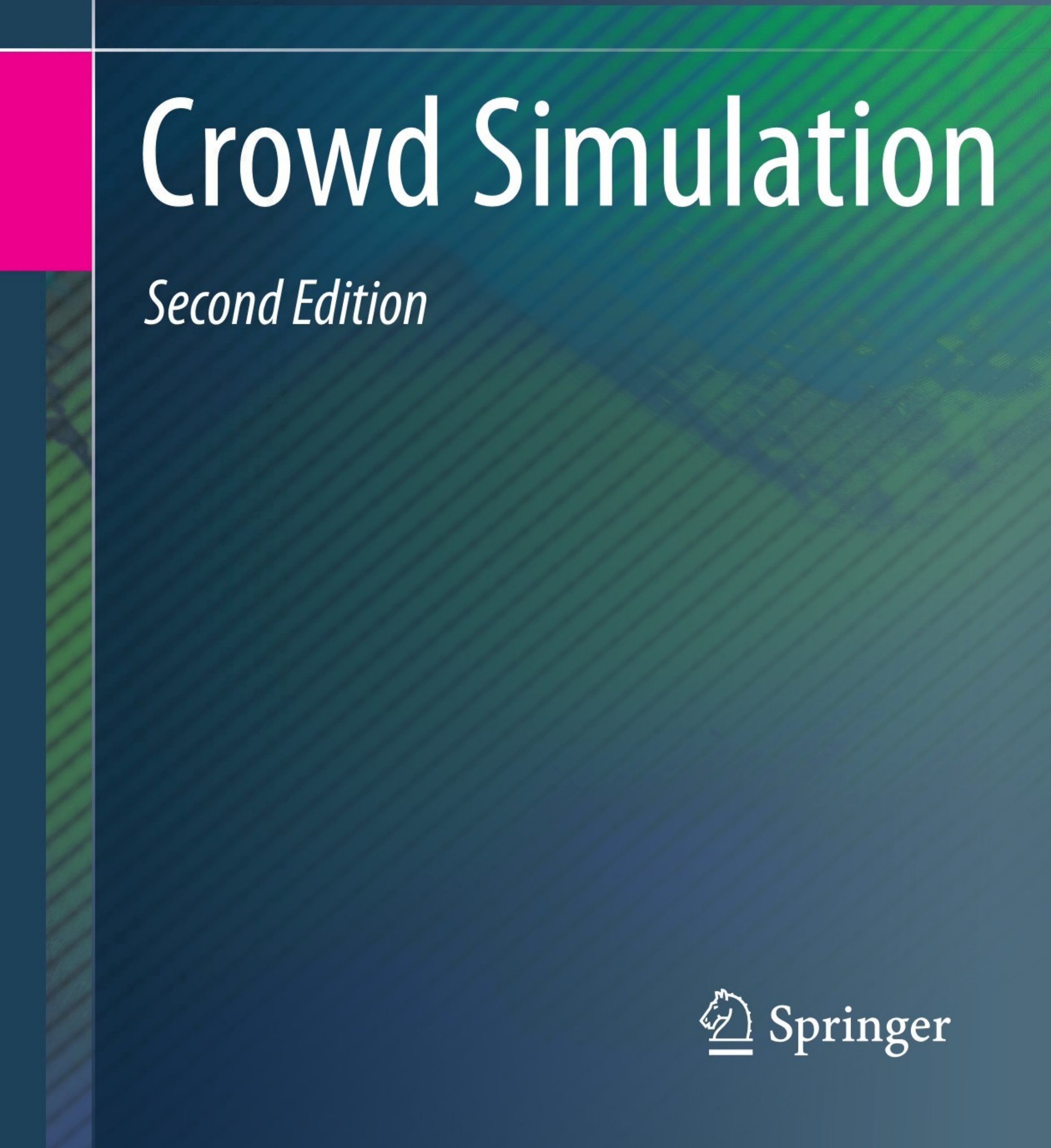
Daniel Thalmann · Soraia Raupp Musse

Crowd Simulation

Second Edition



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Daniel Thalmann
Institute for Media Innovation
Nanyang Technological University
Singapore, Singapore
and
IC-DO
EPFL
Lausanne, Switzerland

Soraia Raupp Musse
Graduate Course in Computer Science
Pontifical Catholic University of Rio Grande do Sul
Porto Alegre, Rio Grande do Sul, Brazil

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(Daniel)
To my beloved wife Nadia and beloved
daughters Melanie, Vanessa, and Sabrina

(Soraia)
To my daughters Marina and Helena and husband Claudio, who enlighten my life.

Preface

This book surveys algorithms and techniques of crowd simulation, and is intended for graduate students, researchers, and professionals. In particular, computer animation researchers, developers, designers, and urban planners will greatly benefit from this book. This second edition presents new techniques and methods proposed since 2007, when we published the first edition of the book.

In 1996, when the authors started researching into crowd simulation, there was very little material available on this topic in the Computer Science literature. Daniel Thalmann supervised Soraia Raupp Musse's PhD thesis in 1997 and since then they have both extensively published in the domain. As a result, many other research groups have also started working in the area. As early pioneers in this research, the authors organized the first workshop on Crowd Simulation (V-Crowds) in 2005 in Lausanne. Today, Daniel Thalmann at the Nanyang Technological University in Singapore and Soraia Raupp Musse at PUCRS in Brazil keep working on crowds. Crowd simulation is now a popular area of research and many techniques have been developed, with the entertainment industry in particular realising the potential of crowd animation. But why is this subject so fascinating?

Aggregated motion is both beautiful and complex to contemplate. Beautiful due to the synchronisation, homogeneity and unity described in this type of motion, and complex because there are many parameters to be handled in order to provide these characteristics. History shows that there has always been interest in understanding and controlling the motion and behaviour of crowds of people. Psychologists and sociologists have studied the behaviours of groups of people for several years, primarily to study the effects that occur when people with the same goal become one entity—a crowd or a mass. When this happens, people can lose their individuality and adopt the behaviour of the crowd entity, behaving in a different way than if they were alone.

The simulation of large crowds in real time requires many instances of similar characters. We need algorithms to allow for each individual in the crowd to be unique. In this book we present some possibilities of character generation and customization. We emphasize population modelling, including shapes, sizes, and colors. We also discuss the importance of adding accessories like bags, glasses, mobile phones, and their impact on animation. This topic is very important in the sense that it provides coherent visualization of populations, as discussed in Chap. 3.

Crowd animation is fundamentally based on the animation of the individual virtual humans. Chapter 4 explains the methods used to animate these individuals especially their locomotion. We explain walking models based on methods like Principal Component Analysis. We also insist on animation variety as it is essential for realistic crowd behaviour.

Certain problems arise only when studying crowds. For instance, crowds have a certain intelligence in collective behaviors, whilst individual intelligence and behaviors can be observed at the same time. Interaction (verbal or non-verbal) among individuals, groups and crowds can be perceived in low density flow of persons. Navigation is probably the most crucial behavior for crowds that can be simulated on a computer. We discuss in detail techniques of path planning including a new hybrid approach between navigation graphs and potential-based methods. Collision avoidance problems related to a large number of individuals in the same place require different strategies in comparison with the methods used to avoid collision between individuals. In real life people can stop because they don't have enough space to walk, and unfortunately they can even die because the high density of individuals in the same space. We also introduced a new Section on gaze attention as we think it is important that individuals seem aware of the environment and other people. The relationship between people and the environment is given by some aspects such as culture, knowledge, experience, memory, etc. Computers should generate behavior patterns to achieve such levels of interaction. Chapters 4 and 5 present some aspects to contribute with this discussion.

Moreover, a crowd is not only a large group of individuals, but can also be formed by groups which in turn are related to individuals. In addition other levels of behaviour can exist when treating crowds in this hierarchical structure. The group behaviours can be used to specify the way a group moves, behaves and acts. Individual abilities can also be required in order to improve the autonomy and intelligence of crowds, for instance perception, emotional status, memory, communication, etc. However, when we consider thousands of individuals, these complex behaviours cannot be provided individually due to the hardware constraints and to computational time rates. A further problem relates to how to improve the intelligence and provide autonomy to scalable crowds, in real-time systems. In Chap. 6 we discuss the integration of crowd simulation and computer vision to bring new ground in this discussion.

Chapter 7 discusses techniques for rendering crowds especially when real time simulations are required to populate virtual environments in virtual reality systems. We introduce a complete pipeline for fast rendering including levels of details, deformable and non-deformable characters as well as impostors. A new section explains how crowd patches can be used to generate unlimited populated environments.

Crowd simulation is dependent on the environment, which means that this environment has to be modelled in a specific way. Chapter 8 discusses how to model such informed environments including terrains and buildings. It also shows how ontologies can play an essential role in crowd simulation.

The last Chapter is dedicated to applications and case studies like crowds in Virtual heritage and Safety systems. We have added a new Section on the revival of the Pompeii city and another on immersion in crowds.

Some crowd requirements along with strategies and techniques that can be adopted to deal with these, are described in this book. Some of the topics presented are related to population modelling, virtual human animation, computer vision techniques focusing on crowd control and crowd rendering, and some applications are analysed.

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Contents

Chapter 1
Introduction

Animation of crowds finds applications in many areas, including entertainment (e.g., animation of large numbers of people in movies and games), creation of immersive virtual environments, and evaluation of crowd management techniques (for instance, simulation of the flow of people leaving a football stadium after a match). Several techniques for modeling crowd dynamics already exist, but important aspects of crowd simulation have remained open for further research. Specifically, (i) the existing approaches are often focused on panic situations rather than usual (normal) behavior, in which people in the crowd have goals to seek; (ii) behaviors are usually individual and groups or families are not treated; (iii) separate pre-programmed techniques are usually needed to calibrate the movement of people in low or high density crowds, and to affect local and global motion planning; and (iv) existing crowd-modeling methods are often complex, and they require careful parameter tuning to obtain visually convincing results [TM07, UdHCMT06].

In the past two decades researchers from a broad range of fields such as architecture [SOHTG99, PT01, TP02], computer graphics [Rey87, HB94, BG96, MT01, TLC02b, UT02, BMB03], physics [HM95, HFV00, FHV02], robotics [PJ01], safety science [TM95a, Sti00, Sim04], training systems [Bot95, Wil95, VSMA98], and sociology [CPC92, TSM99, JPvdS01] have been creating simulations involving collections of individuals. Nevertheless, despite the apparent breadth of the crowd simulation research basis, interdisciplinary exchange of ideas is rare; researchers in one field are usually not very aware of works done in other fields.

In order to have a persuasive application using crowds in virtual environments, various aspects of the simulation have to be addressed, including behavioral animation, environment modeling, and crowd rendering. If there is no satisfactory rendering, even the best behavior model will not be very convincing. If there is no good model of a behavior, even a simulation using the best rendering method will look dumb after only a few seconds. If there is no appropriate model of the environment, characters will not behave believably, as they will perform actions in the wrong places, or not perform at all.

Most approaches were application-specific, focusing on different aspects of the collective behavior, using different modeling techniques. Employed techniques

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range from those that do not distinguish individuals such as flow and network models in some of the evacuation simulations [TT92], to those that represent each individual as being controlled by more or less complex rules based on physical laws [HIK96, HFV00], chaos equations [SKN98], behavioral models in training systems [Wil95], or sociological simulations [JPvdS01].

We can distinguish two broader areas of crowd simulations. The first one is focusing on a *realism of behavioral aspects* with usually simple 2D visualizations like evacuation simulators, sociological crowd models, or crowd dynamics models. In this area, a simulated behavior is usually from a very narrow, controlled range (for example, people just flying to exit or people forming ring crowd structures) with efforts to quantitatively validate correspondence of results to real-world observations of particular situations [TM95b]. Ideally, a simulation's results would then be consistent with data sets collected from field observations or video footage of real crowds either by human observers [SM99] or by some automated image processing method [MVCA98, CYC99]. Visualization is used to help understand simulation results, but it is not crucial. In most cases, a schematic representation, with crowd members represented by colored dots, or sticky figures, is enough, sometimes even preferable as it allows highlighting important information.

In the second area, a main goal is *high-quality visualization* (for example, in movie productions and computer games), but usually the realism of the behavior model is not the priority. What is important is a convincing visual result, which is achieved partly by behavior models, partly by human intervention in the production process. A virtual crowd should both look good and be animated in a believable manner, the emphasis of the research being mostly on rendering and animation methods. Crowd members are visualized as fully animated three-dimensional figures that are textured and lit to fit into the environment [DHOO05]. Here, behavior models do not necessarily aim to match quantitatively the real world; their purpose is more to alleviate the work of human animators, and to be able to respond to inputs in case of interactive applications.

1.1 Requirements and Constraints for Crowd Modeling

Real-time crowds bring different challenges compared with the systems either involving a small number of interacting characters (for example, the majority of contemporary computer games), or non-real-time applications (as crowds in movies, or visualizations of crowd evacuations after off-line model computations). In comparison with single-agent simulations, the main conceptual difference is the *need for efficient variety management* at every level, whether it is visualization, motion control, animation, or sound rendering. As everyday experiences hint, virtual humans composing a crowd should look different, move different, react different, sound different, and so forth. Even if assuming perfect simulation of a single virtual human would be possible, creating a simulation involving multiple such humans would still be a difficult and tedious task. Methods easing control of many characters are needed; however, such methods should still preserve the ability to control individual agents. Moreover, behaviors should be coherent in comparison with reality.

In comparison with non-real-time simulations, the main technical challenge is *increased demand on computational resources* whether it is general processing power, graphics performance, or memory space. One of the foremost constraining factors for real-time crowd simulations is crowd rendering. Fast and scalable methods both to compute behavior, able to take into account inputs not known in advance, and to render large and varied crowds, are needed. While non-real-time simulations are able to take advantage of knowing a full run of the simulated scenario (and therefore, for example, can run iteratively over several possible options selecting the globally best solution), real-time simulations have to react to the situation as it unfolds in the moment.

1.2 Crowd Simulation Areas

In order to create a full simulation of the crowd in the virtual environment, many issues have to be solved. The areas of relevance for crowd simulation and some associated questions include:

Generation of virtual individuals: How to generate a heterogeneous crowd? How to create a population with desired distribution of features [GKMT01, SYCGMT02, BBOM03]? Chapter 3 discusses some of these aspects.

Crowd animation: How should virtual entities move around and avoid collisions with both a static environment and dynamic objects How can a group move in a coordinated manner? [ALA*01, GKM*01, AMC03, LD04, BBM05]? Chapter 4 presents some techniques to solve these problems.

Crowd behavior generation: How should a virtual crowd respond to changes in their surroundings? How should agents respond to behaviors of other agents? What is an appropriate way of modeling perception for many agents [Rey87, TT94, HB94, BCN97, BH97, Rey99, Mus00, UT02, NG03]? Chapter 5 describes some methods used for solving these questions.

Interaction with virtual crowds: How and which information should be exchanged from real people to control virtual humans? What is the most efficient metaphor to direct crowds of virtual extras [FRMS*99, UdHCT04]? Chapter 6 presents some discussion concerning these aspects.

Virtual crowd rendering: How to display many animated characters, quickly? How to display a wide variety of appearances [ABT00, LCT01, TLC02a, WS02, dHSMT05, CM05]? Chapter 7 explains some details concerning crowd rendering.

Integration of crowds in virtual environments: Which aspects of the environment need to be modeled? Which representation of environmental objects is best suited for fast behavior computation [FBT99, BLA02a, KBT03, LMA03, PVM05]? Chapter 8 presents some discussion about these aspects.

Many of these aspects are to a greater or lesser extent intertwined. For example, efficiency of rendering constrains the possible variety of behaviors and appearances; higher-level behavior generation controls lower-level motion systems, but the behavior should also respond appropriately to collisions encountered while moving; the behavior model affects interaction possibilities; the environment representation affects possible behaviors; relating real and virtual humans allows handling of more complex behavior and environment representations and so on.

This book aims to discuss some of these aspects, organized in nine chapters, also including a state-of-the-art and presentation of some relevant applications developed by the authors.

References

[ABT00] AUBEL A., BOULIC R., THALMANN D.: Real-time display of virtual humans: Levels of detail and impostors. *IEEE Transactions on Circuits and Systems for Video Technology 10*, 2 (2000), 207–217.

[ALA*01] ASHIDA K., LEE S., ALLBECK J., SUN H., BADLER N., METAXAS D.: Pedestrians: Creating agent behaviors through statistical analysis of observation data. In *Proceedings of IEEE Computer Animation* (Seoul, Korea, 2001), pp. 84–92.

[AMC03] ANDERSON M., MCDANIEL E., CHENNEY S.: Constrained animation of flocks. In *Proc. ACM SIGGRAPH/Eurographics Symposium on Computer Animation (SCA'03)* (2003), pp. 286–297.

[BBM05] BRAUN A., BODMAN B. J., MUSSE S. R.: Simulating virtual crowds in emergency situations. In *Proceedings of ACM Symposium on Virtual Reality Software and Technology—VRST 2005* (Monterey, California, USA, 2005), ACM, New York.

[BBOM03] BRAUN A., BODMANN B. E. J., OLIVEIRA L. P. L., MUSSE S. R.: Modelling individual behavior in crowd simulation. In *Proceedings of Computer Animation and Social Agents 2003* (New Brunswick, USA, 2003), IEEE Computer Society, Los Alamitos, pp. 143–148.

[BCN97] BOUVIER E., COHEN E., NAJMAN L.: From crowd simulation to airbag deployment: Particle systems, a new paradigm of simulation. *Journal of Electrical Imaging 6*, 1 (January 1997), 94–107.

[BG96] BOUVIER E., GUILLOTEAU P.: Crowd simulation in immersive space management. In *Proc. Eurographics Workshop on Virtual Environments and Scientific Visualization'96* (1996), Springer, London, pp. 104–110.

[BH97] BROGAN D., HODGINS J.: Group behaviors for systems with significant dynamics. *Autonomous Robots 4* (1997), 137–153.

[BLA02a] BAYAZIT O. B., LIEN J.-M., AMATO N. M.: Better group behaviors in complex environments using global roadmaps. In *Proc. Artificial Life'02* (2002).

[BMB03] BRAUN A., MUSSE S., BODMANN L. O. B.: Modeling individual behaviors in crowd simulation. In *Computer Animation and Social Agents* (New Jersey, USA, May 2003), pp. 143–148.

[Bot95] BOTTACI L.: A direct manipulation interface for a user enhanceable crowd simulator. *Journal of Intelligent Systems 5*, 4 (1995), 249–272.

[CM05] COURTY N., MUSSE S. R.: Simulation of large crowds in emergency situations including gaseous phenomena. In *Proceedings of Computer Graphics International 2005* (Stony Brook, USA, 2005), IEEE Computer Society, Los Alamitos, pp. 206–212.

[CPC92] McPhail C., Powers W., Tucker C.: Simulating individual and collective actions in temporary gatherings. *Social Science Computer Review 10*, 1 (Spring 1992), 1–28.

[CYC99] Chow T. W. S., Yam J. Y.-F., Cho S.-Y.: Fast training algorithm for feedforward neural networks: Application to crowd estimation at underground stations. *Artificial Intelligence in Engineering 13* (1999), 301–307.

[DHOO05] Dobbyn S., Hamill J., O'Conor K., O'Sullivan C.: Geopostors: A real-time geometry/impostor crowd rendering system. In *SI3D'05: Proceedings of the 2005 Symposium on Interactive 3D Graphics and Games* (New York, NY, USA, 2005), ACM, New York, pp. 95–102.

[dHSMT05] de Heras P., Schertenleib S., Maïm J., Thalmann D.: Real-time shader rendering for crowds in virtual heritage. In *Proc. 6th International Symposium on Virtual Reality, Archaeology and Cultural Heritage (VAST 05)* (2005).

[FBT99] Farenc N., Boulic R., Thalmann D.: An informed environment dedicated to the simulation of virtual humans in urban context. In *Eurographics'99* (Milano, Italy, 1999), Brunet P., Scopigno R. (Eds.), vol. 18, pp. 309–318.

[FHV02] Farkas I., Helbing D., Vicsek T.: Mexican waves in an excitable medium. *Nature 419* (2002), 131–132.

[FRMS*99] Farenc N., Raupp Musse S., Schweiss E., Kallmann M., Aune O., Boulic R., Thalmann D.: A paradigm for controlling virtual humans in urban environment simulations. *Applied Artificial Intelligence Journal—Special Issue on Intelligent Virtual Environments 14*, 1 (1999), 69–91.

[GKM*01] Goldenstein S., Karavelas M., Metaxas D., Guibas L., Aaron E., Goswami A.: Scalable nonlinear dynamical systems for agent steering and crowd simulation. *Computers & Graphics 25*, 6 (2001), 983–998.

[GKMT01] Goto T., Kshirsagar S., Magnenat-Thalmann N.: Automatic face cloning and animation. *IEEE Signal Processing Magazine 18*, 3 (2001), 17–25.

[HB94] Hodgins J., Brogan D.: Robot herds: Group behaviors for systems with significant dynamics. In *Proc. Artificial Life IV* (1994), pp. 319–324.

[HFV00] Helbing D., Farkas I., Vicsek T.: Simulating dynamical features of escape panic. *Nature 407* (2000), 487–490.

[HIK96] Hosoi M., Ishijima S., Kojima A.: Dynamical model of a pedestrian in a crowd. In *Proc. IEEE International Workshop on Robot and Human Communication'96* (1996).

[HM95] Helbing D., Molnar P.: Social force model for pedestrian dynamics. *Physical Review E 51* (1995), 4282–4286.

[JPvdS01] Jager W., Popping R., van de Sande H.: Clustering and fighting in two-party crowds: Simulating the approach-avoidance conflict. *Journal of Artificial Societies and Social Simulation 4*, 3 (2001).

[KBT03] Kallmann M., Bieri H., Thalmann D.: Fully dynamic constrained Delaunay triangulations. In *Geometric Modelling for Scientific Visualization* (2003), Brunnett G., Hamann B., Mueller H., Linsen L. (Eds.), Springer, Berlin, pp. 241–257.

[LCT01] Loscos C., Chrysanthou Y., Tecchia F.: Real-time shadows for animated crowds in virtual cities. In *Proceedings of the ACM Symposium on Virtual Reality Software and Technology (VRST'01)* (New York, 2001), Shaw C., Wang W. (Eds.), ACM, New York, pp. 85–92.

[LD04] Lamarche F., Donikian S.: Crowds of virtual humans: A new approach for real time navigation in complex and structured environments. *Computer Graphics Forum 23*, 3 (September 2004), 509–518.

[LMA03] Loscos C., Marchal D., Meyer A.: Intuitive crowd behavior in dense urban environments using local laws. In *Proc. Theory and Practice of Computer Graphics (TPCG'03)* (2003).

[MT01] Musse S. R., Thalmann D.: A hierarchical model for real time simulation of virtual human crowds. *IEEE Transactions on Visualization and Computer Graph-*

ics 7, 2 (April–June 2001), 152–164.

[Mus00] MUSSE S. R.: *Human Crowd Modelling with Various Levels of Behaviour Control*. PhD thesis, EPFL, Lausanne, 2000.

[MVCA98] MARANA A. N., VELASTIN S. A., COSTA L. F., LOTUFO R. A.: Automatic estimation of crowd density using texture. *Safety Science 28*, 3 (1998), 165–175.

[NG03] NIEDERBERGER C., GROSS M.: Hierarchical and heterogenous reactive agents for real-time applications. *Computer Graphics Forum 22*, 3 (2003), 323–331. (Proc. Eurographics'03.)

[PJ01] MOLNAR P., STARKE J.: Control of distributed autonomous robotic systems using principles of pattern formation in nature and pedestrian behavior. *IEEE Transactions on Systems, Man and Cybernetics B 31*, 3 (June 2001), 433–436.

[PT01] PENN A., TURNER A.: Space syntax based agent simulation. In *Pedestrian and Evacuation Dynamics* (2001), Schreckenberg M., Sharma S. (Eds.), Springer, Berlin.

[PVM05] PAIVA D. C., VIEIRA R., MUSSE S. R.: Ontology-based crowd simulation for normal life situations. In *Proceedings of Computer Graphics International 2005* (Stony Brook, USA, 2005), IEEE Computer Society, Los Alamitos.

[Rey87] REYNOLDS C. W.: Flocks, herds and schools: A distributed behavioral model. In *Proceedings of the Annual Conference on Computer Graphics and Interactive Techniques (SIGGRAPH'87)* (New York, NY, USA, 1987), ACM, New York, pp. 25–34.

[Rey99] REYNOLDS C. W.: Steering behaviors for autonomous characters. In *Game Developers Conference* (San Jose, California, USA, 1999), pp. 763–782.

[Sim04] Simulex, 2004. Evacuation modeling software, product information, http://www.ies4d.com.

[SKN98] SAIWAKI N., KOMATSU T., NISHIDA S.: Automatic generation of moving crowds in the virtual environments. In *Proc. AMCP'98* (1998).

[SM99] SCHWEINGRUBER D., MCPHAIL C.: A method for systematically observing and recording collective action. *Sociological Methods & Research 27*, 4 (May 1999), 451–498.

[SOHTG99] SCHELHORN T., O'SULLIVAN D., HAKLAY M., THURSTAIN-GOODWIN M.: Streets: An agent-based pedestrian model. In *Proc. Computers in Urban Planning and Urban Management* (1999).

[Sti00] STILL G.: *Crowd Dynamics*. PhD thesis, Warwick University, 2000.

[SYCGMT02] SEO H., YAHIA-CHERIF L., GOTO T., MAGNENAT-THALMANN N.: Genesis: Generation of e-population based on statistical information. In *Proc. Computer Animation'02* (2002), IEEE Press, New York.

[TLC02a] TECCHIA F., LOSCOS C., CHRYSANTHOU Y.: Image-based crowd rendering. *IEEE Computer Graphics and Applications 22*, 2 (March–April 2002), 36–43.

[TLC02b] TECCHIA F., LOSCOS C., CHRYSANTHOU Y.: Visualizing crowds in real-time. *Computer Graphics Forum 21*, 4 (December 2002), 753–765.

[TM95a] THOMPSON P., MARCHANT E.: A computer-model for the evacuation of large building population. *Fire Safety Journal 24*, 2 (1995), 131–148.

[TM95b] THOMPSON P., MARCHANT E.: Testing and application of the computer model 'simulex'. *Fire Safety Journal 24*, 2 (1995), 149–166.

[TM07] THALMANN D., MUSSE S. R.: *Crowd Simulation*. Springer, London, 2007.

[TP02] TURNER A., PENN A.: Encoding natural movement as an agent-based system: An investigation into human pedestrian behaviour in the built environment. *Environment and Planning B: Planning and Design 29* (2002), 473–490.

[TSM99] TUCKER C., SCHWEINGRUBER D., MCPHAIL C.: Simulating arcs and rings in temporary gatherings. *International Journal of Human–Computer Systems 50* (1999), 581–588.

[TT92] TAKAHASHI T. S. H.: Behavior simulation by network model. *Memoirs of Kougakuin University 73* (1992), 213–220.

[TT94] TU X., TERZOPOULOS D.: Artificial fishes: Physics, locomotion, perception, behavior. In *Computer Graphics (ACM SIGGRAPH'94 Conference Proceedings)* (Orlando, USA, July 1994), vol. 28, ACM, New York, pp. 43–50.

[UdHCMT06] ULICNY B., DE HERAS CIECHOMSKI P., MUSSE S. R., THALMANN D.: EG 2006 course on populating virtual environments with crowds. In *Eurographics 2006* (2006), ch. State-of-the-art: Real-time crowd simulation.

[UdHCT04] ULICNY B., DE HERAS CIECHOMSKI P., THALMANN D.: Crowdbrush: Interactive authoring of real-time crowd scenes. In *Proc. ACM SIGGRAPH/Eurographics Symposium on Computer Animation (SCA'04)* (2004), pp. 243–252.

[UT02] ULICNY B., THALMANN D.: Towards interactive real-time crowd behavior simulation. *Computer Graphics Forum 21*, 4 (Dec. 2002), 767–775.

[VSMA98] VARNER D., SCOTT D., MICHELETTI J., AICELLA G.: UMSC small unit leader non-lethal trainer. In *Proc. ITEC'98* (1998).

[Wil95] WILLIAMS J.: *A Simulation Environment to Support Training for Large Scale Command and Control Tasks*. PhD thesis, University of Leeds, 1995.

[WS02] WAND M., STRASSER W.: Multi-resolution rendering of complex animated scenes. *Computer Graphics Forum 21*, 3 (2002), 483–491. (Proc. Eurographics'02.)

Chapter 2
State-of-the-Art

One of the largest areas where crowd behaviors have been modeled is the domain of safety science and architecture with the dominant application of crowd evacuation simulators. Such systems model movements of a large number of people in usually closed and well-defined spaces like inner areas of buildings [TM95a, BBM05], subways [Har00], ships [KMKWS00], or airplanes [OGLF98]. Their goal is to help designers to understand the *relation between the organization of space and human behavior* [OM93].

The most common use of evacuation simulators is the modeling of crowd behavior in case of forced evacuation from a confined environment due to some threat like fire or smoke. In such a situation, a number of people have to evacuate the given area, usually through a relatively small number of fixed exits. Simulations are trying to help answer questions like: Can the area be evacuated within a prescribed time? Where do the holdups in the flow of people occur? Where are the likely areas for a crowd surge to produce unacceptable crushing pressure [Rob99]? The most common modeling approach in this area is the use of cellular automata serving both as a representation of individuals and as a representation of the environment.

Simulex [TM95a, TM95b] is a computer model simulating the escape movement of persons through large, geometrically complex building spaces defined by 2D floor plans and connecting staircases. Each individual has attributes such as position, body size, angle of orientation, and walking speed. Various algorithms as distance mapping, way finding, overtaking, route deviation, and adjustment of individual speeds due to proximity of crowd members are used to compute egress simulation, where individual building occupants walk toward and through the exits.

G. Still developed a collection of programs named *Legion* for simulation and analysis of the crowd dynamics in evacuation from constrained and complex environments like stadiums [Sti00]. Dynamics of crowd motion is modeled by mobile cellular automata. Every person in the crowd is treated as an individual, calculating its position by scanning its local environment and choosing an appropriate action.

Helbing et al. [HM95, HFV00, WH03] proposed a model based on physics and sociopsychological forces in order to describe the human crowd behavior in panic situations. The model is set up by a particle system where each particle i of mass m_i

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has a predefined speed v_i^0, i.e., the desired velocity, in a certain direction $\mathbf{e}_i^0$ to which it tends to adapt its instantaneous velocity $\mathbf{v_i}$ within a certain time interval τ (for 1st term of Eq. (2.1)). Simultaneously, the particles try to keep a velocity-dependent distance from other entities j and walls w controlled by interaction forces $\mathbf{f}_{ij}$ and $\mathbf{f}_{iw}$ (second and third terms of Eq. (2.1)), respectively. The change of velocity with time t is given by the dynamical equation:

$$m_i \frac{dv_i}{dt} = F_i^{(H)} = m_i \frac{v_i^0 \mathbf{e}_i^0 - \mathbf{v}_i(t)}{\tau_i} + \sum_{j \neq i} \mathbf{f}_{ij} + \sum_{w} \mathbf{f}_{iw} \tag{2.1}$$

Braun et al. [BMB03, BBM05] extended the Helbing Model ($F_i^{(H)}$) in order to deal with different individuals and group behaviors, and also with complex environments. In this work, the agents' population can be composed heterogeneously by individuals with different attributes.

This chapter presents several works on crowd domain, as crowd dynamics and simulation.

2.1 Crowd Dynamics

The behavior of real crowds was analyzed in [Hen71, Hen74, Fru71, Hel97, Sti00]; results of their analysis provide a useful reference for simulation and animation of crowds. Two important aspects that guide the motion of real people are: goal seeking, reflecting the target destination of each individual; and the least-effort strategy, reflecting the tendency of people to reach the goal along a path requiring the least effort [Sti00]. According to these strategies, people travel along smooth trajectories, since this requires less energy than frequent changes of direction or speed. In particular, adjustments of direction and speed, required to avoid collisions, are minimized. Further consequences of the least-effort strategy are the formation of lanes and the speed reduction effect. The first term refers to the tendency of people walking in the same directions to reduce their effort by closely following each other, while the second one refers to the reduction of speed in dense crowds.

The concept of personal space, the subject of study of interpersonal interactions in a spatial context (proxemics) [Hal59], also plays an important role in population dynamics. Personal space can be thought of as an area with invisible boundaries, surrounding each individual, which should not be penetrated by other individuals in order for interpersonal interactions to occur comfortably. The size of this zone depends on the environment as well as the people culture, and decreases as the crowd density gets higher. In the context of simulations, the personal space determines the minimum distance that should be maintained among the agents.

2.2 Sociological Models of Crowds

Despite being a field primarily interested in studying collective behavior, only a relatively small number of works on crowd simulations have been done in sociology.

McPhail et al. [CPC92] studied individual and collective actions in temporary gatherings. Their model of the crowd is based on perception control theory [Pow73] where each separate individual is trying to control his or her experience in order to maintain a particular relationship to others: in this case it is a spatial relationship with others in a group. The simulation program *GATHERING* graphically shows movement, milling, and structural emergence in crowds. The same simulation system was later used by Schweingruber [Sch95] to study the effects of reference signals common to coordination of collective behavior and by Tucker et al. [TSM99] to study formation of arcs and rings in temporary gatherings.

Jager et al. [JPvdS01] modeled clustering and fighting in two-party crowds. A crowd is modeled by a multi agent simulation using cellular automata with rules defining approach–avoidance conflict. The simulation consists of two groups of agents of three different kinds: hardcore, hangers-on, and bystanders, the difference between them consisting in the frequency with which they scan their surroundings. The goal of the simulation was to study effects of group size, size symmetry, and group composition on clustering, and “fights”.

2.3 Crowd Simulation

Virtual crowds are usually modeled as collections of interacting agents, although treating a crowd as a continuum (for example, obeying laws of fluid dynamics) is also possible [TCP06]. In *behavioral models*, movements of a group of agents are an emergent property of individual agents, which are both influenced by and influencing their neighbors. These individual behaviors are defined using sets of simple goal-oriented rules, such as “move with the average speed of your neighbors” or “keep an optimal distance to your neighbors”. Behavioral animation was pioneered by Reynolds [Rey87], who simulated flocks of birds and schools of fish assuming that each agent has direct access to the motion characteristics (position and velocity) of other agents. Tu and Terzopoulos [TT94] improved the conceptual realism of this work by endowing artificial fish with synthetic vision and perception of the environment. Both the original results of Reynolds and the models of Tu and Terzopoulos were confined to relatively small, low-density groups of animals.

To control human crowds, Musse and Thalmann [MT01] proposed a hierarchical crowd organization with groups of different levels of autonomy. In a related work, Ulicny and Thalmann [UT01] proposed a model that provided agent control at the level of an individual, a group, and the crowd.

The rules governing the movements of agents in behavioral models may be viewed as an abstract representation of the “psychology” of modeled individuals. In contrast, in *force-field models*, interactions among agents (in this case, often referred to as particles) are based on analogies with physics. For example, Bouvier et al. [BCN97] modeled individuals in a high-density crowd as charges moving in electric fields. Helbing et al. [HM97, HFV00] introduced abstract attraction and repulsion forces to simulate groups of people in panic situations. Braun et al. [BMB03] extended this model by endowing agents with individual characteristics and including the concept of groups, which improved the realism of simulations.

In *data-driven models*, the motion of real crowds is used to calibrate simulations. For example, Musse et al. [MJJB07] used computer vision techniques to track individual agents in images obtained using a video camera, then applied the resulting statistics to drive a physically-based simulator, while Lee et al. [LCHL07] used aerial images for a similar purpose. Lerner and collaborators [LCL07] proposed a model for collision avoidance using a manually-built database of videos of pedestrians. The goal of this work was to improve the realism of collisions treatment using real-world data.

Hybrid methods have also been proposed. For instance, the approaches presented by [PAB07] and [vdBPS*08] integrate behavioral and force-fields techniques in order to improve crowd control, aiming to minimize the drawbacks of both technologies. However, the negative aspect of these methods is the increase in complexity of the implementation.

Each category of models presents a tradeoff. Behavioral models are suited for an individualized specification of agents, but global crowd control is more difficult to achieve because of the emergent character of the motions. In contrast, force-field models offer good global crowd control in high-density situations, but tend to generate less realistic motions of individual characters, which reflect their simplistic physical basis. Finally, data-driven models make it possible to improve the realism of simulations, but the acquisition and interpretation of real-life data is often difficult. This sets the stage for our method, in which crowds of agents obeying simple behavioral rules can be globally controlled and relatively realistic motions can be obtained without tedious parametrization as emergent properties of the model.

2.4 Behavioral Animation of Groups and Crowds

Human beings are arguably the most complex known creatures, therefore they are also the most complex creatures to simulate. A behavioral animation of human (and humanoid) crowds is based on foundations of group simulations of much more simple entities, notably flocks of birds [Rey87, GA90] and schools of fish [TT94]. The first procedural animation of flocks of virtual birds was shown in the movie by Amkraut, Girard, and Karl called Eurhythmy, for which the first concept [AGK85] was presented at The Electronic Theater at SIGGRAPH in 1985 (final version was presented at Ars Electronica in 1989). The flock motion was achieved by a global vector force *field* guiding a flow of flocks [GA90].

In his pioneering work, Reynolds [Rey87] described a distributed behavioral model for simulating aggregate motion of a flock of birds. The technical paper was accompanied by an animated short movie called “Stanley and Stella in: Breaking the Ice” shown at the Electronic Theater at SIGGRAPH’87. The revolutionary idea was that a complex behavior of a group of actors can be obtained by simple local rules for members of the group instead of some enforced global condition. The flock is simulated as a complex particle system, with the simulated birds (called boids) being the particles. Each boid is implemented as an independent agent that navigates according to its local perception of the environment, the laws of simulated physics, and the set of behaviors. The boids try to avoid collisions with one another and with other objects in their environment, match velocities with nearby flock mates, and move toward a center of the flock. The aggregate motion of the simulated flock is the result of the interaction of these relatively simple behaviors of the individual simulated birds. Reynolds later extended his work by including various steering behaviors as goal seeking, obstacle avoidance, path following, or fleeing [Rey99], and introduced a simple finite-state machines behavior controller and spatial queries optimizations for real-time interaction with groups of characters [Rey00].

Tu and Terzopoulos proposed a framework for animation of artificial fishes [TT94]. Besides complex individual behaviors based on perception of the environment, virtual fishes have been exhibiting unscripted collective motions as schooling and predator evading behaviors analogous to flocking of boids. An approach similar to boids was used by Bouvier et al. [BG96, BCN97] to simulate human crowds. They used a combination of particle systems and transition networks to model crowds for the visualization of urban spaces. At the lower level, attractive and repulsive forces, analogous to physical electric ones, enable people to move around the environment. Goals generate attractive forces, obstacles generate repulsive force fields. Higher level behavior is modeled by transition networks with transitions depending on time, visiting of certain points, changes of local population densities, and global events.

Brogan and Hodgins [HB94, BH97] simulated group behaviors for systems with significant dynamics. Compared to boids, a more realistic motion is achieved by taking into account physical properties of motion, such as momentum or balance. Their algorithm for controlling the movements of creatures proceeds in two steps: first, a perception model determines the creatures and obstacles visible to each individual, and then a placement algorithm determines the desired position for each individual given the locations and velocities of perceived creatures and obstacles. Simulated systems included groups of one-legged robots, bicycle riders, and point-mass systems. Musse and Thalmann [Mus00, MT01] presented a hierarchical model for real-time simulation of virtual human crowds. Their model is based on groups, instead of individuals: groups are more intelligent structures, where individuals follow the groups specification. Groups can be controlled with different levels of autonomy: guided crowds follow orders (as go to a certain place or play a particular animation) given by the user in run-time; programmed crowds follow a scripted behavior; and autonomous crowds use events and reactions to create more complex behaviors. The environment comprises a set of interest points, which signify goals and way points; and a set of action points, which are goals that have some actions associated. Agents move between way points following Bezier curves.

Recently, another work was exploring group modeling based on hierarchies. Niederberger and Gross [NG03] proposed an architecture of hierarchical and heterogeneous agents for real-time applications. Behaviors are defined through specialization of existing behavior types and weighted multiple inheritance for creation of new types. Groups are defined through recursive and modulo based patterns. The behavior engine allows for the specification of a maximal amount of time per run in order to guarantee a minimal and constant frame rate.

Ulicny and Thalmann [UT01, UT02] presented a crowd behavior simulation with a modular architecture for multiagent system allowing autonomous and scripted behavior of agents supporting variety. In their system, the behavior is computed in layers, where decisions are made by behavioral rules and execution is handled by hierarchical finite-state machines. Most recently, a real-time crowd model based on continuum dynamics has been proposed by [TCP06]. In their model, a dynamic potential field integrates global navigation with moving obstacles, efficiently solving for the motion of large crowds without the need for explicit collision avoidance. Perceived complexity of the crowd simulation can be increased by using levels of detail (LOD). O'Sullivan et al. [OCV*02] described a simulation of crowds and groups with level of details for geometry, motion, and behavior. At the geometrical level, subdivision techniques are used to achieve smooth rendering LOD changes. At the motion level, the movements are simulated using adaptive levels of detail. Animation subsystems with different complexities, as a keyframe player or a real-time reaching module, are activated and deactivated based on heuristics. For the behavior, LOD is employed to reduce the computational costs of updating the behavior of characters that are less important. More complex characters behave according to their motivations and roles, less complex ones just play random keyframes. The behavior of autonomous characters has been widely studied in the area of crowd simulation during the past few years. Most crowd simulation models obtain plausible macroscopic behaviors but have a limited ability to manage behavioral autonomy. Decision systems are generally applied to simple reactive behaviors such as collision avoidance because of the computational cost of implementing existing rational models with a crowd of virtual people. To address these challenges, Paris and Donikian [PD09] proposed a crowd simulation cognitive model that can be used to develop complex goal-oriented behaviors for numerous virtual people in real time. The model integrates a decision process that provides a full bidirectional link between four layers, biomechanical, reactive, cognitive, and rational (see Allen Newell's Unified Theories of Cognition). Each layer informs the layer directly above it of specific information on imposed constraints and controls the layer directly underneath it. Each layer is built independently and exchanges only a set of identified data.

Shao and Terzopoulos artificial life approach [ST07] integrates motor, perceptual, behavioral, and cognitive components within a comprehensive model of pedestrians as individuals. They claimed that the model can yield results of unprecedented fidelity and complexity for fully autonomous multi-human simulation in a large urban environment. Following Tu and Terzopoulos [TT94], they adopted a bottom-up strategy that uses primitive reactive behaviors as building blocks that in turn support more complex motivational behaviors, all controlled by an action selection mechanism. The behavioral model consists of basic reactive behaviors, navigational behaviors, motivational behaviors, mental state and action selection. Realistic behavioral modeling, whose purpose is to link perception to appropriate actions, is a big challenge in the case of autonomous virtual humans. Even for 3 pedestrians, the complexity of any substantive behavioral repertoire is high. Except computer graphics, many relevant studies in psychology, ethology, artificial intelligence, robotics, and artificial life are devoted to this subject. With these behavioral models, virtual humans can be interacted with in some situations. Here the behavioral models are limited to the applications of pedestrians. The cognitive and perceptual components are also helpful in improving the plausibility of crowd simulation, e.g. the problem of local collision can be avoided by behavioral modeling. However, complex behavioral models are usually too expensive to be used in real-time massive crowd simulation. For the interactive crowd simulation, a behavioral model is necessary, and we have to face the tradeoff between precision of the behavioral the model and the computing time.

2.5 Crowd Management Training Systems

The modeling of crowds has also been essential in police and military simulator systems used for training in how to deal with mass gatherings of people.

CACTUS [Wil95] is a system developed to assist in planning and training for public order incidents such as large demonstrations and marches. The software designs are based on a world model in which crowd groups and police units are placed on a digitized map and have probabilistic rules for their interactive behavior. The simulation model represents small groups of people as discrete objects. The behavioral descriptions are in the form of a directed graph where the nodes describe behavioral states (to which correspond actions and exhibited emotions) and transitions represent plausible changes between these states. The transitions depend on environmental conditions and probability weightings. The simulation runs as a decision making exercise that can include pre-event logistic planning, incident management, and debriefing evaluation.

Small Unit Leader Non-Lethal Training System [VSMA98] is a simulator for training U.S. Marines Corps in decision making with respect to the use of nonlethal munitions in peacekeeping and crowd control operations. Trainees learn rules of engagement, the procedures for dealing with crowds and mobs, and the ability to make decisions about the appropriate level of force needed to control, contain, or disperse crowds and mobs. Crowds move within a simulated urban environment along instructor-predefined pathways and respond both to actions of a trainee and to actions of other simulated crowds. Each crowd is characterized by a crowd profile—series of attributes like fanaticism, arousal state, prior experience with nonlethal munitions, or attitude toward Marines. During an exercise, the crowd behavior computer model operates in real time and responds to trainee actions (and inactions) with appropriate simulated behaviors such as loitering, celebrating, demonstrating, rioting, and dispersing according to a set of Boolean relationships defined by experts.

2.6 Group Behavior in Robotics and Artificial Life

Researchers working in the field of artificial life are interested in exploring how group behavior emerges from local behavioral rules [Gil95]. Software models and groups of robots were designed and experimented with in order to understand how complex behaviors can arise in systems guided by simple rules. The main source of inspiration is nature, where, for example, social insects efficiently solve problems such as finding food, building nests, or division of labor among nestmates by simple interacting individuals without an overseeing global controller. One of the important mechanisms contributing to a distributed control of the behavior is *stigmergy*, indirect interactions among individuals through modifications of the environment [BDT99].

Dorigo introduced *ant systems* inspired by behaviors of real ant colonies [Dor92]. Ant algorithms have been successfully used to solve a variety of discrete optimization problems including the traveling salesman problem, sequential ordering, graph coloring, or network routing [BDT00]. Besides insects, groups of more complex organisms such as flocks of birds, herds of animals, and schools of fish have been studied in order to understand principles of their organization. Recently, Couzin et al. presented a model of how animals that forage or travel in groups can make decisions even with a small number of informed individuals [CKFL05].

Principles from biological systems were also used to design behavior controllers for autonomous groups of robots. Mataric studied behavior-based control for a group of robots, experimenting with a herd of 20 robots whose behavioral repertoire included safe wandering, following, aggregation, dispersion, and homing [Mat97]. Molnar and Starke have been working on assignment of robotic units to targets in a manufacturing environment using a pattern formation inspired by pedestrian behavior [PJ01]. Martinoli applied swarm intelligence principles to autonomous collective robotics, performing experiments with robots that were gathering scattered objects and cooperating to pull sticks out of the ground [A.99]. Holland and Melhuish experimented with a group of robots doing sorting of objects based on ant behaviors where ants sort larvae and cocoons [HM99]. In an interesting work using a robot to control animal behavior, Vaughan et al. developed a mobile robot that gathers a flock of real ducks and maneuvers them safely to a specified goal position [VSH*00].

2.7 Environment Modeling for Crowds

2.7.1 Environment Models

Environment modeling is closely related to behavioral animation. The purpose of the models of the environment is to facilitate simulation of entities dwelling in their surrounding environments. Believability of virtual creatures can be greatly enhanced if they behave in accordance with their surroundings. On the contrary, the suspense of disbelief can be immediately destroyed if they perform something not expected or not permitted in the real world, such as passing through the wall or walking on water. The greatest efforts have therefore been directed to representations and algorithms preventing forbidden behaviors from occurring; until quite recently the two major artificial intelligence issues concerning game development industry were collision avoidance and path-planning [Woo99, DeL00]. The majority of the population in the developed world lives in cities; it is there that most human activities take place nowadays. Accordingly, most of the research has been done for modeling of virtual cities. Farenc et al. [FRMS*99] introduced an informed environment dedicated to the simulation of virtual humans in the urban context. The informed environment is a database integrating semantic and geometrical information about a virtual city. It is based on a hierarchical decomposition of an urban scene into environment entities, like quarters, blocks, junctions, streets, and so on. Entities can contain a description of the behaviors that are appropriate for agents located on them; for example, a sidewalk tells that it should be walked on, or a bench tells that it should be sat on. Furthermore, the environment database can be used for a path-finding that is customized according to the type of client requesting the path, so that, for example, a pedestrian will get paths using sidewalks, but a car will get paths going through roads.

Another model of a virtual city for a behavioral animation was presented by Thomas and Donikian [TD00]. Their model is designed with the main emphasis on traffic simulation of vehicles and pedestrians. The environment database is split into two parts—a hierarchical structure containing a tree of polygonal regions, similar to the informed environment database; and a topological structure with a graph of a road network. Regions contain information on directions of circulation, including possible route changes at intersections. The agents then use the database to navigate through the city. In a recent work, Sung et al. [SGC04] presented a new approach to control the behavior of a crowd by storing behavioral information into the environment using structures called situations. Compared with previous approaches, environmental structures (situations) can overlap; behaviors corresponding to such overlapping situations are then composed using probability distributions. Behavior functions define probabilities of state transitions (triggering motion clips) depending on the state of the environment features or on the past state of the agent.

2.7.2 Path Planning

Path planning is an important and challenging task in crowd simulation, which helps each agent to find the path to its individual goal. The path planning problem has been widely explored by the robotics community. Although the multiple-agent path planning has been addressed for cooperative tasks of multiple robots, it is still a challenge to solve the path planning problem for large crowds in real time, especially for large-scale crowds. Because the methods used for robots are usually exponential in the number of robots, which are too expensive to be adopted in crowd simulation.

Benefit from motion planning algorithms in robotics, geometric representation of probabilistic roadmaps (PRM) can also be used for path planning in crowd simulation. PRM was applied to solve the problem of determining a collision-free path between a starting configuration of the robot and a goal configuration [KSLO96]. Arikan et al. [ACF01] used the visibility graph for the path planning for large numbers of virtual agents. The visibility graph connects together vertices of the environment if and only if they see each other. The PRM-based approaches were improved by being integrated with other techniques [BLA02a, BLA02b, SKG05]. Kallmann et al. [KBT03] proposed a fast path-planning algorithm based on a fully dynamic constrained Delaunay triangulation. Bayazit et al. [BLA02a] used global roadmaps to improve group behaviors in geometrically complex environments. Groups of creatures exhibited behaviors such as homing, goal searching, covering, or shepherding, by using rules embedded both in individual flock members and in roadmaps. Tang et al. [TWP03] used a modified A* algorithm working on a grid overlaid over a height-map generated terrain. Other approaches of geometric representation of environments have been explored specially for the path planning of multi-agent systems. Lamarche and Donikian [LD04] built an accurate hierarchical topological structure from geometric database of a virtual environment. They performed the following steps for the final navigation: spatial subdivision, topology abstraction, roadmap generation, and triangulation construction. It is reported that this approach can allow the navigation of several hundreds of agents in real time. Kamphuis and Overmars defined a walkable corridor that ensured sufficient clearance to allow a given group of units to pass [KO04]. The Voronoi diagram can be used to subdivide a free space based on a set of points, from which edges are generated to produce the roadmap. Sud et al. [SAC*08] proposed a new data structure based on Voronoi diagrams, which is used to perform path planning and proximity computations for each agent in real time. Inspired from Voronoi diagrams, Pettré et al. [PLT05, PdHCM*06, PGT08] presented a novel approach to automatically extract a topology from a scene geometry and handle path planning using a navigation graph. The environment is usually discretized into a fine regular grid in the potential field method. Kapadia et al. [KSHF09] introduced a discretization method of egocentric fields with variable resolution information representation. Helbing's social force model [HM95] is one of the most influential models in agent-based motion planning. This model considers each agent as a particle subject to long-ranged forces induced by the social behavior of individuals. The movement of agents can be described with a main function which determines the physical and social forces, similar to Newtonian mechanics. The social force model is capable of describing the self-organization of several observed collective effects of pedestrian behavior. Nevertheless, due to lack of anticipation and pre-diction, the characters interact when they get sufficiently close. Consequently, the resulting motions tend to look unnatural and contain undesirable oscillations. The problem becomes more obvious in large and cluttered environments. This model was extended to achieve more realistic crowd behaviors [HBJW05, LKF05]. Karamouzas et al. [KHBO09] introduced the evasive force to improve the social force model. Their approach is based on the hypothesis that an individual adapts its route as early as possible, trying to minimize