, the approach is used to develop a series of putative equations for emotion calculation.

Based on these putative equations, the emotion generation model enables autonomous virtual humans to change emotion states according to stimuli of the virtual environment. A heuristic decision-making strategy is adopted in this virtual human model. This technique provides a possible way of realising decision-making with only partial knowledge and a mechanism of how to jump out of searching when encountering with limited time. In comparison with other decision-making models, the heuristic models investigated in this work support a new approach to integrate emotions into rational decision-making, which endue virtual humans with more realistic and individualised emotional reactions.

This work merged two different fields: emotion calculation and virtual human modelling (through motion capture based animation compositions), along with emotion measurement and simulation research, to deliver a complete and specialised solution for emotional virtual human modelling.

The implementation and the testing results of the virtual human model with emotion capability show that it is possible to model emotional autonomous virtual humans in a real-time system. It proves that the emotion features of virtual humans can be simulated beyond a rule-based system. The virtual human system investigated here is an open, modularised system. More module parts can be integrated into this system in order to improve the virtual humans based on the need of users.

9.2 Future work

There are some issues are considered as future works and hopefully can help subsequent researchers:

1. Synthetic motion techniques can be integrated into the system to guarantee the smooth transition between different motion tracks. This is a traditional branch in virtual human research which keeps on trying to improve the reality of virtual humans.

2. Expanding the generic emotional motion database to enable motion deformation on different body types, including different genders, ages, body mass index (BMI), ethnical groups, etc. this is also recognized as motion deformation or 3D deformation technique.
3. Comparison of different emotion measurement techniques and introduce new emotion equations. As an emotional virtual human modelling is a multidisciplinary topic, approaches from different research areas need be considered, such as new techniques for emotion measurement in psychology.
4. Investigating facial motion capture with expressions.
5. Investigating synthetic audition, synthetic olfaction and other synthetic perceptions.
6. Studying a method for emotional motion recognition between virtual characters. To simulate the sociality of virtual humans, the recognition of emotions among different virtual individuals is an important research topic.
7. Improving the current decision-making method and adopting more sophisticated algorithms.

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> To instantly generate desired infinite realistic human motion is still a great challenge in virtual human simulation. In this paper, the novel emotion effected motion classification and anatomical motion classification are presented, as well as motion capture and parameterization methods. The framework for a novel anatomical approach to model human motion in a HTR (Hierarchical Translations and Rotations) file format is also described. This novel anatomical approach in human motion modelling has the potential to generate desired infinite human motion from a compact motion database. An architecture for the real-time generation of new motions is also proposed

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Appendix A
Motion Capture Process

Equipment Setting Up

1. Distribute 7 tripods evenly around expected capture volume (roughly camera distance would be 2 times capture volume distance from the capture centre).
2. Wide spread each tripod (to make it most stabile to prevent tripod fall causing damage to the camera).
3. Take the connection cables in bundle to underneath each tripod according to the distance to the hub (long distance with big bundle).
4. Take each cable red end to the hub, leave sufficient cable at the tripod end, and tidy the cable up far from the capture volume and not on the ways.
5. Connection to the hub. Connect the round power cable connecter with biggest pig up to any round socket in the two line sockets on the upper back of the hub; insert the network cable to the any network socket in the two line sockets on the lower back of the hub; insert a single network cable to the rightmost socket in the two line sockets (not the single socket), and that single network cable connects to the network socket in the middle of the back of PC.
6. Put the L frame at the centre of capture volume.
7. Set each camera zoom to 18 and focus to ∞.
8. Connect the round power cable connector with biggest pig up to the camera back first right socket, and insert network cable.
9. Insert the camera into tripod and push the flipper to lock the camera (while one hand hold the camera), with one hand hold the camera loose the big knob on the tripod ball joint, adjust the camera to target the L frame and avoid to face other cameras, if necessary use the winder to lift tripod end up (life the camera). Before stepping down make sure camera are tightly fastened.

System Setting up

1. Switch on the computer first and then EagleHub3, click the EVaRT icon to launch the EVaRT software.
2. Create your own working folder on hard drive to store all data files to be generated.
3. Open a previous project with similar setting up, and save it in the new folder with a new name (normally, ddmmyy.prj).
4. Tick Connect to Cameras underneath the viewpoints, all camera’s infra-red ring light should be on, 7 camera’s push-buttons underneath the viewpoints should be green.

If less than 7 cameras being identified, accept it, then all recognised cameras will be light on, the one without infra-red ring light is the one with bad connection, trace that camera's connection from camera to hub. (On the left back of the hub, the yellow LED lights indicating the power connection to each camera and the green LED lights indicating the signal connection to each camera).

If one or two camera's push buttons in grey, adjust the brightness of these cameras, then enable them. Or reboot all cameras.

5. Setting up

   Setting panel

   Camera sub panel

   Camera type: Eagle/Hawk
   Frame Rate: 60
   Shutter Speed: 1000 (1/sec)

   Misc sub panel

   From raw video files: real time
   Skeleton Engine: Calcium Solver

   Calibration panel

   Calibrate sub panel

   Details…
   Calibration frames: Z up, millimetres,
   (0,0,0) (200,0,0) (600,0,0) (0,400,0)
   Origin offset: all 0
   Lenses / Orientation: 18 Normal
   Capture volume: accordingly

6. From Menu Tools – Camera Settings. Check each camera's Threshold around 400 and brightness% to 100.
7. From right click mouse menu, tick show camera field-of-view, and adjust each camera to cover the capture volume (tick Show Volume).
8. Push all on button at the lower left corner to show all cameras' coverage, at Refine sub-panel tick show camera coverage, change minimum number of camera value to see the cubic coverage.
9. In calibration panel calibrate sub-panel, tick the Preview calibration check-box, then press the Run button. (All the number buttons on the bottom of the EVaRT interface should turn yellow if all of them can see the L-frame).
10. Optimize each camera's position and brightness.
    Check in each camera view. If there are less than four markers, adjust the view of the camera or adjust the brightness of camera to see more markers. If there are more than four points, mask extraneous point. To mask, press Pause button (the button will become Run). While in one of the 2-D views, press the middle mouse button and hold it, drag a square over the bad data to mask. Also reduce

the brightness of the camera which may reduce the extraneous data points.

11. Click the collect and calibrate button on the calibrate sub-panel (tick over write if necessary); with button on Run mode displaying Pause.
12. Save the project in the folder created in system setting up.
13. Remove the L-frame reference markers, before remove mark the coordinate origin and X, Y axis on the floor.
14. Use T-wand in the capture field and press collect and calibrate (600 seconds). In order to cover the entire capture volume by waving the wand both horizontally and vertically through the cameras field of view. In the 2-D view of each camera, points should cover most of the area.
15. Don't tick the Heavily Weighted Seed, and click the 'run again' button more than three times until the U-Res. Date do not decreasing sharply.
    Wand Length Avg. 400 (around) Dev. <1
    3D Residuals Avg. <1, Dev. <0.3
16. Wave the T wand on the floor and up the capture height to explore the boundary of all cameras can see and marks the boundary on the floor.

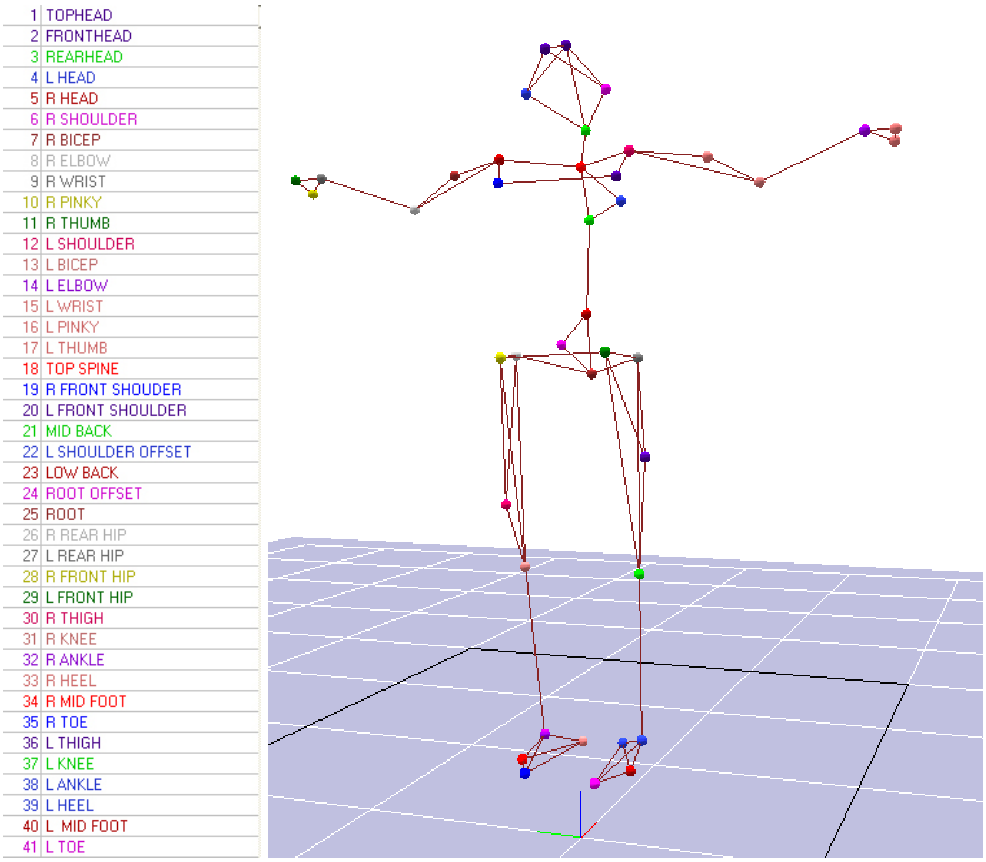


Figure A-1 41-marker setting plan for motion capture

Extra Notes

Camera setup

For the virtual intelligent human project, motion capture session involving only one subject each time, where the occlusion of markers is not a main problem. Six cameras may be adequate for majority one-subject motion capture task. This configuration is often been commended for gait analysis and other similar biomechanical applications. As a wider range of motion is allowed for emotional motion capture, the probability of markers being occluded will increases. To this point, seven cameras are required and set up for tracking movement of each marker during motion capture as much as possible. For optimum results, all cameras are settled at least 2.5 meters above the floor. The end cameras nearby the long axis of the view areas are often tilted. This is in order to cover the maximum field around the centre of the view area.

In order to capture and recreate human's emotional motions, camera-setting approaches have been reviewed, and two particular camera-setting planning has been developed based on the speciality of motion capture equipment has been used for virtual human modelling project.

The first camera setting plan, which we called the circle plan, is sufficient to finish majority whole body motion capture cases. This setting plan could cover the maximum motion capture volume in area. 7 cameras are settled on every vertex of a regular heptagon area. It is suspected to guarantee all markers could be viewed by at least 3 cameras at the same time as much as possible during the motion capture. It is been proved that it could capture majority basic motions and majority complex emotional motions. See **Figure A-2**.

It is necessary to point out, a suitable space is important for an optical motion capture system. Ordinarily, the space should be kept out of sunshine; there should be neither reflected nor refracted infrared ray resources in camera view; there should be no other heating resource in the motion capture field.

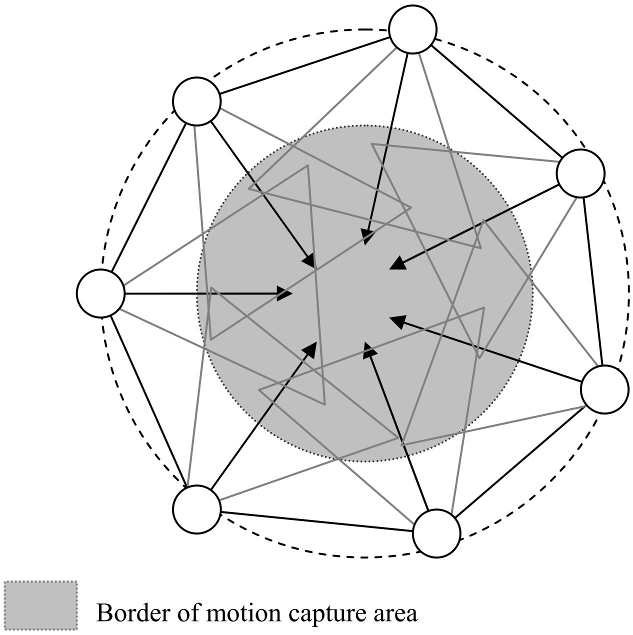


Figure A-2 The circle plan: 7-Camera setup for motion capture with maximum capture volume

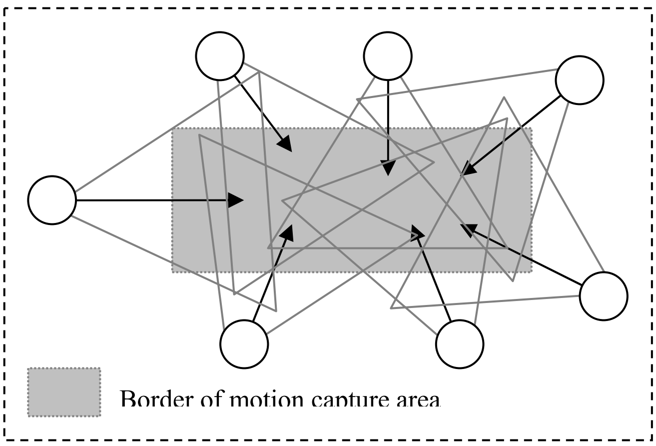


Figure A-3 The rectangle plan: 7-Camera setup for motion capture with relative smaller area

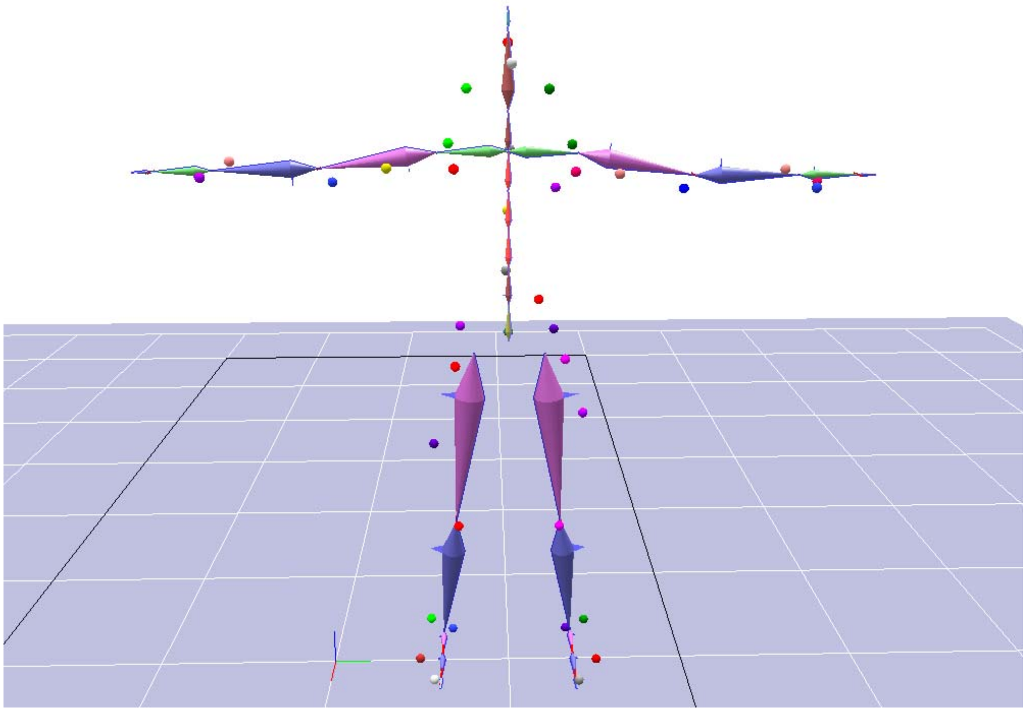
For some more complex motion capture session, such as emotional gait and running *et al*, there is more important to capture the motion details on certain direction, rather than keep maximum motion capture volume. The locations of the 7 cameras are reset. This setting enables cameras to cover a relative smaller area but with more detail on the long axis of motion capture volume area, which is called the rectangle plan for camera-setting. The new motion capture area is 5 metres long and 2 metres width. See **Figure A-3**. This is also minimum recommended configuration for whole body human motion analysis applications. For further details about cameras setup please reference to the EVaRT Users Manual.

Body suit and marker setting

The number of markers used in motion capture depends on the complexity of corresponding motions. Considering the continuity of the motion capture data, a 41-marker setting plan is created for emotional body motion capture. The marker set is based on Helen Hayes marker sets marker placement (Motion Analysis Corporation 2005). Markers are set on joints and some other necessary body parts. This setting is created in order to get all the specific details of body motions for emotional motion analysis.

Appendix B
Hierarchical Skeleton Structure Design

A 28-segment hierarchical skeleton structure is designed for the virtual humans. In this work, minimum skeleton segments are used to represent maximum emotional body motions and drive body figure mesh. For example, the number of bone segments for limbs is increased while the spinal columns are simplified into only five segments.

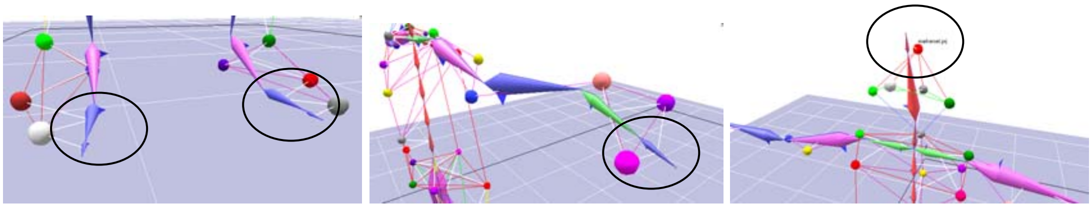


Root segment ("IriaRoot") is **6DOF-Global**. All skeletons are assumed to have one, and only one, root bone of this type. All other bones must be a child (or grandchild, etc...) of the root bone.

Each segment has its own joint type. A Shared joint specifies it has a correlated master segment, such as Spine segments.

A hinge joint only has one rotation axis; a universal joint has 2 rotation directions. A gimballed joint have all 3 rotation axes (as does a joint of Global type).

Details of the skeleton structure



Appendix C
Emotional Motion Capture Guide

Emotion	Motion			
	Idle	Sitting	Walking	Running
Hope	Hands clutched together. Shaking with anticipation Head raised, wondering.	Upright, tense Upper body as Idle	Short Step distance. Upper body as Idle	Fast. Head High. Tense, short steps
Fear	Shaking, hands raised in defensive position. Covering ears or mouth. Hunched shoulders. Cautiously turning head. Leaning to different directions.	Similar to Idle covering head.	Can be on tip-toes. Short step distance. Upper body as Idle	Large step distance. Hunched over. Head can be down or looking back
Joy	Bouncy, bobbing head. Hands open, shoulder relaxed. swaying slightly. Hands can be behind back or head	Upper body as Idle. Can be tapping knee, or foot.	Bouncy step, slight hop Large confident strides.	Bouncy. Large arm swing. Large step distance.
Continued to the next page				

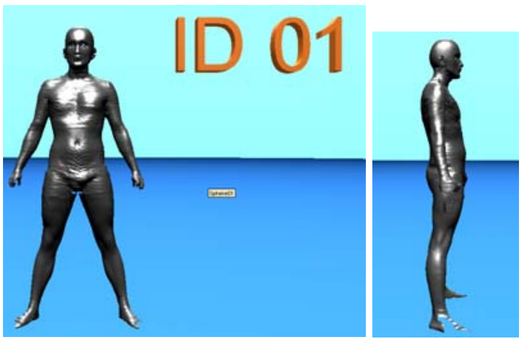
Distress	Hunched, hand clenched. Hugging arms, head down. Shaking head, sighing. Biting fingernails.	Tense, hunched, rubbing forehead. bobbing forward and back Clutching head.	Slow looking at floor, short steps. Hugging oneself, hunched over	Similar to fear but confused
Pride	Head high, standing erect, Shoulders back, chest out, weight supported on one leg. Hands on hips	Folding arms Looking up or stroking chin Legs wide open Arms can be folded	Slow, Large confident strides. Large arm swing Chest out	Similar to Walking
Shame	Looking towards shoulder Slouching feet close together. kicking the floor	Averting gaze Hands on head Body as in Idle	Slow, Short step distance looking at feet hand behind back or in pockets Upper body as Idle	N/A
Admiration	elbow resting on palm with hand on face tilt head to the side	same as Idle, but sitting	Same as Idle but walking	N/A
Reproach	Hands on hips Pointing, shaking fists wagging finger	similar to Idle but sitting	Shoulders raised, fists clenched or hands on hips Head leaning forward	N/A
Continued to the next page				

Like	Nodding in agreement Open hand movement	leaning forward arms open, back straight	Upright, large strides similar to joyful walking	Similar to joyful running
Dislike	Leaning back Shaking head Hand pushing away, gesture weight on one leg	folded arms leaning back eyes focused legs apart	Hands in pockets head forward shoulders raised	N/A

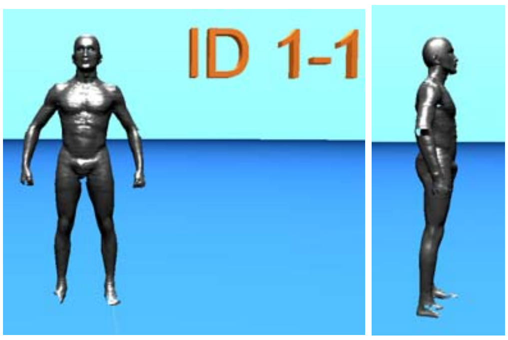
Table C-1 Instruction of some emotional motions to motion capture actor/actress

Body Scanning Mesh List

34 individuals (29 males and 4 females) with different body types and ages have been scanned for virtual human body mesh modelling. For each scanned body mesh, the head part has been replaced.



01



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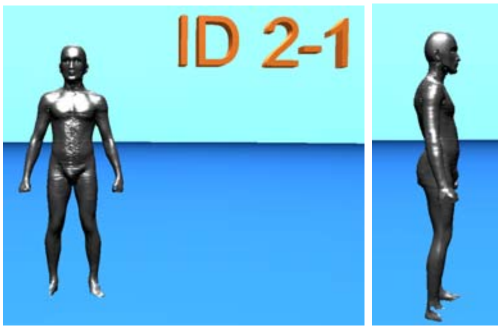

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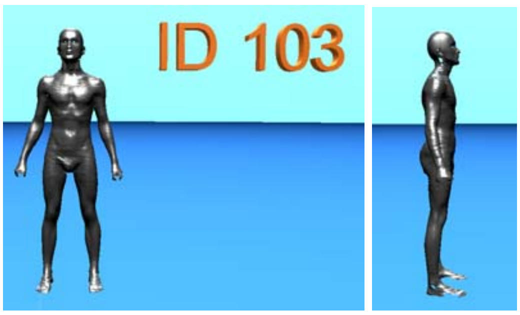
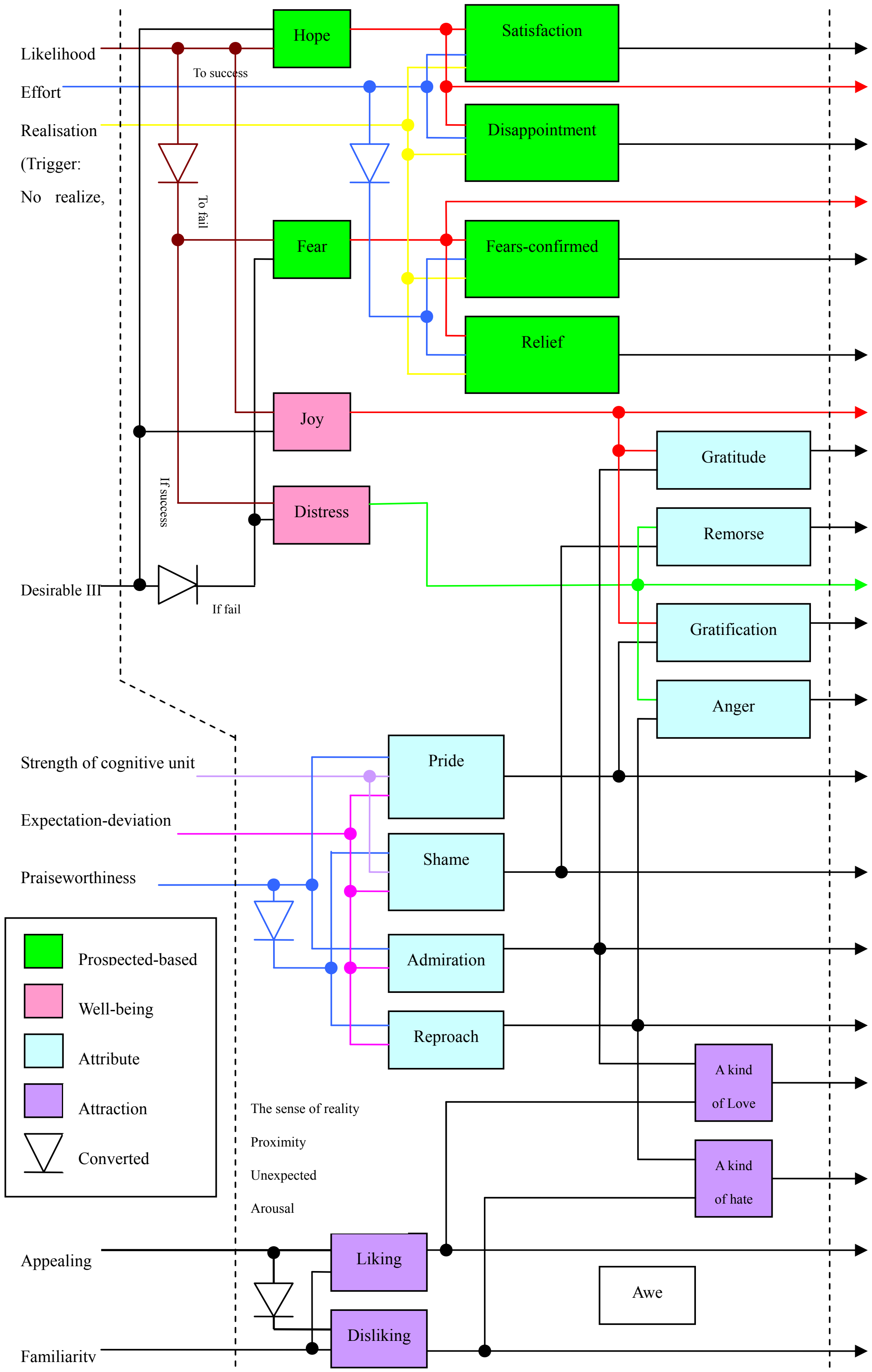


04

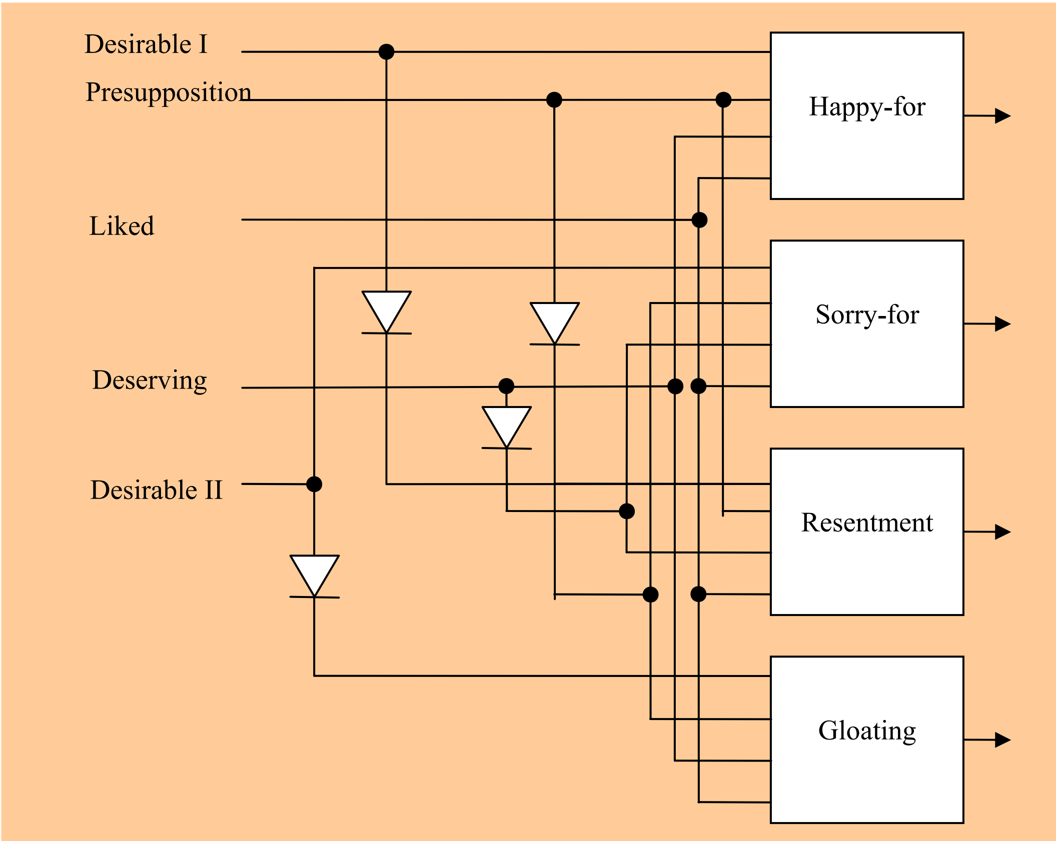
Figure C-2 Examples of 3D body scanning mesh using in the emotional virtual human modelling

Appendix D



Likelihood
Effort
Realisation
(Trigger:
No realize,
Desirable III
Hope
To success
To fail
Fear
Joy
Distress
If success
If fail
Satisfaction
Disappointment
Fears-confirmed
Relief
Gratitude
Remorse
Gratification
Anger
Strength of cognitive unit
Expectation-deviation
Praiseworthiness
Pride
Shame
Admiration
Reproach
A kind of Love
A kind of hate
The sense of reality
Proximity
Unexpected
Arousal
Appealing
Familiarity
Liking
Disliking
Awe
Prospected-based
Well-being
Attribute
Attraction
Converted

Desirability 1: desired/undesired about desirable event for the other
Desirability 2: desired/undesired about undesirable event for the other
Desirability 3: desired/undesired about event for oneself



Flow chart of the hierarchical emotion calculation structure

Variables that affecting emotions and their shortened form

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1. The degree to which the event is desirable/undesirable; (desirable III)
2. The likelihood of the event; (likelihood)
3. The effort expended in trying to attain/prevent the event; (effort)
4. The degree to which the event is realised; (realisation)
5. The strength of cognitive unit with the actual agent; (strength of cognitive unit)
6. Deviation of the agent's action from person/role-based expectations; (expectation-deviation)
7. The degree of praiseworthiness/blameworthiness; (praiseworthiness)

---

8. The degree of familiarity with the object; (familiarity)
9. The degree to which the object is appealing/unappealing; (appealingness)

---

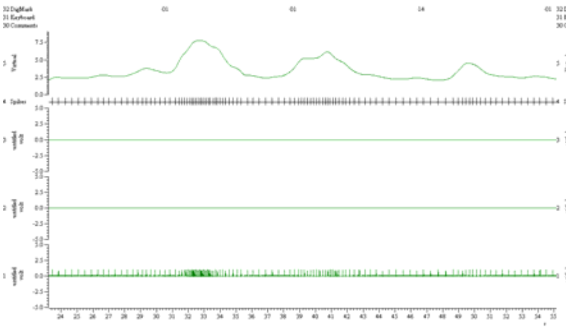
10. The degree to which the desirable event for the other is desirable for oneself; (desirable I)
11. The degree to which the event is presumed to be desirable/undesirable for the other person; (presupposition)
12. The degree to which the other person is liked/not liked; (liked)
13. The degree to which the other person deserved/did not deserve the event; (deserving)
14. The degree to which the desirable event for the other is undesirable for oneself. (desirable II)

Appendix E

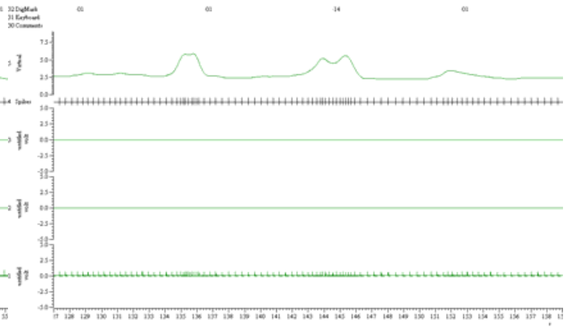
SCR Test Results (fear related)

Group one 'snake pictures'

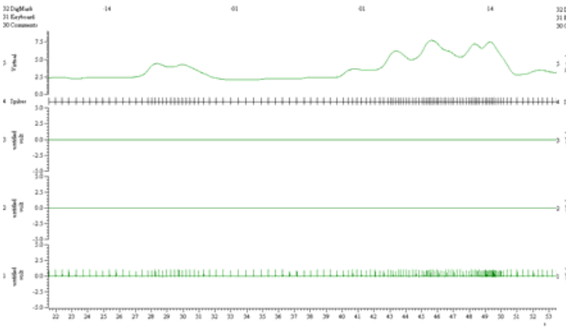
Subject A

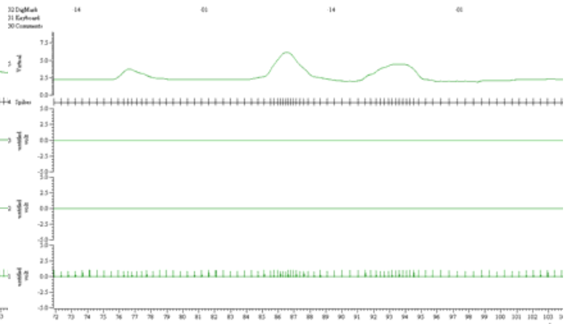


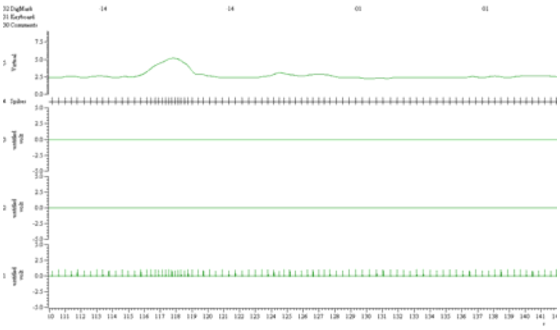
Subject F



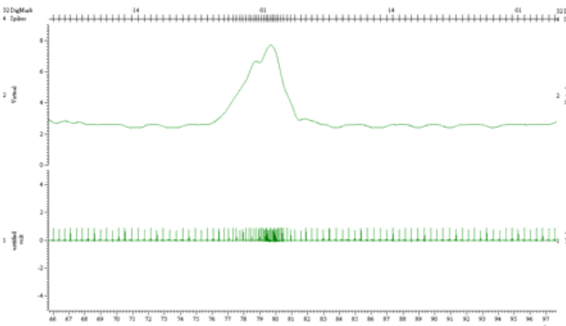
Subject B

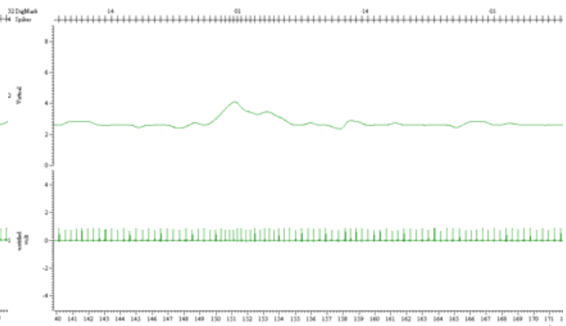




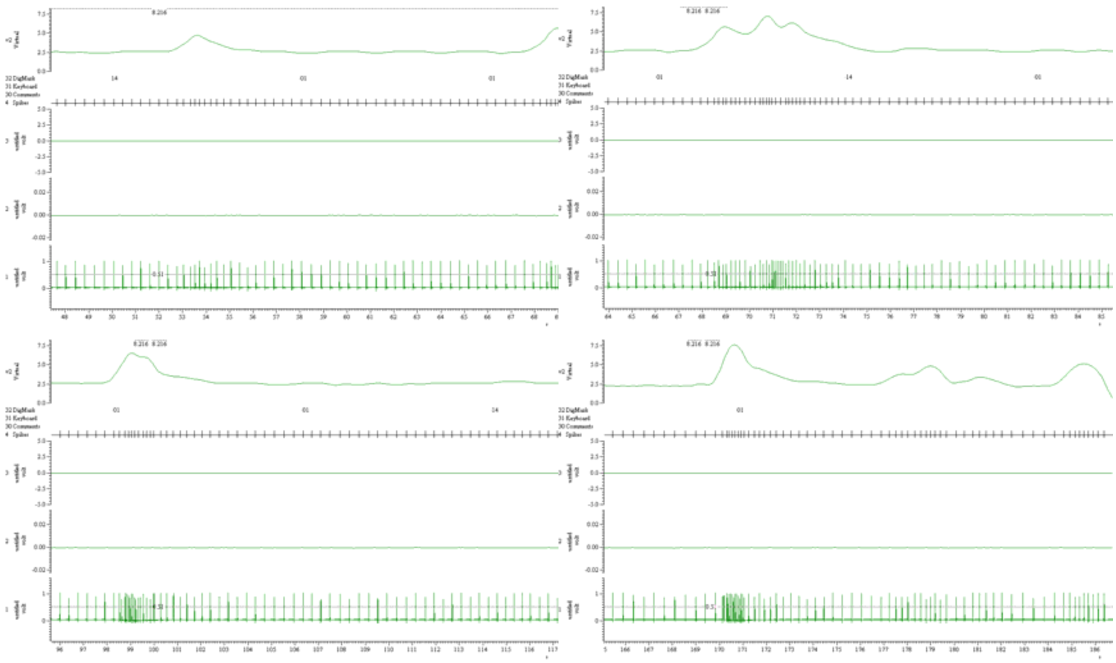


Subject E

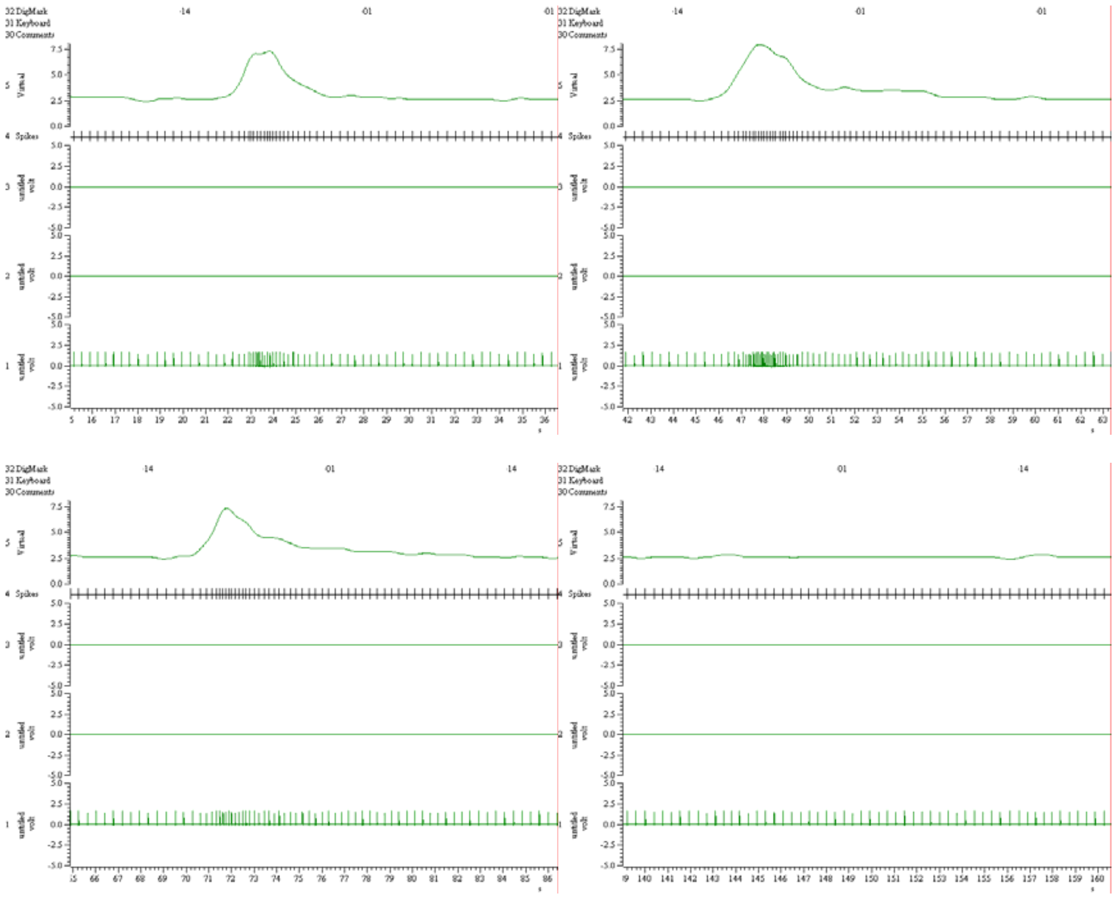




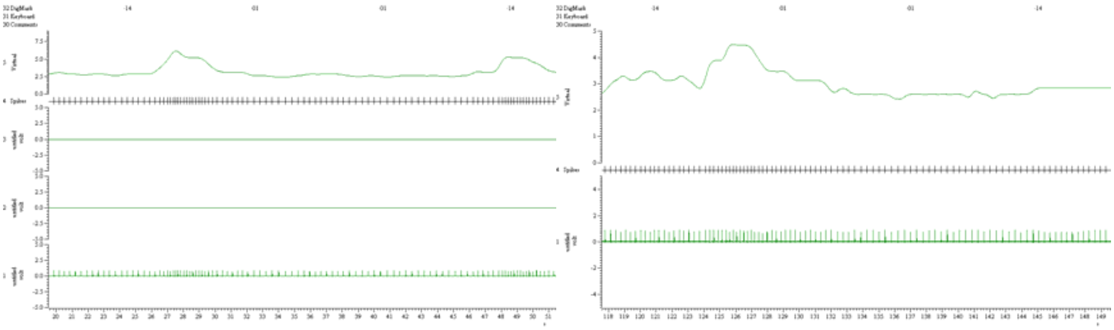
Subject C



Subject D

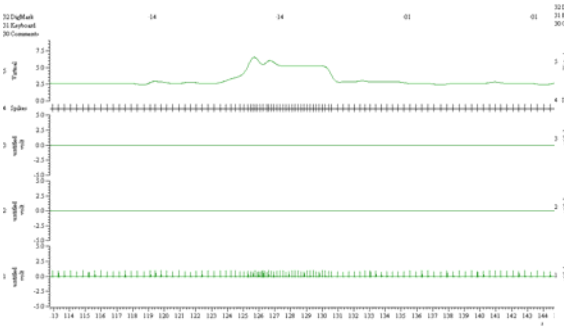


Subject G (spider)

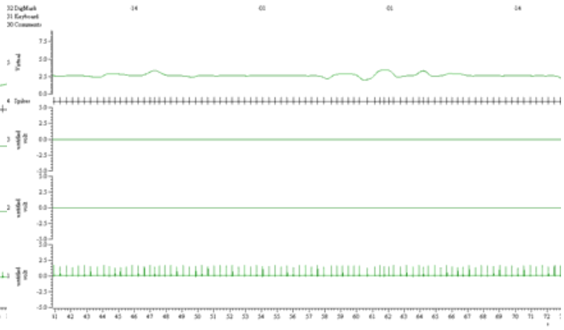


Group two 'face pictures'

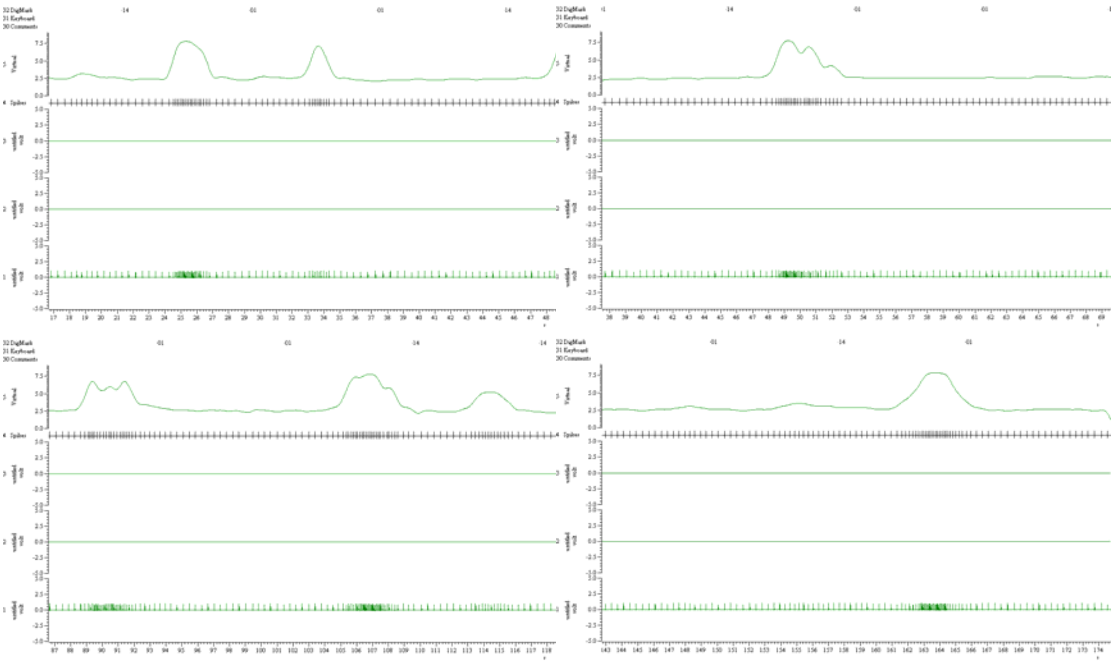
Subject A



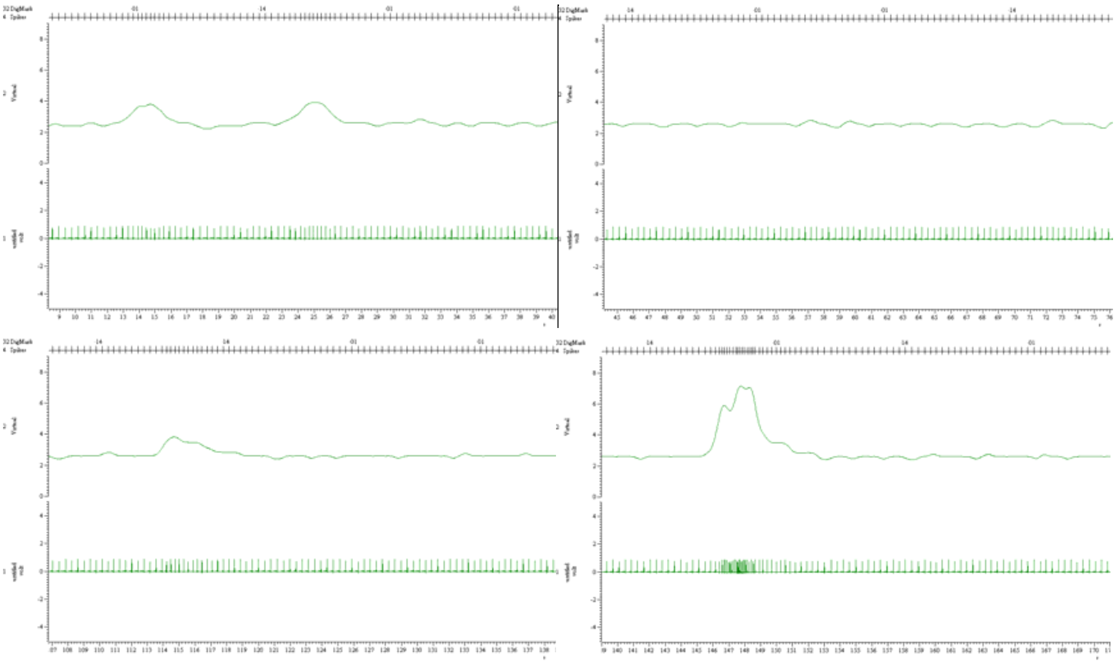
Subject C



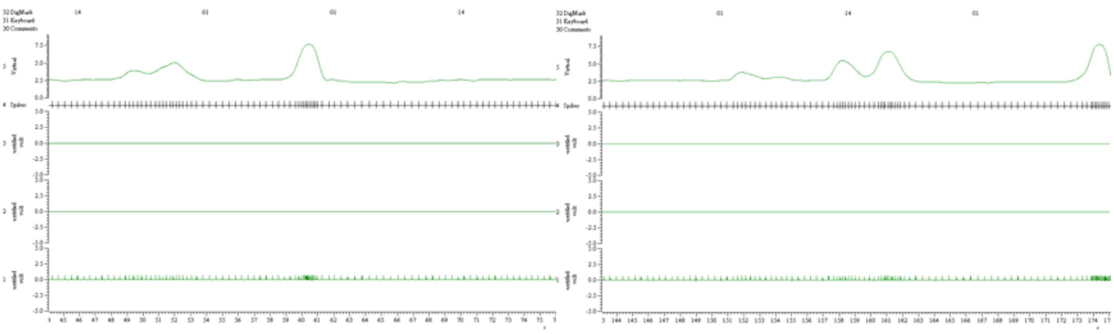
Subject B



Subject I

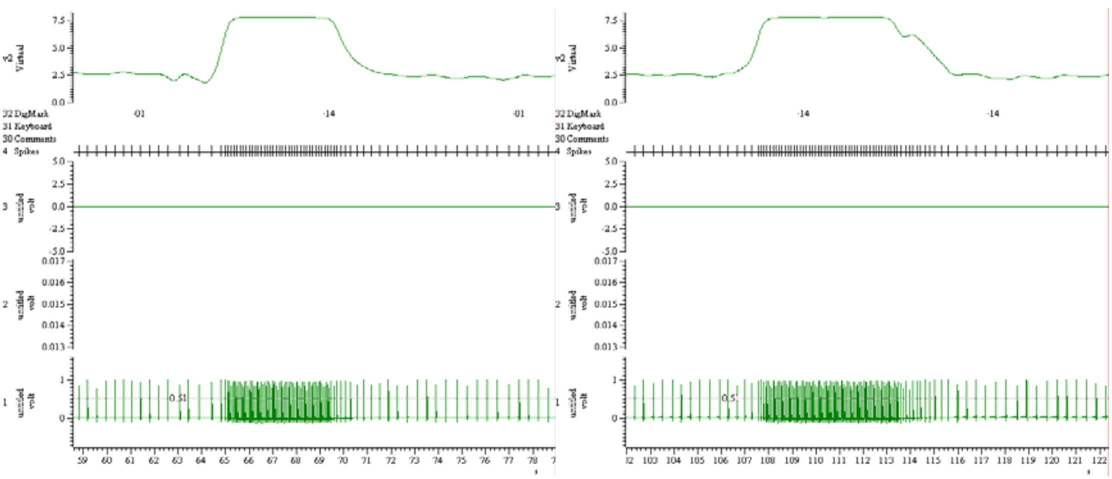


Subject J

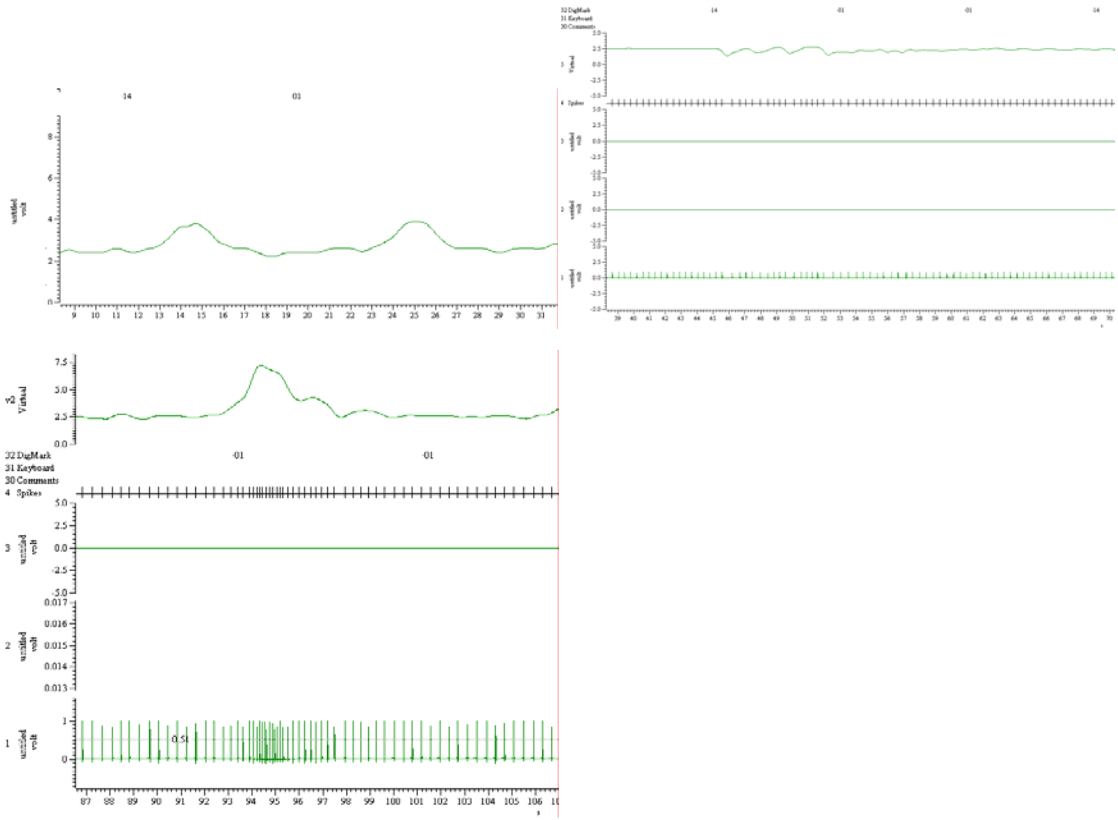


Some other data

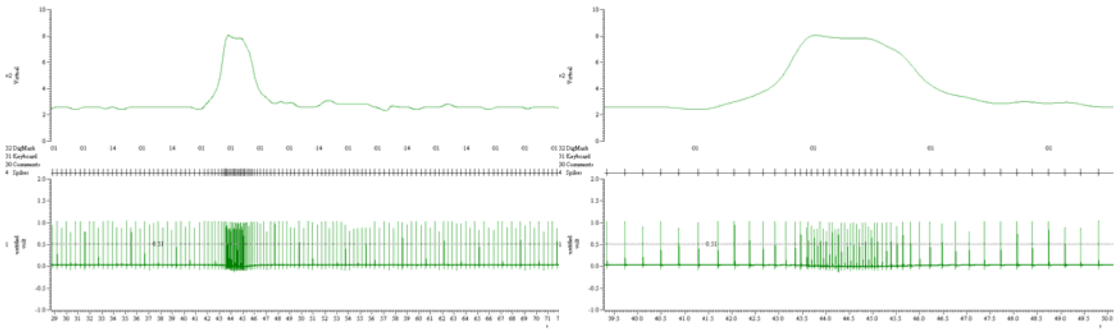
Out of limitation



Noise



Familiar with the test



Appendix F
Related Works

1 Cooperative personality detection from biological motion

Thirty males, who were pre-assessed using reliable and well-validated self-report measures of cooperative disposition, moved boxes for personal benefit (earning £1 per box moved), or for a stranger's benefit (who received £1 per box moved). Motion capture technology was utilised in order to isolate signals of cooperativeness from other signaller characteristics, such as, attractiveness and facial expressions. Seven cameras are used to record movement of 40 reflective markers on each subject's body during box-moving.

Five-second motion capture videos of these tasks were shown to evaluators who rated box-movers' effort. Evaluators, who were blind to condition and cooperative disposition of the signaller, rated those with more cooperative dispositions as exerting relatively high levels of effort in the working-for-stranger condition compared to the working-for-self condition.

The results represent the first clear evidence that cooperative disposition is detectable via bodily motion alone, and suggests that the evolution of human cooperation was facilitated by sophisticated cognitive skills for assessing cooperativeness.

2 Facial expression motion analyses

Facial expression provides cues about emotion, regulates interpersonal behaviour, and communicates psychopathology. Human-observer based methods for measuring facial expression are labour intensive, qualitative, and difficult to standardise across laboratories, clinical settings, and over time. To make feasible more rigorous, quantitative measurement of facial expression in diverse applications, motion capture technology was utilised in order to isolate individual differences that might affect the judgement of observers, such as gender, attractiveness, facial features (nevus, scar). 36 reflective markers are attached on each subject's face and seven cameras are used to record facial expression.

The results show observers, who were blind to condition, can still recognise emotions through simplified facial marker linkage setting. It is a reliable, valid, and efficient measurement of emotion expression assesses at least 12 facial emotional expressions, which can provide new path for both psychology and computer sciences researches.

Appendix G

Publications Derived from the Thesis and Awards

Best Poster Award, Rocky Mountain Bioengineering Symposium, Inc.

RMBS 2007, Denver, Colorado, US