Anthropomorphism of Artificial Agents: A Comparative Survey of Expressive Design and Motion of Virtual Characters and Social Robots

Sébastien Dalibard, Nadia Magnenat-Talmann, Daniel Thalmann

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Abstract Autonomous virtual characters and social robots are meant to interact with humans. They should be able to communicate, express emotions and exhibit personality. Their social skills are highly dependant on their physical design, as well as on their motion capabilities. This paper presents a comparative survey of design choices and motion generation techniques used in the computer animation community and in the robotics community when creating social agents. It addresses the central question of anthropomorphism of artificial agents and discusses the points of convergence and divergence between computer animation and robotics research.

1 Introduction

Creating an autonomous, human-like, social and emotional character can be seen as one of the ultimate goals of research in both virtual humans and social robots. It spans many research fields such as artificial intelligence, computer animation, computer graphics, robotics and human-robot interaction. For recent surveys of research in autonomous virtual characters, one can refer to [1, 2], and for the equivalent in social robotics, to [3, 4]. Throughout this paper, we will speak of *artificial agents* to refer to virtual characters or robots.

In recent years, the computer animation community and the social robotics community have produced a large variety of research work dealing with artificial agents. There are some common difficulties, such as modeling realistic cognitive behaviours of autonomous individuals, and some specific ones like rendering in computer animation, or physical motion control in robotics. This

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paper deals with the two following common issues: (i) choosing the right design for a social and emotional agent; (ii) animating agents in an expressive and believable way.

In the rest of this section, we will first detail commonly desired characteristics of social agents, and then justify our focus on anthropomorphic designs for virtual characters and social robots.

1.1 Social agents

In [3], Fong et al. define socially interactive robots as robots that exhibit the following human social characteristics:

- express and perceive emotions;
- communicate with high-level dialogue;
- recognize models of other agents;
- establish and maintain social relationships;
- use natural cues (gaze, gestures, etc.);
- exhibit distinctive personality and character;
- may learn/develop social competencies

This description can be used to define social agents in virtual worlds as well. Among that list, several abilities are deeply linked to agents' appearance and motion, such as expressing emotion, using natural cues, exhibiting personality or mood. This motivates our survey on how researchers from computer animation and robotics have chosen to address the challenge of designing and animating artificial social agents. The other social characteristics listed here are important fields of research in artificial agents as well, but will not be addressed in this paper.

1.2 Motivations for anthropomorphism

Humans are social agents, interacting with one another. They are attuned to human characteristics, such as human voice [5], appearance of human face [6] and anthropomorphic body motion [7]. For these reasons, artificial agents meant to interact with humans in a human-like way are usually equipped with faces, speech capabilities, and anthropomorphic – or at least zoomorphic – body motion capabilities. The portrayals of android robots and highly realistic virtual humans in popular culture and science-fiction has also driven generations of researchers towards creating anthropomorphic artificial agents, as well as influenced the general public expectations. However, one should note that humanized faces or bodies do not necessarily imply realistic design. Animators and roboticists have explored many different ways of empowering artificial agents with sufficient social cues, in order to interact with people, without following strict realism. We have thus reviewed the different options in social agent design with a focus on realism and proximity to human appearance. Anthropomorphic body design raises the issue of animating it in a believable way. Because the human body is a complex system, it is difficult to use automatic motion generation techniques on it. This has motivated the second part of this paper, which reviews motion generation methods for anthropomorphic characters, as used in computer animation and robotics.

1.3 Outline

Next section (Sect. 2) will list expressive designs used for social agents in computer animation and social robotics, with a particular focus on realism and anthropomorphism. Following this review, we will discuss the points of divergence (Sect. 3) in artificial agent design. We then present a short overview of facial animation techniques (Sect. 4), anthropomorphic motion generation methods (Sect. 5) and of navigation algorithms (Sect. 6) used for autonomous social agents. Sect. 7 summarizes the comparison of motion generation techniques in computer animation and social robotics.

2 Appearance of computer animation characters and social robots

As introduced in the previous section, there are many reasons to design social agents that look like humans. On the other hand, Mori presented in [8] the concept of the *uncanny valley*. It illustrates the fact that humans' sense of familiarity towards a virtual agent is not a monotonic function of the agent's similarity to humans. For unrealistic agents, the sense of familiarity increases with the similarity of the agent to humans. The so-called "valley" is a region populated by highly realistic, although not quite perfect, robots. There, the small imperfections in appearance or motion can become highly repulsive to humans. Mori gives the examples of zombie, corpse or prosthetic hands to illustrate the repulsion. Fig 1 shows the dependency of familiarity to human similarity for still and moving agents.

The conclusion of Mori's study is to aim for robot designs on top of the first peak of the curves shown on Fig. 1, rather than highly realistic ones that have a higher chance to fall into the valley. In this section, we will first show designs of social robots and virtual agents that follow this recommendation. We will then review recent attempts at designing highly realistic characters.

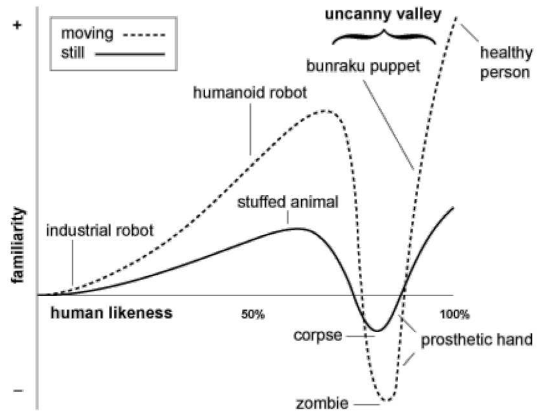

Fig. 1 Mori's "uncanny valley" (from [8]).

2.1 Zoomorphism

Many social robot designs are inspired by living animals, and more specifically household animals. According to [3], this could be an easy way to avoid the uncanny valley, since human-creature relationships are simpler than human-human relationships. Thus, humans' expectations towards robotic pets are lower than towards anthropomorphic robots. The robotic dog Sony AIBO [9] is a well-known commercial example of a social robotic pet. Paro [10] is a robotic seal, intended to be a therapeutic companion for elderly people. Similarly to Paro, Leonardo [11], developed at the MIT Media Lab, is a social robot designed as a stuffed animal. Fig. 2 shows pictures of these different robots.

Fig. 2 Examples of zoomorphic social robots, from left to right: Aibo [9], Paro [10] and Leonardo [11].

In a similar way, people in virtual worlds [12] sometimes choose zoomorphic representations for themselves, proving that non-anthropomorphic virtual characters can be used as social avatars. Fig 3 shows examples of social animal avatars, or furries, used in *second life* [13]. In [14], Zanbaka et al. show through user studies that zoomorphic agents can perform some social tasks as well as anthropomorphic ones.

Fig. 3 Social non-anthropomorphic characters used in *second life* (from [15]).

2.2 Key social attributes of unrealistic characters

In animation, the fact that a character does not need to be realistic to be believable has been studied for a long time [16]. Believability and emotion expression can be achieved by focusing human attention on specific social features, while ignoring overall realism. This approach has been followed for some social robot designs. Scheef et al. describe in [17] how these animation techniques can be used in social robotics. More recently, in [18], Ribeiro et al. explicitely adapt the principles and practices from Disney$^{\text{TM}}$to social robotics. A famous and pioneering example of these principles is Kismet [19], a social robot developed at the MIT AI Lab, which features an unrealistic face, including large expressive eyes, eyebrows and mouth. In a related field, Nowak and Biocca observe in [20] that a virtual avatar's realism does not play a role in the sense of presence when used in a telepresence context. Fig. 4 shows examples of expressive unrealistic animated characters, as well as some robotic equivalents.

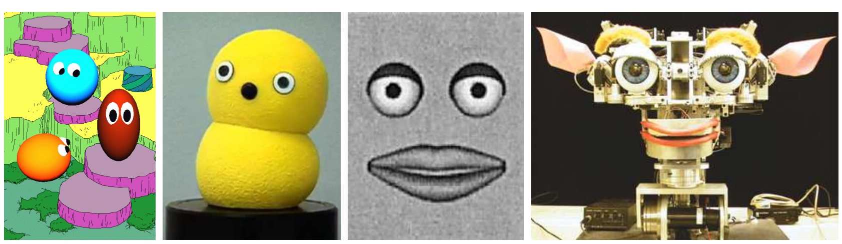

Fig. 4 From left to right: the Woggles, from the Oz project at Carnegie Mellon University [21], Keepon a social robot designed for nonverbal interaction with children [22], the unrealistic avatars used in [20], and Kismet [19].

2.3 Mixed reality agents

Some recent research deals with so-called *mixed reality* agents. In [23], Holz et al. place social agents along Milgram's reality-virtuality continuum [24]. They define mixed reality, or ubiquitous agents as those who appear and interact both in physical and virtual worlds. For a review of how social robotics has started to use mixed reality concepts, one can refer to [25]. When the virtual part of a mixed reality social agent is visually represented, the designs of this virtual representation and of the corresponding physical entity have to converge, for humans to understand that both representations correspond to one single social agent. In [26], Robert and Breazeal refer to these embodied mixed reality agents as *blended reality characters*. [27] showcases a single artificial pet, Pleo, embodied in physical and virtual worlds. Similarly, Robert et al. describe in [28] a gaming platform developed at MIT Media Lab, in which a tele-operated robot, Miso, appears in a 3D virtual environment and in the physical world. Fig. 5 shows the designs of those two agents.

Fig. 5 Mixed reality social agents. On the left, physical and virtual Pleo [27], and on the right physical Miso facing its virtual counterparts [28].

2.4 Anthropomorphism

Disregarding Mori's recommendations, some roboticists and animators have tried to design realistic human-like agents. Improvements in rendering and modelling technologies for virtual humans and on artificial skin and motor control for social robots have recently lead to the creation of highly realistic anthropomorphic agents, both in virtual and physical worlds. Fig. 6 shows some examples of realistic anthropomorphic social robots. Fig. 7 presents some results in human face modeling and rendering from the movie industry. It illustrates the potential for realistic faces in virtual humans.

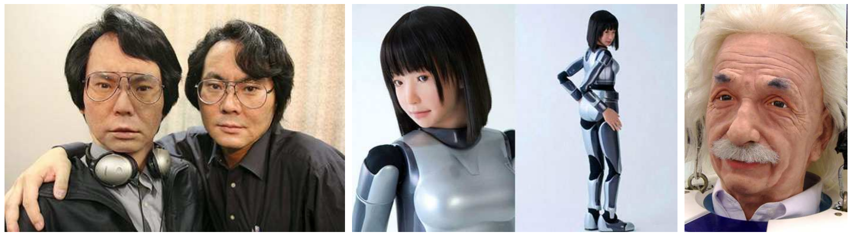

Fig. 6 Anthropomorphic social robots, from left to right: Geminoid HI-1 [29], HRP-4C [30] and Albert HUBO [31].

Fig. 7 Examples of highly realistic human face modeling and rendering for the movie "The matrix reloaded" (from [32]). The face on the right is a synthetic image generated from the model displayed on the left and middle.

2.5 Discussion on the uncanny valley

Having presented a panel of different options in social agent designs, we can look back at Mori's popular uncanny valley theory. Mori's presentation gives some valuable insights on human reaction to social robot design. The idea that a character key social attributes may be enough for some believable social interaction has been long known by animators and proven right in robotics. However, recent studies tend to show that the uncanny valley theory might over-simplify the complexity of human responses to realistic artificial characters. In [39], Hanson et al. show how with different sets of examples, it is possible to manipulate – and even inverse, Mori's curves. Fig. 8 shows the comparison between the original uncanny valley theory curve and chosen different examples. In [40], Seyama et al., based on user studies, confirm the existence of an uncanny valley. Nevertheless, their results show that uncanny feelings only appear when humans are confronted to faces with abnormal features, such as too big eyes. Going from unrealistic to highly realistic characters without generating abnormal features do not result into any uncanny feeling. Their conclusion is that to fully understand the nature of the uncanny valley, researchers need to consider both the realism and the abnormality of artificial characters. In [41], Brenton et al. also call for further research and debate about the uncanny valley theory.

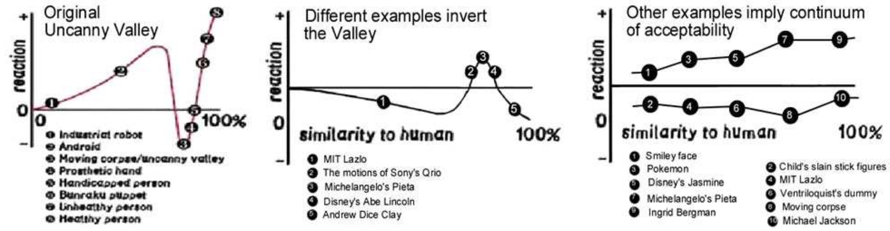

Fig. 8 Mori's original uncanny valley theory, and alternate examples chosen by Hanson et al. (from [39]).

These recent results and discussions underline the fact that while Mori's recommendations are relevant for the entertainment industry, both in animation or robotics, they might be too strict for researchers in social agents. Scientific and technological advances allow us to create more realistic characters, both in virtual and robotic worlds. Only by actually creating them and studying human reaction to these highly realistic characters will we be able to get a more precise understanding of the uncanny feeling that Mori described. In other words, as quoted from [39]: "the science, art and technology of social robots will benefit from the removal of the artificial proscription of the uncanny valley. (Researchers) need to explore the valley". This last advice can be given to researchers in virtual agents as well.

3 Intrinsic differences in design between physical robots and virtual agents

So far, our presentation has shown many similarities between designs of virtual characters and social robots. This section will deal with intrinsic differences that will probably not disappear with scientific and technological progresses.

The main difference between physical social robots and virtual humans is the fact that robots have a physical existence: they are embodied. Embodiment is defined in [33] as "that which establishes a basis for structural coupling by creating the potential for mutual perturbation between system and environment". When considering social robots, i.e. robots that interact with people, it means that the robots are able to physically "perturb" humans. This is known in robotics as physical Human-Robot Interaction (pHRI). While pet robots or robots consisting solely of a face are not directly concerned, fully anthropomorphic social robots, with arms and legs, have to comply with safety rules that used to apply only to industrial robotics. The goal of pHRI is "to design robots that will not harm people, directly or indirectly, in regular operations or in failure" [34]. Different strategies have been explored to design intrinsically safe social robots: by using high bandwidth actuators and sophisticated control techniques [35], using pneumatic control of the robot limbs [36] or tendon/cable driven joints [37, 38]. These complex control issues have repercussions on the design of human size robotics limbs and partly account for the fact that robotics agents are still further away from "cloning" entirely humans, i.e. designing an artificial agent with both realistic human face and body.

Now that we have reviewed different options and trends in artificial agent design, we will present motion generation techniques for these characters. Next section focuses on human-like facial expressions, then Sect. 5 will present whole-body motion generation techniques and Sect. 6 navigation algorithms.

4 Facial expressions

In both social robotics and virtual human research, facial expressions are the primary way to convey the emotions and mental state of virtual agents. This is true for both cartoon-like models and realistic ones. To generate a continuous variety of facial expressions, an emotional state is generally viewed as a point in a high-dimensional emotional space. For example, Ekman et al. present in [42] six common expressions of emotion: fear, disgust, anger, sadness, surprise and joy. Fig. 9, taken from [43], shows a few expressions on two different virtual humans.

Fig. 9 Three different emotional states expressed by two realistic virtual humans (from [43]).

Similar models are used in social robotics, for example on Kismet, which follows the componential model of facial expressions proposed by Smith and Scott in [44]. Fig. 10 illustrates the interpolation based technique used to generate Kismet's facial expression over a three-dimensional space (from [4]).

Besides modeling general emotional spaces, facial animation systems usually also allow animators to define specific deformations if necessary. When defining by hand facial animations, the models used in computer animation and social robotics are different: computer animation uses Facial Animation Parameters (FAP), that represent the displacement of some facial feature points, while social robotics define an animation in a facial joint space. In

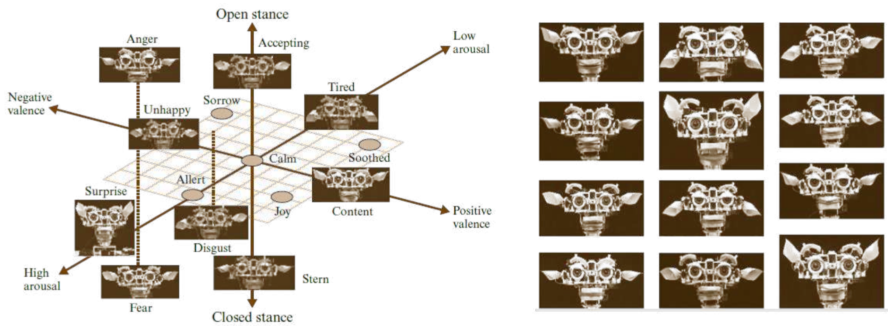

Fig. 10 On the left, the parametric space in which Kismet's expressions are computed, on the right, samples of facial expressions (from [4]).

[45], Kasap et al. have shown how to automatically transfer MPEG-4 FAP(see [46] for a description of the standard) to motor commands for a robotic head, thus allowing similar interaction with both a virtual human and a robotic head. Fig 11 illustrates this convergence.

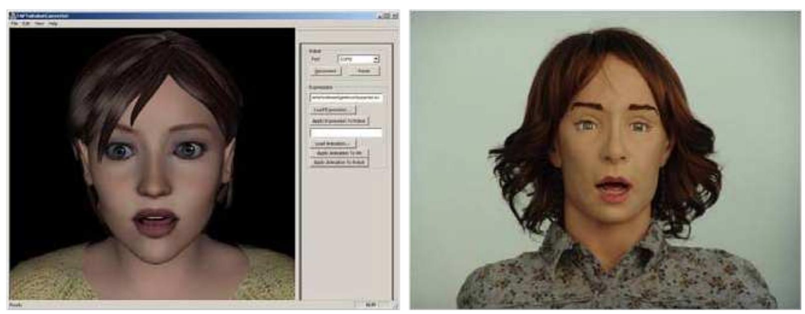

Fig. 11 Social interaction with a virtual human or a social robot. The facial animation parameters defining the virtual human facial expression are automatically translated into motor commands (from [45]).

5 Whole-body motion of anthropomorphic characters

The main difficulty one has to face when animating anthropomorphic characters is the intrinsic complexity of the human kinematic tree. The high number of degrees of freedom of a humanoid figure is a computing challenge when designing and using automatic motion generation techniques. The second important issue is the fact that people are very sensitive to the "naturality" of humanoid motion. While animating artificial agents in a believable way is mandatory for rich social interaction, there is no general quantitative criteria describing how natural a given motion is. To achieve realism, a lot of work has been conducted to base character animation on real physics laws [47], while recent work also tried to import natural motion criteria from human motion observation and neuroscience [48]. For recent comprehensive overviews of anthropomorphic motion generation techniques, one can refer to [49] for the field of computer animation, and [50] for humanoid robots.

This section will present techniques used to generate believable anthropomorphic motion, from the most human guided ones to the most automatic ones: first hand-made animation, then motion capture, automatic motion generation, data driven methods and finally general humanoid motion planning.

5.1 Hand designed animation

The traditional way to create character animations in the computer graphics industry is hand-design by a skillful animator. Typical animation graphical user interfaces (GUI) allow animators to define key-poses by controlling characters in their joint space. To gain efficiency, modern software also provide *pin-and-drag* GUI, where many degrees of freedom are controlled simultaneously by the motion of an end-effector. Fig 12 shows an example of pin-and-drag interface and a resulting motion. These results were taken from [51].

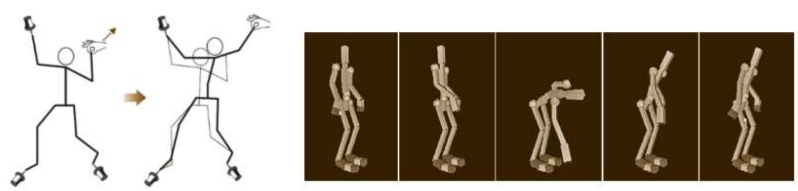

Fig. 12 A pin-and-drag animation GUI, and a result motion of a human character (from [51]).

Using these techniques directly on a humanoid robot is difficult, because of dynamics approximation and potential modeling errors. However, entertainment robotics has the same need for easy-to-use animation software as computer animation industry. Attempts to answer this need have been made recently. For example, Nakaoka et al. propose in [52] a GUI inspired by computer graphics character animation that can handle kinematic and dynamics in real-time. Animators can use this software to create humanoid robot stable animations by inputting key-poses, letting the system compute automatically trajectory adjustment of the interpolated motion.

5.2 Motion capture

Another technique commonly used in the entertainment industry is human motion capture. This technology has been used for a long time by movie studios, and high precision human motion data can now be obtained very easily. When transferring the data to a different human model, the semantics and perception of the motion should be kept, while the exact articular values computed by the motion capture system may need to be changed. This problem is known as motion retargeting and has been investigated for a long time in the computer animation community, see for example [53, 54]. When transferring motion capture data to a humanoid robot, the problem of retargeting has to be addressed, along with dynamic filtering to ensure robot balance. For example, [55, 56] present humanoid robots performing Japanese folk dance (see Fig. 13). The robotic motion has been generated from human motion data.

Fig. 13 Humanoid robot performing a Japanese dance. The motion has been generated by retargeting and dynamically filtering human motion capture data (from [56]).

5.3 Automatic on-line motion generation

The techniques presented so far can be used to generate character animations offline. When controlling autonomous social characters, it is sometime necessary to adapt a motion to constraints whose values are context dependant and cannot be pre-established. If an artificial character is having a conversation with a human, the character might have to shake hands with the human, or gaze at the human face. These behaviours cannot be achieved by playing an offline animation.

In this scope, methods have been developed to generate believable motion not by imitating human, but rather by automatically solving geometric tasks. When the considered system is a pure kinematic representation of the artificial character, this problem is referred to as *inverse kinematics*. Taking into account the high redundancy of the human kinematic tree and the need for natural looking motion, inverse kinematics methods used in robotics or computer animation often propose ways to take care of constraint priority as well as joint limits. In [57], Baerlocher and Boulic propose a numerical prioritized inverse kinematics solver based on task jacobian pseudo inverse. Their solver is used on computer animation problems. In its design and implementation, it is very similar to what has been proposed in the humanoid robotics community, such as [58, 59]. Thanks to the progresses in numerical method implementation, coupled with the improvements in available computing power these methods can now run faster than real-time, solving tens of constraints on a humanoid kinematic model.

On the other hand, the problem of finding forces and torques that solve given geometric or dynamic tasks is referred to as *inverse dynamics* [60]. Recently, the framework of prioritized inverse kinematics has been extended to solve prioritized inverse dynamics problems. Again, solutions have been proposed both in the computer animation community [61] and in the robotics community [62]. As for prioritized inverse kinematics, the fact that the problems are expressed in the same way in both communities has lead researchers to propose very similar solutions, based here on recursive quadratic programming solvers. Current implementations run almost at real-time rate on anthropomorphic models, meaning that it will soon be possible to use prioritized inverse dynamics to generate motion during social interactions.

5.4 Data driven on-the-fly flexible methods

In computer animation, generic data driven motion generation methods also have been researched with success. Based on captured input data, they create new motions in real time by interpolation or extrapolation. They benefit both from the believability of motion capture data and from the generality and adaptability of on-line motion generation techniques. In [63] for example, Glardon et al. use principal component analysis (PCA) to represent motion capture data in a concise way. At run time, their method allows generation of new motion on different character models, as well as smooth transitions between different types of motion. A different approach is presented by Kovar et al. in [64], where a corpus of motion capture data is represented as a *motion graph*, representing pieces of original motion as well as transitions between motions. Nowadays, this kind of mixed approaches are very popular in computer animation. However, as resulting motions would need dynamic filtering before being used on a humanoid robot, it is difficult to use them in real-time in robotics. Sect. 6 will compare in more details how the problem of real-time locomotion pattern generation is solved in robotics and computer animation.

5.5 Motion planning

The methods presented above are not meant to generate collision-free movements. If the environment surrounding a social character (objects, humans, *etc*) is simple enough, collision avoidance can be achieved by integrating unilateral constraints into an inverse kinematics or inverse dynamics problem. On the other hand, if the obstacles are numerous and complex, there is a need for general motion planning. When dealing with a high-dimensional system such as a human body, most exact motion planning algorithms are outperformed by randomized techniques [65]. Randomized motion planning algorithms have been adapted to take into account stability or dynamic constraints in order to compute feasible and collision-free whole-body humanoid motion, see for example [66]. This problem is difficult and computationally expensive. Even recent contributions to this field [67, 68] are not fast enough to guarantee real-time execution, and thus unable to match the human interaction rate required by social applications. In that respect, real-time whole-body collision avoidance for social agents can only be achieved – for now – by the use of heuristics, or within simple enough environments.

6 Locomotion and navigation

Anthropomorphic characters navigate like humans do: by walking. In computer animation, locomotion controllers are often based on pre-obtained animations either by motion capture or hand designed. These animations can usually be adapted to a given model or navigation trajectory in real-time [69]. For example, [70] proposes a locomotion engine capable of on-line extrapolation of experimental locomotion data. Locomotion is a very challenging area in humanoid robotics because of dynamic balance constraints. The dominant methods for bipedal locomotion in the humanoid robotics community are based on the zero-moment point (ZMP) [71] criterion, to ensure that the robot does not fall over while walking. The ZMP depends on whole-body dynamics, and therefore is computationally expensive to control. To achieve real-time control of the ZMP during locomotion, a lot of research propose to follow simplified and overly conservative models, see for example the *cart-table model* presented in [72]. Efficient as they are, these simplifications have the drawback of generating a distinctive “robot walk”, that currently does not match the visual quality of locomotion controllers used in computer animation.

Computing navigation trajectories is a problem shared by both computer animation and robotics communities, and the algorithms to solve it in a general way are quite similar. One relevant example is [73], which applies the computer animation method described in [74] to a humanoid robot problem. When a robot navigates among humans or when a virtual human is part of a virtual crowd [75], some rules about socially acceptable human-agent distance are implemented. These rules are sometimes called “social forces” [76] in crowd simulation, while the social robotics community often speaks of “proxemics”, see for example [77, 78]. Again, their implementation is similar in both community, robot navigation tending to be a little more conservative for safety and comfort reasons.

7 Convergence of motion generation methods?

To summarize the comparison between motion generation methods for virtual characters and social robots, one can say that automatic motion generation methods are roughly the same in both communities. Inverse kinematics has been used for a long time and now runs in real-time on any anthropomorphic character. Robust inverse dynamics, even if it is not as widely available yet, almost runs in real-time on animation and humanoid robotics problems. General motion planning for complex collision avoidance problems is not mature yet for human-machine interaction problems, but its algorithms can be used by both communities.

On the other hand, it is still easier to use, edit or combine motion capture data for computer animation. Because of dynamic constraints, hand design and editing of whole-body animations is a difficult task on a humanoid robot, while it is widely used in computer animation. In the same way, using a corpus of captured data to generate various human-like behaviours, switching smoothly from one to another is an important field of research in computer animation with little equivalent in humanoid robotics. There is no fundamental reason for this to change, as the constraints in both community will stay different. The focus on physical safety in social robotics will not disappear and will force roboticists to generate more conservative motions than computer animators. A relevant example is locomotion. Whereas it seems to be a well-solved problem in computer animation, it is still an open issue in humanoid robotics. As a consequence, currently, most social robots navigating among humans – outside research laboratories, are equipped with wheals rather than legs, see for example [79].

8 Conclusion

In this paper, we have reviewed design choices and motion generation techniques for social agents in virtual worlds and robotic world. Autonomous social robots and virtual humans have a lot in common, even though some of their requirements are different. Our study showed that progresses in material design and motor control for robotics, and modeling and rendering for computer animation have recently permitted to explore highly realistic designs for social agents. Despite the fear of designing uncanny characters, researchers strive to "clone" humans in virtual and robotic world. Realistic human-like characters seem to allow richer social interactions, while they also higher humans' expectations towards artificial cognitive capabilities. This trend is shared by both virtual characters and social robots.

Concerning the autonomous motion capabilities of these agents, deeper differences remain. Some automatic methods are shared among the computer animation and social robotics community, including facial animation techniques, inverse kinematics and dynamics, and navigation strategies. On the other hand, the necessity to consider human and robot safety constraints forces roboticists to be more conservative in the motion they design, as compared to the animation of virtual humans. There is still more room for animators' creativity in virtual worlds than in robotics. The consequence is that social robotics is a little behind in terms of expressive and believable whole-body motions used for social interaction. However, one should note the recent efforts of parts of the humanoid robotics community towards importing interactive motion design tools from computer animation.

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