AGENT-BASED MODEL FOR MICROSIMULATION OF LARGE SCAL PEDESTRIAN CROWD

RABIAA CHIGHOUB, FOUDIL CHERIF

Department of Computer Sciences,
Lesia Laboratory, Biskra University
Biskra, Algeria
CH_Rabiaa1@yahoo.fr, foud_cherif@yahoo.fr

ABSTRACT

In this paper, we addresses the development of agent-based model for real-time simulation of large scale pedestrian crowds.

Its focus is to produce realistic pedestrian navigation and path planning within the environment whilst maintaining real time frame rates.

The main assumption of this work is that the navigational behaviors of pedestrians are modeled realistically through hierarchical motions in multi layers of path planning, local path determination and locomotion. The inter-relationship between these layers is defined.

Our method can be easily combined with most current local collision-avoidance methods and we use two such methods as examples to highlight the potential of our approach. .

We also demonstrate some simulation results of Guarder to show that it could efficiently simulate life like crowd behaviors in a large-scale and complex environment.

KEYWORDS: Real time simulation, crowd behavior, micro-scale representation, multi-layered framework.

1 INTRODUCTION

Simulating the movement of pedestrian crowd is a field of research that receives growing interest during the last years. This is due to various reasons:

First of all, the wide range of its potential applications to the study the dynamics of human individuals in a crowd with high densities including crowd management, and especially building evacuation analysis [1, 16, 25]. More light-hearted application is the planning and designing of public facilities such as shopping malls, airports and transfer stations, and other large scale public buildings. Shedding light on the self-organization processes and the formation of fascinating patterns in crowd dynamics especially in critical circumstances, such as lane formation in bidirectional flows, behavior near corners, and strips in crossing flows [19]. And finally [22], despite the significant advancement and progress in the animation and rendering techniques and hardware that allow fast and realistic results in crowd simulations.

In the last decade, several behavior models have been proposed specifically for animating large crowds, and many efforts have been made to modulate intuitive navigation control and real time crowd behavior simulation.

The perspective requirement of real time crowd simulation is to design an efficient model that should be able to simulate a large number of virtual pedestrians exhibiting behaviors consistent with an observed large crowd of humans in the real world.

Generally, the crowds, in turn, seen as a large number of people in a given area, who also show very complex behaviors in a diverse set of specific situations. Each individual in a crowded areas is able to act in its unique way and move with its preferred speed to reach its personal destination in space, avoiding obstacles. People need to move and interact with the environment and other characters in a seemingly intelligent way. Additionally, it needs to continuously interact with the surroundings and other pedestrians in a seemingly intelligent way tending to produce emergent behaviors in large and dynamic environments.

The main focus of this work is to develop a system able to handle all these features of a virtual pedestrian in a natural looking manner. This is a challenging problem, as visual fidelity, the enormous complexity of behaviors, and the size of crowd all have a strong impact on the available computational resources of realistic simulation process.

To overcome these conflicting goals, we design a scalable simulation to handle at least several hundreds or even thousands of pedestrians, running in real-time, particularly with respect to the complexity of the environment and the realism of behaviors required by the crowd, we investigate to find a good balance between visual credibility of complex crowd behaviors and computational requirements, where the behaviors of human crowd can be viewed on a two different level of detail: from the chaotic, fluctuating interactions between individual objects on the finest scales, to the coherent aggregate flow of the system on the largest scales.

We evaluate this approach experimentally along two criteria: the impact of our methodology on the computational resources, and an estimate of the dissimilarity between a full microscopic simulation and a simulation with our methodology. Finally we discuss the results obtained and propose enhancements for future works.

The remainder of this paper is organized as follows. First, the background and related work on the simulation behavior of virtual crowd in computer graphics are introduced to give the readers some background information. Then, section 3 proposes the key ideas as well as the new framework for simulating the movement of crowds. The macroscopic and behavioral models are introduced in section 4. We describe a strategy that allows dealing with the interaction and the online-switching of simulation models for crowd behaviors studying. Section 5 demonstrates the simulation results in several common scenarios. Finally, the conclusion section outlines the directions for future work.

2 RELATED WORK

In this section, we briefly review some prior work on modeling crowd movements. We also refer the reader to comprehensive surveys [16], [23], and present a broad review below.

From a conceptual point of view, the models of pedestrian crowd simulation can be classified into three different categories microscopic, mesoscopic and macroscopic models by their spatial problem [22].

The microscopic models offer a much more refined framework to exhibit complex human behaviors by describing pedestrians on an individual level, they formally simulate the behaviors of each individual and its interaction and let the crowd's behavior emerge; the modeling, therefore, is thorough enough to allow realistic agent behavior while at the same time trying to retain the computational complexity to an acceptable upper limit [24].

Based on the theoretical variable like time and space, it can adopt that microscopic models are further classified as continuous, discrete, or mixed models.

Continuous models consider a pedestrian as a particle in a continuous space. In the most elaborated continuous models, Reynolds (1987) [17]developed a distributed behavioral model to generate a life like flocking, schooling and herding motions. Later work [18] extends this model by defining various objectives for individual characters. These objectives determine what rules will be followed by an agent regarding other agents in the environment.

The social force model, developed by Helbing et al. [7], uses the acceleration, attraction and repulsive forces to describe the pedestrian's motion and the interaction between him and his neighboring pedestrians, this model allow to show self-organization phenomena occurring in the building escape panic. Because the social-force model can reproduce significant features of pedestrian flow and is flexible enough to incorporate many factors that affect pedestrian movements, many researchers developed their own social-force models [5].

Due to complex calculations, it is very difficult to simulate complicated geometries and large-scale scenarios with continuous models. Consequently, discrete models have been introduced in pedestrian evacuation simulations.

The cellular automata is the most widely used discrete approach for modeling pedestrian behavior, it handles the physical environment as a square grid, or an hexagonal cells that pedestrian can occupy [26]. In terms of pedestrian motion-driven rules, it can be classified as a micro-simulation model, Lattice Gas Model [1], Floor Field Model, Real-coded CA Model or Multi-grid Model [25]. The common characteristic of these models is that the probabilities for a pedestrian's route choice are decided by either the long-range environmental conditions, the short-range pedestrian dynamics or both [12].

Many researchers have proposed approaches to simulate various aspects of human and crowd behaviors [6, 14, 22, 24]. Ulincy and Thalmann [21] used a modular behavioral architecture to allow a mixture of automated and scripted behavior in multi-agent simulations. Musse and Thalmann [13] proposed a model for crowd simulation with hierarchically structured crowds having different levels of autonomy. Their model is based on groups, rather than individuals: groups' are more intelligent structures, where individuals follow the group's specification. A cognitive model of crowd behavior was proposed [11] by applying the Festinger's (1954) social comparison theory, which is the general process underlying the social phenomena, to simulate pedestrian movement in a simple virtual environment. Pelechano et al. [15] described a multi agent model called HiDAC model to simulate the flow of a high-density population in the dynamic virtual environment. Durupinar et al. [4] modeled the effects personality factors have on local behavior.

Continuum methods such as [8] and [20] treat the crowd as a whole and model the motion and interactions of agents based on equations that represent aggregate flow. Hughes [8] implemented a continuum approach inspired from fluid dynamics to simulate the two dimensional pedestrian flow, this approach was later extended by Treuille et al. [20], who presented the continuum model in order to generate realistic motion planning for crowds. Their method calculates the potential function for a group once, and then it simultaneously derives the optimal paths for all group members. Recently, Huang et al. [9] revisited a dynamic macroscopic model of pedestrian flow proposed by Hughes and advanced an efficient solution algorithm. Jiang et al. [10] used the continuum model to simulate plausible crowd movement within multi-floor structures, such as a large pedestrian overpass, a subway station and an office building.

In [3], hybrid simulation architecture that combines the strengths of two classes of crowd modeling to achieve flexible, interactive, high-fidelity simulation on large environment. This architecture couples a microscopic model of individual navigation with a novel continuum approach for the collective motion of pedestrians; it can apply to simulate the behaviors and movement patterns of extremely large crowds at near real-time rates on commodity hardware.

3 THE PROPOSED MODEL

The main requirement of the work is to design an innovative efficient model dedicated for real time simulation of pedestrian dynamics in large scale heterogeneous virtual crowds. It focuses on modeling large numbers of individual people in complex dynamic environments for chosen scenarios, when each individual can change his motion behavior over time. We adopt an agent-based modeling methodology for generating realistic crowd dynamics with a wide variety of individual, and emerging behaviors during real time simulation.

This model of crowd simulation constitute of several components and sub-components. At the most basic level, two key components are modeled: an environment model and a model of virtual pedestrians involved (Fig. 1). The representations of these components are designed to allow agents to interact with other agents and perceive the environment.

The representation of the space of a model is tightly coupled with the previous set and supported by two main classes:

- Geometry sub-component is the basis of the space representation model, it is, as its names implies, 3 dimensional Euclidean environment that allows people to move and occupy space. Movement can be either in all three dimensions (for example birds, fish, etc.) or only in two dimensions (for example herds, humans, etc.) This two dimensional movement could be approximated with only two dimensional space. The main part of this layer is 3D geometric model of the environment that is employed for display and the semantic information extraction for the next semantic representation layer.

- Topologic space subcomponent: is responsible to describe the connectivity and adjacency between separated regions in the interior space such as rooms and hallways.

- Structure map: In a complex environment, there are numerous objects, like handrails, walls, windows, pillars and so on, distributed widely in different regions. In order to facilitate organization and implementation, we divided the whole space into several independent but adjacent regions according to common sense. We called these naturally separated regions, like an entire floor, stairs, or a corridor, as Block, and all the objects placed in the same region are included into the same block. All blocks along with their objects are organized into structure map.

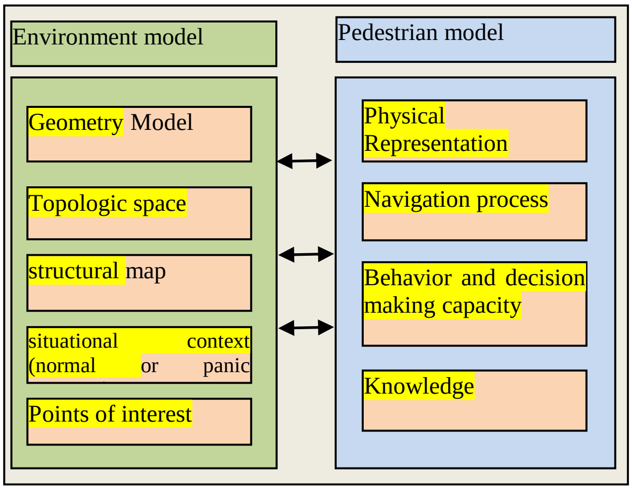


Figure 01: Conceptual of our simulation model including setup of environment and agents

- Model of the individual: The model of the individual is the most important part of an agent based crowd model and there are a wide variety of ways in which this can be done. There are a variety of things to be considered when a human is being modeled. These include:

- Physical Representation: This refers to the physical characteristics of the humans being like the shape and size of the model used. This is discussed in much detail in [3, 63]. Some papers suggest that for accurate modelling an elliptical shape is best but to make this computationally efficient a 3 circle model can also be used. The speed of movement of the humans and the time taken for pre-evacuation behavior can also be considered to be part of the physical representation.

- Navigation: Navigation refers to how the agents move within an environment. Depending on the scale of the environment, this generally consists of a higher level path planning which is generally A-Star and a lower level collision avoidance algorithm. The choice of collision avoidance algorithms can have significant effects on the dynamics produced.

- Knowledge: This can refer to either knowledge of events or knowledge of the environment/ layout. Most models assume complete knowledge of both. However, there are some that do model individual specific knowledge and exchange of information. These will be discussed in more detail later sections.

- Behavior and decision making capacity: This refers to the detail in which some of the behavior. This also refers to the social interactions that takes place between the evacuees. Some models do not consider behavior at all, while others have sophisticated models of decision and behavior. The same behavior can sometimes be produced by using different techniques. Some models use a functional analogy, like social forces, which approximate behavior through mathematical formulas; while others use rule based techniques or more complicated hierarchical models. These will be discussed in the following sections.

4 VIRTUAL PEDESTRIAN MODEL

One of the fundamental objectives for the research in virtual humans is to demonstrate realistic navigation behaviors in a crowd scene, to correctly simulate this behavior in real time, it is important to propose an accurate representation of a pedestrian that can be used for several applications with believable and coherent behaviors. An ideal proposed solution should be able to simulate a large number of virtual pedestrian that behave like a large group of humans in the real world [3].

4.1 Theoretical Basis on pedestrian behaviors

In this section, we make many observations to facilitate the modeling of pedestrians behaviors in the crowd simulation. These assumptions are proposed based on some of the previous pedestrian work reviewed in the literatures.

Observation 1: Pedestrian is an active entity. This indicates a pedestrian acts automatically and has a specific strategy to make its own behaviors. Under normal condition, it needs to follow naturally a route without detours and to move with its own individual, most comfortable walking speed for reaching its goals in precise time. However in the panic situations, the pedestrian exhibits an aversion to walking faster than usual, taking detours more often or moving opposite to the desired walking direction.

Observation 2: Pedestrian is an intelligent character, it has the ability to decide its behaviors in different specific contexts, this refers to the process by which the person evaluates the perceived information about the world around it, produces and or/ selects movements according to its own status.

Observation 3: Virtual pedestrian is defined as an independent individual. Pedestrian must display various behaviors in its unique style, for this it is characterized by set of individual parameters to differentiate it from others. Such diversities will be efficiently enough to result in differences in decision making process and movements.

Observation 4: The human navigation process is described typically through hierarchical movements in multiple layers of decision making, path planning determination and local path following. In everyday situation, the navigation behavior of pedestrians is usually not executed at one time. On the contrary, they divide the whole journey into multiple small parts in order to set many local intentions, and then find out a comfortable way to achieve each of these intentions by running a sequences of basic actions. It refers to achieve a specific goal as a large-scale or macro-navigation, which includes path planning and way-finding behaviors to identify a rough route from the source to the destination. To perform the macroscopic movements, microscopic local movements such as collision avoidance and shortest path selection take place.

4.2 Hierarchical Motion Modeling Structure

The most essential part of the scene will be the agents themselves. In our research, the focus is on the real time simulation of large numbers of people performing complex navigation behaviors in virtual dynamic environment. In this context, the navigation is defined as the process by which an individual pedestrian first plans his route towards a goal location based on his cognitive map and then moves along this route towards the goal [3].

Thus based on observation 4, we propose to tackle the modeling of complex navigational behaviors through a hierarchical motion structure. Instead of the traditional bi-layer structure, a tri-layer hierarchy of the motion system, which consists of "path planning", "local path determination" and "locomotion".

In this section, we focus on describing the behaviors involved at the "local path determination" layer and their relationship with the other two layers in detail.

4.3 Physical and psychological pedestrian characteristics

- **Geometric representation of pedestrian:** In order to generate a most realistic simulation, the pedestrians’ external appearance was described by a complex 3D model (such as mesh model), the physical size of a human body determines the plan view of an average adult male body by considering only his body depth and his shoulder breadth. We did not make distinctions between the agents on this point, setting the dimensions to 0.5 x 0.3 m.
- **Pedestrian Personal Space:** Originating from psychological studies, personal space indicates the invisible area surrounding individuals. The concept of personal space is considered as a social factor that strongly impacts communication or

contact between people. This free zone, which has the shape of a parabolic curve, is influenced by several parameters such as the pedestrian body's size, his wanted walking speed, the density of the surrounding population and his acquaintances with his neighbors (social relations, familiarity, etc.), etc. The personal space is divided into four categories known as the Intimate, Personal, Social Consultative and Public Zones based on the distance between humans within the public spaces.

- the intimate zone (from 0 to 45 cm) where the presence of another pedestrian is highly disturbing,
- the personal zone (from 45 to 120 cm) is the distance that every individual tries to maintain between him and another pedestrian (whoever that is),
- the social zone (from 120 to 360cm) in which the presence is allowed with special conditions (high density, acquaintance with the character, avoiding an obstacle, social situations, etc.),
- the public zone (360cm and beyond) where other pedestrians are seen but not taken into account while navigating.

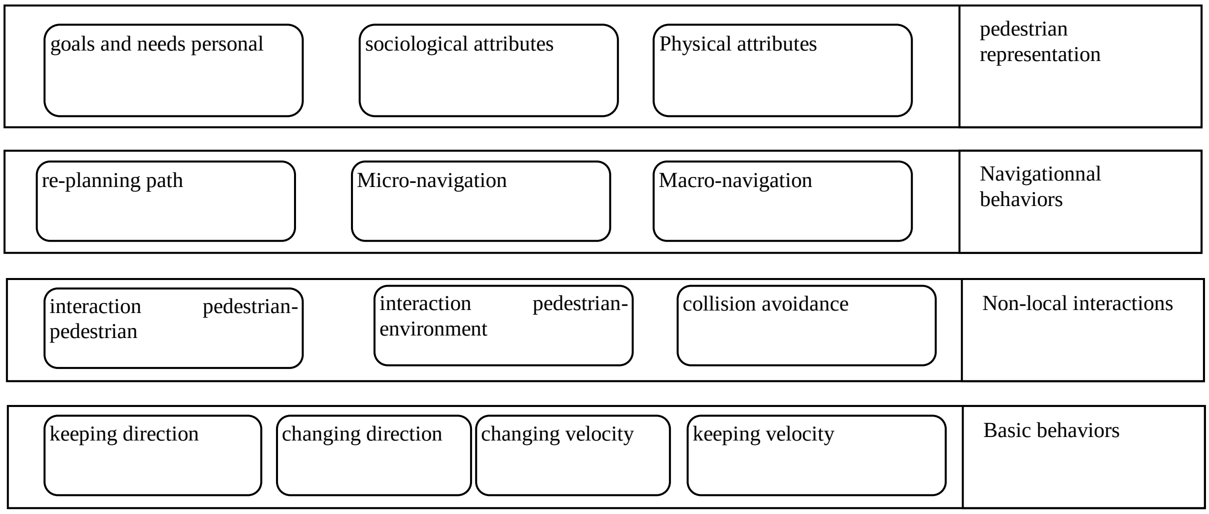


Figure 02: Hierarchical model for pedestrian behaviors

- Velocity. This is the current velocity that an agent possesses and, contrary to the strength, this attribute has both magnitude and direction. This is the rate of change of the agent's location; thus, it is used to obtain the next position. It is calculated with the acceleration that the total force produces on the agent.
- Maximum Speed. This is the higher punctual speed that an agent can move in the world with. Do not confuse this with how fast an agent can change of physical state, which is related with forces and mass (acceleration). Consider the next example: a cheetah can change from 0 to 100 km/h in a matter of seconds (high acceleration); on the other hand, a high-speed train, which needs a lot of force (strength with direction) to move such a big mass, has much smaller acceleration, but it can travel at 200 km/h (high maximum speed).
- Vision Radius. This property determines which portion of the world the agent is aware of. This is mainly used to calculate the other agents that one agent can perceive, which will conform its neighborhood. Therefore, an explorer may have a large vision radius, meanwhile a blind agent will have vision radius 0, and will need to receive information about the world.

4.4 Modeling Pedestrian Movements

- In this section, we explain the basis of our approach that is used to model the crowd behaviors during the real time crowd simulation. We use the social force model to perform low-level tactical navigation and collision avoidance. The social force model is selected for the low-level tactical navigation for four main reasons: it is simple to understand and implement, it is widely used in many simulation models, it successfully reproduces many crowd phenomena, and it has been validated using actual pedestrian data [5, 7].
- The social force model states that pedestrian movement can be approximated by applying multiple force vectors to a pedestrian. The force vectors can include attraction vectors for groups or goals and repulsion vectors for obstacles, fire, or other pedestrians. In our model, we just focus on the mobility of people and do not consider more complex behaviors. From the survey, we synthesize 6 behaviors:

4.4.1 Move without changing its goal

A given pedestrian has an intention to reach a location area to realize a specific activity. this is modeled by a motivation force pointing towards that location.

This covers people that had intended to move and do not change their activity as a result of the earthquake (e.g. people who are on their way to work)

This covers people that had change continuously its current position by keeping its desired direction and its preferable velocity.

$$P(t) = P(t-1) + v(t)e(t) \times \Delta t \qquad (1)$$

4.4.2 Changing velocity with keeping its activity

The pedestrian velocity $v(t)$ is continuously changing and thus acceleration is governed by the social forces $f(t)$, which represent the sum of the different influences upon the individual pedestrian (that is environment and other pedestrians). There is also a consideration for random fluctuations within the system which account for random behavioral fluctuations which gives rise to $\vec{\xi}(t)$. So, the acceleration obtained is

$$\frac{d\vec{v}}{dt} = \vec{f}(t) + \vec{\xi}(t)$$

4.5 Navigational Layer

The Navigational layer is responsible to represent the navigation process. Hence, the navigation process will allow to people to follow the known route or choose a new path based on changes in the environment and their psychological parameters. This process focus to analyze the representation and compute a optimal path between any two locations in the environment [3].

In this context, navigation process could be either local or global. Local Path Planning means the path is done while the pedestrian is moving; this process is capable of producing a new route in response to environment changes, i.e. user inserts or removes one or set of obstacles in the environment, or a door appearing blocked which makes that path invalid or creates a bottleneck in some part of the desired path.

On the other hand, Global Path Planning requires that the environment be completely known. In this approach, an offline process (before the simulation is started) generates a complete path from the start point to the destination point, and then the route is pre-calculated and stored in the topological graph in order to achieve real-time interactive navigation.

The Local Path Planning Process is used in case where the entity and his sub-goal are in the same region, but the Global Path Planning Process is executed if the pedestrian and his sub-goal are in two different zones. Both these two processes send the shortest path in form a set of waypoints (attractor points) to the Behavior Mechanism to carry out the required motion to reach it.

5 ENVIRONMENT MODEL

The environment in which the simulation takes place is the surrounding of the pedestrians, where they move along, interact and navigate to get from one location to another, typically, it includes walkable areas, obstacles of different natures, and destination. Whereas, fixed obstacles can be defined as regions that no pedestrian can access, moving obstacles are other pedestrians occupying predefined space from the environment which is consequently not anymore available. Finally, origin and destination areas, where pedestrians enter and exit the system must be defined. Those could be doors, elevators, stairs, and of course the boundaries of the modeled area.

The first step in designing a crowd navigation system is to construct an efficient abstract representation of the virtual environment where the pedestrian can rapidly perform wayfinding. The representation of the physical environment seems to be one of the first sources in the behavioral animation.

In this study, we define a representation method which handles two types of structure data to clearly represent and to organize the topological relationship among the different geometrical areas of a large complex environment. This approach provides a well consistence resulting from the continuous interaction between two models of different level of detail.

- Topological graph: Usually, the virtual environment is defined by a 3d model to constitute a geometric representation of the real world. Such a representation of the spatial data makes it difficult to handle by virtual pedestrian in order to find its own paths through the environment. Hence the most way to facilitate this representation is to obtain the topological relation of the environment and its geographical areas captured in a graph based structure (Fig.2). The topological graph uses nodes and edges to indicate the adjacency, connectivity, the inclusion and the intersection between the different parts of the environment, in which a node defines spatial areas and a possible path can be defined as edge. The internal spatial areas can be defined as a bounded volume in 3D space (such as a room, a corridor, a flight of stairs or even an entire floor) with bottom flat that contains several objects inside it (e.g., ground, walls, benches).
- Finer grid: Every zone from the topological graph is further divided into a uniform lattice of cells, each representing a portion of the simulated environment and comprising information about its current state, both in terms of physical occupation

by an obstacle or by a pedestrian. The size of the subareas could be reduced to the average space occupied by a single pedestrian implying that the evacuation instructions are provided at the individual level.

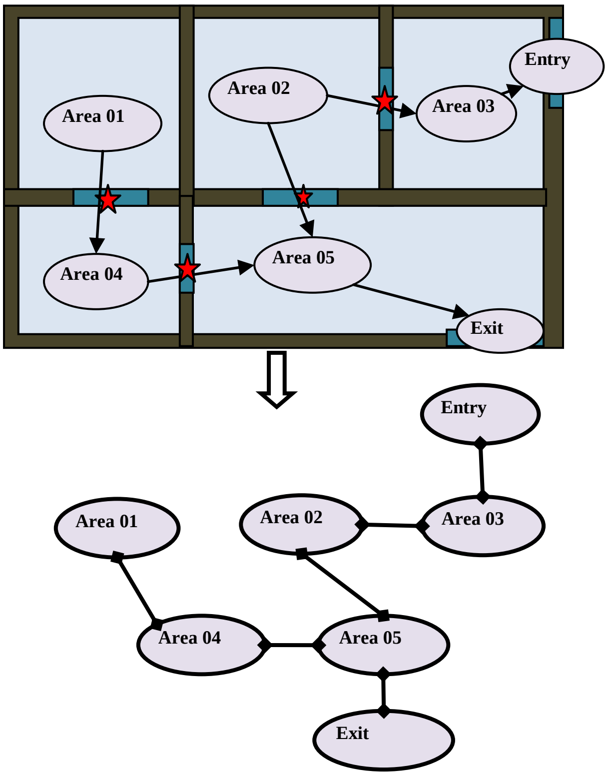


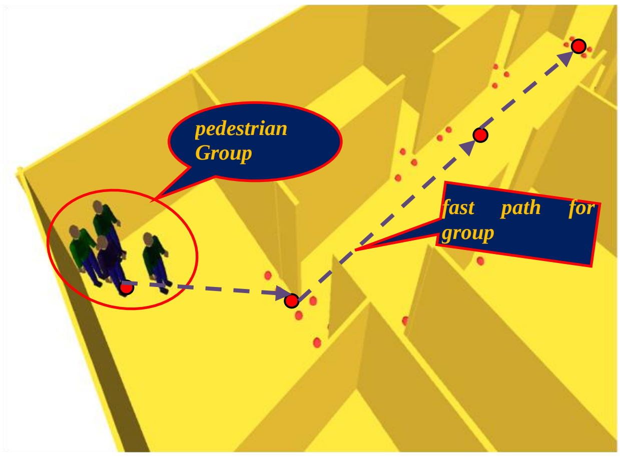
Figure 03: Topological graph representation of the virtual environment

6 RESULTS

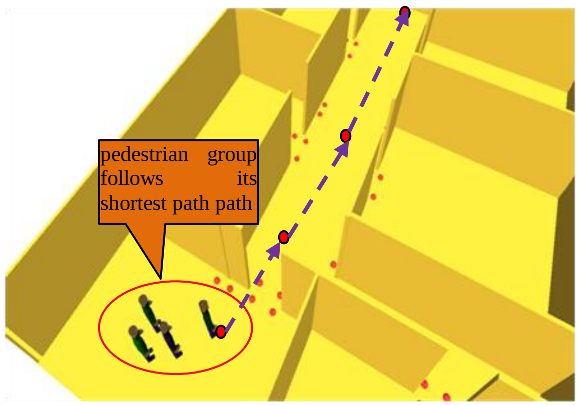
In this section we present and describe the experiments for the evaluation of our model for interactive visual simulation of large scale crowd of virtual pedestrian. In order to evaluate the effectiveness and the robustness of our approach presented in this paper, we have conducted to realize a number of simulations with different initial distributions and conditions (mainly changing the density of pedestrian crowd in the environment) in a situation in which experiments focused at analyzing the impact of the density of crowd on the pedestrian behavior that could be handled was being investigated.

The objective of the experiments which we use is to show the proposed model performs well to produce results that closely simulate real human behaviors in these situations, and to study whether the proposed model can describe the qualitative dynamic properties of the pedestrian's movement under situations with three different level of density (low, medium and high density) in terms of number of pedestrians that could be handled with reasonable performance.

Fig.4 shows the simulation results of the pedestrian dynamic produced by the microscopic model which is selected to apply according to the pedestrian density calculated as the numbers of pedestrians existing in the restricted areas under consideration. This model is considered to be qualitatively more accurate than the macroscopic model. This experiment shows that when the number of virtual pedestrian is small (Fig.4 (a)), the microscopic modeling approach has been employed to simulate each pedestrian as an individually entity with its own its own personality, and its behavior which is determined by both the global and local movement. In this scenario, we demonstrated that a leader has a major influence on people especially in evacuation situation, in order to formulate the leader-follow behaviors. Fig.4 (b) shows this case, when, we can observed the red flow follow a leader which has a global view of the simulated environment, then he find the shortest path into the exit, but the blue flow has no leader, then he choose the shortest door which leads it to follow the longest path.



(a) Grouping of pedestrian and finding the global path

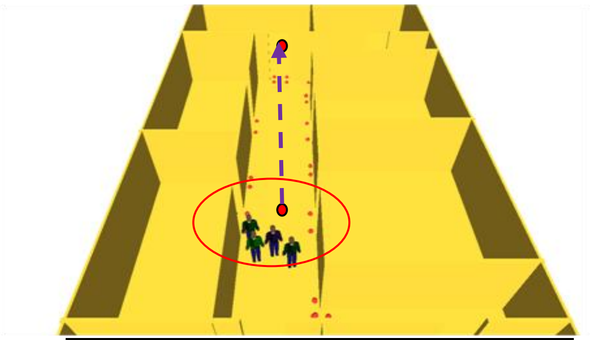


(b) pedestrian group start to follow its path

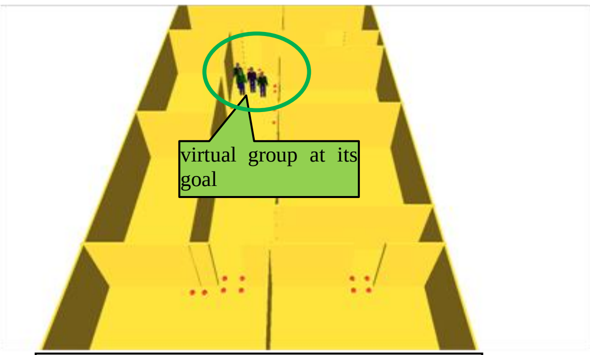
Figure 04: Leader-follow behaviors

During the second experiment (Fig.5), we noticed that pedestrian's density increases in the same subarea; the macroscopic is adopted to handle the pedestrian's behaviors within a crowd of high density. This model facilitates the construction of small groups of individuals that shows a slight cohesion and natural fragmentation into subgroups that might be simple and therefore much more compact.

Group phenomenon is an interesting area of research for pedestrian simulation, because it is very common in the every-day life, people standing closer to its familiars and forming small groups. In panic situation, people relatively tend to gather together closer. In these situations, people are mostly linked by the (temporary) sharing of a common goal, and the overall group tends to maintain only week compactness, with a following behavior between members. In Fig. 5, the macroscopic used to cluster the pedestrians into a structured group by assuming a common goal, passing a direction and speed that applied to all of the members. As a member of a group, each pedestrian coordinates with others in the same group and show an aggregate motion as they move together.



(a) Virtual entity continues to follow their path to destination

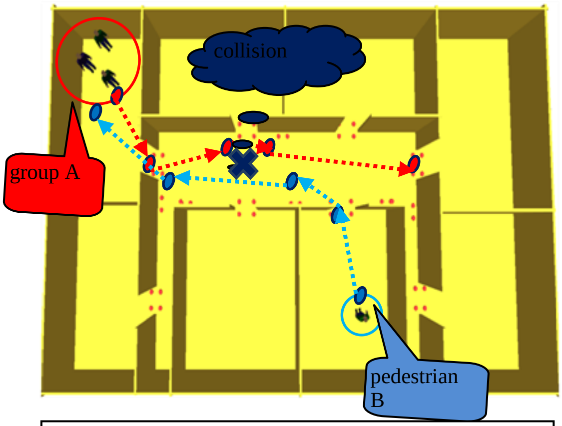


(b) Virtual entity achieves its goal

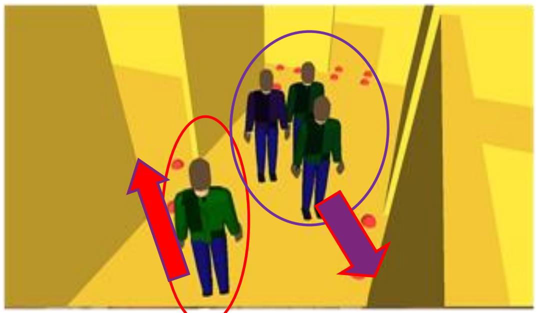
Figure 05: Construction of Group behavior

Dynamic obstacle avoidance

We have tried in this example to illustrate how an entity avoid collision with other moving pedestrian, as shown in the images below: here is a sequence of images of this example (fig. 6)



(a) detection of dynamic collision between 2 entities



(c) Calculate new directions and speeds for each entity

Figure 06: Collision avoidance behavior

7 CONCLUSION

Multi-approach modeling is proposed in this work as an adaptive simulation strategy for exhibiting the pedestrian crowd movements and its emergent behaviors in high density situation. Our method makes it possible to exploit advantages from both macroscopic and microscopic models. The two types of models work simultaneously in a single simulation system, and are executed over different mutually exclusive partitions.

Our model also ensures that no visible disturbance is generated the crowd to move from one partition to another, and a suitable strategy is considered that is able to switch dynamically from one to another.

It would be worthwhile to investigate the addition of social behaviors to our method to enhance the realism of the results, and we anticipate that our approach can be explored emergent resulting from various types of behavioral rules. Further work, the coupling of mesoscopic models with our model will develop to apply in the region with middle density.

REFERENCES

[1] Abdelghany, A., Abdelghany, K., Mahmassani, H., Al-Ahmadi, H., & Alhalabi, W. (2010). Modeling the evacuation of large-scale crowded pedestrian facilities. Transportation Research Record: Journal of the

Transportation Research Board, 2198, pp. 152–160.

[2] Alizadeh, R. (2011). A dynamic cellular automaton model for evacuation process with obstacles. Safety Science, 49(2), pp. 315–323.

[3] Chighoub, R., & Cherif, F. (2016). Toward a Hybrid Approach for Crowd Simulation. International Journal of Advanced Computer Science and Applications, 7(1), 51-61.

[4] Durupinar, F., Allbeck, J., Pelechano, N., & Badler, N. (2008): Creating crowd variation with the OCEAN personality model. In: Proceedings of the 7th International Joint Conference on Autonomous Agents and Multiagent Systems (May 12-16, 2008)

[5] Guo R Y., & Huang H. J. (2008). A mobile lattice gas model for simulating pedestrian evacuation. Physica A; 387: pp. 580–6.

[6] Guy S, Chuggani J, Curtis S, Dubey P, Lin M, & Manocha D., (2010), Pledestrians: A least-effort approach to crowd simulation. Technical report. Department of Computer Science, University of North Carolina,

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

[8] Hughes, R.L., (2002): A continuum theory for the flow of pedestrians. Transp. Res. Part B Methodol. 36(29), pp. 507–535

[9] Huang, L., Wong, S., Zhang, M., Shu, C., W., & Lam, W. H., (2009), Revisiting Hughes' dynamic continuum model for pedestrian flow and the development of an efficient solution algorithm, Transportation Research Part B: Methodological 43 (1): pp. 127–141

[10] Jiang, H., Xu, W., Mao, T., Li, C., Xia, S., & Wang, Z., (2009): Continuum Crowd Simulation in Complex Environments. Computers & Graphics 2010 34(5), pp. 537–544

[11] Kaminka G-A, & Fridman N., (2006), A cognitive model of crowd behavior based on social comparison theory. Proceedings of the AAAI-2006 Workshop on Cognitive Modeling, July.

[12] Kirchner, A., & Shadschneider, A., (2002): Simulation of evacuation processes using a bionics-inspired cellular automaton model for pedestrian dynamics. Physica A 312(1–2), pp. 260–276

[13] Musse, S. R., & Thalmann, D., (2001). Hierarchical model for real time simulation of virtual human crowds, IEEE Trans. Visualization Comput. Graph. 7, pp. 152–164.

[14] Narain R, Golas A, Curtis S, & Lin M C., (2009), Aggregate dynamics for dense crowd simulation. In: ACM Transactions on Graphics (Proc. of ACM SIGGRAPH Asia)

[15] Pelechano, N., Allbeck, J., & Badler, N., I., (2007): Controlling individual agents in high-density crowd simulation. In: Proceedings of the 2007 ACM SIGGRAPH/Eurographics Symposium on Computer Animation Eurographics Association, pp. 108–118.

[16] Pelechano, N., Allbeck, J., M., & Badler, N., I., (2008), Virtual Crowds: Methods, Simulation and Control. Morgan and Claypool Publishers,

[17] Reynolds, C.W. (1987). Flocks, herds, and schools: A distributed behavioural model. In: Computer Graphics Proceedings of SIGGRAPH 1897, vol. 21, pp. 25–34.

[18] Reynolds, C. (1999). Steering behaviours for autonomous characters. In: Game Developers Conference, pp. 763–782.

[19] Thalmann, D., & Musse, S.R. (2007), Crowd Simulation, 1st edn. Springer

[20] Treuille, A., Cooper, S., Popovic, Z., (2006): Continuum crowds. In: SIGGRAPH 2006: ACM SIGGRAPH 2006 Papers, ACM, New York pp. 1160–1168.

[21] Ulicny, B., & Thalmann, D., (2001). Crowd simulation for interactive virtual environments and VR training systems, Comput. Anim. Simul., pp. 163–170.

[22] Xiong, M., Tang, S., & Zhao, D., (2014). A hybrid model for simulating crowd evacuation. New generation Computing, 31, pp. 211–235.

[23] Xu, M.,L., Jiang, H., Jin, X., G., & Zhigang Deng, Z., (2014). Crowd simulation and its applications: Recent advances. Journal Of Computer Science And Technology 29(5): pp. 799-81. DOI 10.1007/s11390-014-1469-y

[24] Xiong, M., Tang, S., & Zhao, D., (2014). A hybrid model for simulating crowd evacuation. New generation Computing, 31, pp. 211–235.

[25] Zhao, H., & Gao, Z. (2010). Reserve capacity and exit choosing in pedestrian evacuation dynamics. Physics A: Mathematical and Theoretical, 43(10), 105001.

[26] Zheng X, Zhong T, & Liu M., (2009), Modeling crowd evacuation of a building based on seven methodological approaches. Building and Environment; 44(3): pp. 437–445.