Towards an Agent-Based Proxemic Model for Pedestrian and Group Dynamic

Lorenza Manenti, Sara Manzoni, Giuseppe Vizzari
Complex Systems and Artificial Intelligence research center
University of Milano–Bicocca
viale Sarca 336/14, 20126 Milano
{lorenza.manenti,sara.manzoni,giuseppe.vizzari}@disco.unimib.it

Kazumichi Ohtsuka, Kenichiro Shimura
Research Center for Advanced Science & Technology
University of Tokyo
Komaba 4-6-1, Meguro-ku, Tokyo, 153-8904, JAPAN
tukacyf@mail.ecc.u-tokyo.ac.jp
shimura@tokai.t.u-tokyo.ac.jp

Abstract—Models for the simulation of pedestrian dynamics and crowds of pedestrians have already been successfully applied to several scenarios and case studies, off-the-shelf simulators can be found on the market and they are commonly employed by end-user and consultancy companies. However, these models are the result of a first generation of research efforts considering individuals, their interactions with the environment and among themselves, but generally neglecting aspects like (a) the impact of cultural heterogeneity among individuals and (b) the effects of the presence of groups and particular relationships among pedestrians. This work is aimed, on one hand, at clarifying some fundamental anthropological considerations on which most pedestrian models are based, and in particular Edward T. Hall's work on proxemics. On the other hand, the paper will briefly describe the first steps towards the definition of an agent-based model encapsulating in the pedestrian's behavioural model effects capturing both proxemics and influences due to potential presence of groups in the crowd.

I. INTRODUCTION

Crowds of pedestrians are complex entities from different points of view, starting from the difficulty in providing a satisfactory definition of the term crowd. The variety of individual and collective behaviours that take place in a crowd, the composite mix of competition for the shared space but also collaboration due to, not necessarily explicit but often shared (at least in a given scenario), social norms, the possibility to detect self-organization and emergent phenomena they are all indicators of the intrinsic complexity of a crowd. Nonetheless, the relevance of human behaviour, and especially of the movements of pedestrians, in built environment in normal and extraordinary situations (e.g. evacuation), and its implications for the activities of architects, designers and urban planners are apparent (see, e.g., [1] and [2]), especially given recent dramatic episodes such as terrorist attacks, riots and fires, but also due to the growing issues in facing the organization and management of public events (ceremonies, races, carnivals, concerts, parties/social gatherings, and so on) and in designing naturally crowded places (e.g. stations, arenas, airports). Computational models of crowds and simulators are thus growingly investigated in the scientific context, but also adopted by firms[1] and decision makers. In fact, even if research

[1]see, e.g., Legion Ltd. (http://www.legion.com), Crowd Dynamics Ltd. (http://www.crowddynamics.com/), Savannah Simulations AG (http://www.savannah-simulations.ch).

on this topic is still quite lively and far from a complete understanding of the complex phenomena related to crowds of pedestrians in the environment, models and simulators have shown their usefulness in supporting architectural designers and urban planners in their decisions by creating the possibility to envision the behaviour/movement of crowds of pedestrians in specific designs/environments, to elaborate what-if scenarios and evaluate their decisions with reference to specific metrics and criteria.

The Multi-Agent Systems (MAS) approach to the modeling and simulation of complex systems has been applied in very different contexts, ranging from the study of social systems [3], to biological systems (see, e.g., [4]), and it is considered as one of the most successful perspectives of agent–based computing [5], even if this approach is still relatively young, compared, for instance, to analytical equation-based modeling. The MAS approach has also been adopted in the pedestrian and crowd modeling context, especially due to the adequacy of the approach to the definition of models and software systems in which autonomous and possibly heterogeneous agents can be defined, situated in an environment, provided with the possibility to perceive it and their local context, decide and try to carry out the most appropriate line of action, possibly interacting with other agents as well as the environment itself. The approach can moreover lead to the definition of models that are richer and more expressive than other approaches that were adopted in the modeling of pedestrians (that respectively consider pedestrians as particles subject to forces, in physical approaches, or particular states of cells in which the environment is subdivided, in CA approaches).

The main aim of this work is to present the motivations, fundamental research questions and directions, and some preliminary results of an agent–based modeling and simulation approach to the multidisciplinary investigation of the complex dynamics that characterize aggregations of pedestrians and crowds. This work is set in the context of the Crystals project, a joint research effort between the Complex Systems and Artificial Intelligence research center of the University of Milano–Bicocca, the Centre of Research Excellence in Hajj and Omrah and the Research Center for Advanced Science and Technology of the University of Tokyo. In particular, the main focus of the project is on the adoption of an agent-based

pedestrian and crowd modeling approach to investigate meaningful relationships between the contributions of anthropology, cultural characteristics and existing results on the research on crowd dynamics, and how the presence of heterogeneous groups influence emergent dynamics in the context of the Hajj and Omrah. The last point is in fact an open topic in the context of pedestrian modeling and simulation approaches: the implications of particular relationships among pedestrians in a crowd are generally not considered or treated in a very simplistic way by current approaches. In the specific context of the Hajj, the yearly pilgrimage to Mecca that involves over 2 millions of people coming from over 150 countries, the presence of groups (possibly characterized by an internal structure) and the cultural differences among pedestrians represent two fundamental features of the reference scenario. Studying implications of these basic features is the main aim of the Crystal project.

The paper breaks down as follows: the following section describes some basic anthropological and sociological theories that were selected to describe the phenomenologies that will be considered in the agent-based model definition. Section III will present the current state of the art on pedestrian and crowd models, with particular reference to recent developments aimed at the modeling of groups or improving the modeling of anthropological aspects of pedestrians. Section IV briefly describes the first steps towards the definition and experimentation of a model encompassing basic anthropological rules for the interpretation of mutual distances by agents and basic rules for the cohesion of groups of pedestrians. Conclusions and future developments will end the paper.

II. INTERDISCIPLINARY RESEARCH FRAMEWORK

The context of research regards very large events where a large number of people may be gathered in a limited spatial area, this can bring to serious safety and security issues for the participants and the organizers. The understanding of the dynamics of large groups of people is very important in the design and management of any type of public events. The context is also related to crowd dynamics study in collective public environments towards comfort services to event participants. Large people gatherings in public spaces (like pop-rock concerts or religious rites participation) represents scenarios where the dynamics can be quite complex due to different factors (the large number and heterogeneity of participant people, their interactions, their relationship with the performing artists and also exogenous factors like dangerous situations and any kind of different stimuli present in the environment [6], [7]). The traditional and current trend in social sciences studying crowds is still characterized by a non-dominant behavioral theory on individuals and crowds dynamics. Several open issues are still under study, according multiple methodological approaches and final aims. However, in order to develop both empirical and theoretical works on crowd studies, we claim that the theoretical reference framework has to be clarified. This is the main aim of this section.

A. Perceived Distance and Proxemic Behavior

Proxemic behavior includes different aspects which could it be useful and interesting to integrate in crowd and pedestrian dynamics simulation. In particular, the most significant of these aspects being the existence of two kinds of distance: *physical* distance and *perceived* distance. While the first depends on physical position associated to each person, the latter depends on proxemic behavior based on culture and social rules. The term *proxemics* was first introduced by Hall with respect to the study of set of measurable distances between people as they interact [8]. In his studies, Hall carried out analysis of different situations in order to recognize behavioral patterns. These patterns are based on people's culture as they appear at different levels of awareness.

In [9] Hall proposed a system for the notation of proxemic behavior in order to collect data and information on people sharing a common space. Hall defined proxemic behavior and four types of perceived distances: *intimate distance* for embracing, touching or whispering; *personal distance* for interactions among good friends or family members; *social distance* for interactions among acquaintances; *public distance* used for public speaking. Perceived distances depend on some additional elements which characterize relationships and interactions between people: posture and sex identifiers, sociofugal-sociopetal (SFP) axis, kinesthetic factor, touching code, visual code, thermal code, olfactory code and voice loudness.

It must be noted that some recent research effort was aimed at evaluating the impact of proxemics and cultural differences on the fundamental diagram [10], a typical way of evaluating both real crowding situations and simulation results.

B. Crowds: Canetti's Theory

Elias Canetti work [11] proposes a classification and an ontological description of the crowd; it represents the result of 40 years of empirical observations and studies from psychological and anthropological viewpoints. Elias Canetti can be considered as belonging to the tradition of social studies that refer to the crowd as an entity dominated by uniform moods and feelings. We preferred this work among others dealing with crowds due to its clear semantics and explicit reference to concepts of loss of individuality, crowd uniformity, spatio-temporal dynamics and *discharge* as a triggering entity generating the crowd, that could be fruitfully represented by computationally modeling approaches like MAS.

The normal pedestrian behaviour, according to Canetti, is based upon what can be called the *fear to be touched* principle:

> "There is nothing man fears more than the touch of the unknown. He wants to see what is reaching towards him, and to be able to recognize or at least classify it."

> "All the distance which men place around themselves are dictated by this fear."

A discharge is a particular event, a situation, a specific context in which this principle is not valid anymore, since pedestrians are willing to accept being very close (within
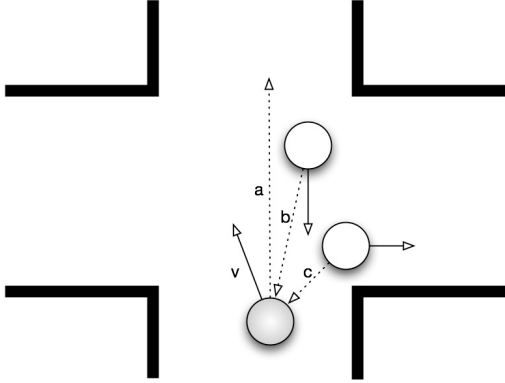
Fig. 1. A diagram exemplifying an analytical model for pedestrian movement: the gray pedestrian, in the intersection, has an overall velocity *v* that is the result of an aggregation of the contributions related to the effects of attraction by its own reference point (*a*), and the repulsion by other pedestrians (*b* and *c*).
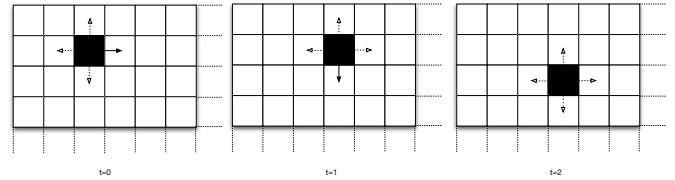

Fig. 2. A diagram showing a sample effect of movement generated through the coordinated change of state of adjacent cells in a CA. The black cell is occupied by a pedestrian that moves to the right in turn 0 and down in turn 1, but these effects are obtained through the contemporary change of state among adjacent cells (previously occupied becoming vacant and vice versa).

touch distance). Canetti provided an extensive categorization of the conditions, situations in which this happens and he also described the features of these situations and of the resulting types of crowds. Finally, Canetti also provides the concept of *crowd crystal*, a particular set of pedestrians which are part of a group willing to preserve its unity, despite crowd dynamics. Canetti's theory (and precisely the fear to be touched principle) is apparently compatible with Hall's proxemics, but it also provides additional concepts that are useful to describe phenomena that take place in several relevant crowding phenomena, especially from the Hajj perspective.

Recent developments aimed at formalizing, embedding and employing Canetti's crowd theory into computer systems (for instance supporting crowd profiling and modeling) can be found in the literature [12], [13] and they represent a useful contribution to the present work.

III. RELATED WORKS

It is not a simple task to provide a compact yet comprehensive overview of the different approaches and models for the representation and simulation of crowd dynamics. In fact, entire scientific interdisciplinary workshops and conferences are focused on this topic (see, e.g., the proceedings of the first edition of the International Conference on Pedestrian and Evacuation Dynamics [14] and consider that this event has reached the fifth edition in 2010). However, most approaches can be classified according to the way pedestrians are represented and managed, and in particular:

- pedestrians as particles subject to forces of attraction/repulsion;
- pedestrians as particular states of cells in a CA;
- pedestrians as autonomous agents, situated in an environment.

A. Pedestrians as particles

Several models for pedestrian dynamics are based on an analytical approach, representing pedestrian as particles subject to forces, modeling the interaction between pedestrian and the environment (and also among pedestrians themselves, in the case of *active walker* models [15]). Forces of attraction lead the pedestrians/particles towards their destinations (modeling thus their goals), while forces of repulsion are used to represent the tendency to stay at a distance from other points of the environment. Figure 1 shows a diagram exemplifying the application of this approach to the representation of an intersection that is being crossed by three pedestrians. In particular, the velocity of the gray pedestrian is determined as an aggregation of the influences it is subject to, that are the attraction to its reference point (the top exit) and the repulsion from the other pedestrians. This kind of effect was introduced by a relevant and successful example of this modeling approach, the *social force* model [16]; this approach introduces the notion of social force, representing the tendency of pedestrians to stay at a certain distance one from another; other relevant approaches take inspiration from fluid-dynamic [17] and magnetic forces [18] for the representation of mechanisms governing flows of pedestrians.

While this approach is based on a precise methodology and has provided relevant results, it represents pedestrian as mere particles, whose goals, characteristics and interactions must be represented through equations, and it is not simple thus to incorporate heterogeneity and complex pedestrian behaviours in this kind of model. It is worth mentioning, however, that an attempt to represent the influence of groups of pedestrians in this kind of model has been recently proposed [19].

B. Pedestrians as states of CA

A different approach to crowd modeling is characterized by the adoption of Cellular Automata (CA), with a discrete spatial representation and discrete time-steps, to represent the simulated environment and the entities it comprises. The cellular space includes thus both a representation of the environment and an indication of its state, in terms of occupancy of the sites it is divided into, by static obstacles as well as human beings. Transition rules must be defined in order to specify the evolution of every cell's state; they are based on the concept of neighborhood of a cell, a specific set of cells whose state will

be considered in the computation of its transition rule. The transition rule, in this kind of model, generates the illusion of movement, that is mapped to a coordinated change of cells state. To make a simple example, an atomic step of a pedestrian is realized through the change of state of two cells, the first characterized by an *"occupied"* state that becomes *"vacant"*, and an adjacent one that was previously *"vacant"* and that becomes *"occupied"*. Figure 2 shows a sample effect of movement generated by the subsequent application of a transition rule in the cellular space. This kind of application of CA-based models is essentially based on previous works adopting the same approach for traffic simulation [20].

Local cell interactions are thus the uniform (and only) way to represent the motion of an individual in the space (and the choice of the destination of every movement step). The sequential application of this rule to the whole cell space may bring to emergent effects and collective behaviours. Relevant examples of crowd collective behaviours that were modeled through CAs are the formation of lanes in bidirectional pedestrian flows [21], the resolution of conflicts in multidirectional crossing pedestrian flows [22]. In this kind of example, different states of the cells represent pedestrians moving towards different exits; this particular state activates a particular branch of the transition rule causing the transition of the related pedestrian to the direction associated to that particular state. Additional branches of the transition rule manage conflicts in the movement of pedestrians, for instance through changes of lanes in case of pedestrians that would occupy the same cell coming from opposite directions.

It must be noted, however, that the potential need to represent goal driven behaviours (i.e. the desire to reach a certain position in space) has often led to extend the basic CA model to include features and mechanisms breaking the strictly locality principle. A relevant example of this kind of development is represented by a CA based approach to pedestrian dynamics in evacuation configurations [23]. In this case, the cellular structure of the environment is also characterized by a predefined desirability level, associated to each cell, that, combined with more dynamic effects generated by the passage of other pedestrians, guide the transition of states associated to pedestrians. Recent developments of this approach introduce even more sophisticated behavioural elements for pedestrians, considering the anticipation of the movements of other pedestrians, especially in counter flows scenarios [24].

Another relevant recent research effort that must be mentioned here is represented by a first attempt to explicitly include proxemic considerations not only as a background element in the motivations a behavioural model is based upon, but rather as a concrete element of the model itself [25].

C. Pedestrians as autonomous agents

Recent developments in this line of research (e.g. [26], [27]), introduce modifications to the basic CA approach that are so deep that the resulting models can be considered much more similar to agent–based and Multi Agent Systems (MAS)

models exploiting a cellular space representing spatial aspects of agents' environment. A MAS is a system made up of a set of autonomous components which interact, for instance according to collaboration or competition schemes, in order to contribute in realizing an overall behaviour that could not be generated by single entities by themselves. As previously introduced, MAS models have been successfully applied to the modeling and simulation of several situations characterized by the presence of autonomous entities whose action and interaction determines the evolution of the system, and they are growingly adopted also to model crowds of pedestrians [1], [28], [29], [30]. All these approaches are characterized by the fact that the agents encapsulate some form of behaviour inspired by the above described approaches, that is, forms of attractions/repulsion generated by points of interest or reference in the environment but also by other pedestrians.

Some of the agent based approaches to the modeling of pedestrians and crowds were developed with the primary goal of providing an effective 3D visualization of the simulated dynamics: in this case, the notion of realism includes elements that are considered irrelevant by some of the previous approaches, and it does not necessarily require the models to be validated against data observed in real or experimental situations. The approach described in [31] and in [32] is characterized by a very composite model of pedestrian behaviour, including basic reactive behaviours as well as a cognitive control layer; moreover, actions available to agents are not strictly related to their movement, but they also allow forms of direct interaction among pedestrians and interaction with objects situated in the environment. Other approaches in this area (see, e.g., [33]) also define layered architectures including cognitive models for the coordination of composite actions for the manipulation of objects present in the environment. Another relevant approach, described in [34], is less focused on visual effectiveness of the simulation dynamics, and it supports a flexible definition of the simulation scenario also without requiring the intervention of a computer programmer. However, these virtual reality focused approaches to pedestrian and crowd simulation were not tested in paradigmatic case studies, modeled adopting analytical approaches or cellular automata and validated against real data.

IV. A SIMPLE AGENT-BASED PROXEMIC MODEL

This section will describe a first step towards an agent–based model encompassing abstractions and mechanisms accounting based on fundamental considerations about proxemics and basic group behaviour in pedestrians. We first defined a very general and simple model for agents, their environment and interaction, then we realized a proof–of–concept prototype to have an immediate idea of the implications of our modeling choices. In parallel to this effort, a set of experiments were conducted (in June 2010) to back-up with observed data some intuitions on the implications of the presence of groups in specific scenarios; two photos of one of the experiments are shown in Figure 4. In particular, this experiments is characterized by two sets of pedestrians moving in opposite
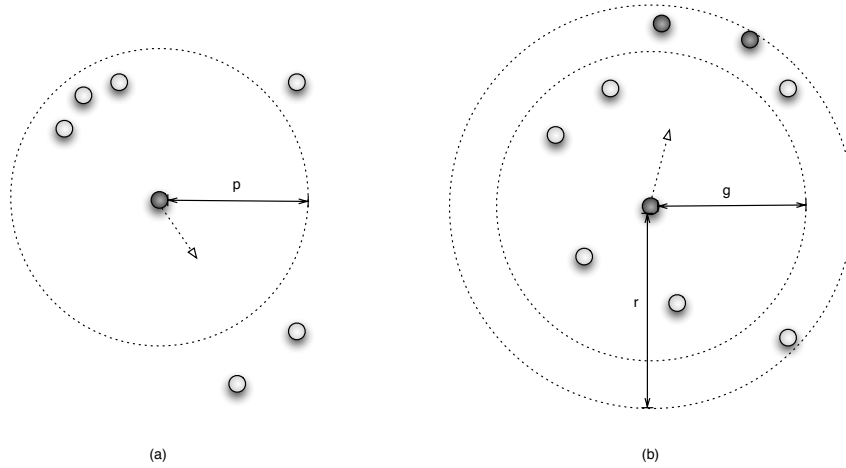
Fig. 3. Basic behavioural rules: a basic proxemic rule drives an agent to move away from other agents that entered/are present in his/her own personal space (delimited by the proxemic distance p) (a), whereas a member of a group will pursue members of his/her group that have moved/are located beyond a certain distance (g) but within his/her perception radius (r) (b).

directions in a constrained portion of space. In the set of pedestrians, in some of the experiments, some individuals were instructed to behave as friends or relatives, tying to stay close to each other in the movement towards their goal. It must be noted that this kind of situation is simple yet relevant for the understanding of some general principle on pedestrian movement and on the implications of the presence of groups in a crowd. In the context of the project a set of observations will be carried out in order to extend and improve the available data for model calibration and validation.

The simulated environment represents a simplified real built environment, a corridor with two exits (North and South); later different experiments will be described with corridors of different size (10m wide and 20 m long as well as 5m wide and 10 m long). We represented this environment as a simple euclidean bi-dimensional space, that is discrete (meaning that coordinates are integer numbers) but not "discretized" (as in a CA). Pedestrians, in other words, are characterized by a position that is a pair $\langle x, y \rangle$ that does not not denote a cell but rather admissible coordinates in an euclidean space. Movement, the fundamental agent's action, is represented as a displacement in this space, i.e. a vector. The approach is essentially based on the Boids model [35], in which however rules have been modified to represent the phenomenologies described by the basic theories and contributions on pedestrian movement instead of flocks. Boundaries can also be defined: in the example Eastern and Western borders cannot be crossed and the movement of pedestrians is limited by the pedestrian position update function, which is an environmental responsibility. Every agent $a \in A$ (where A is the set of agents representing pedestrians of the modeled scenario) is characterized by a position pos_a represent by a pair of coordinates $\langle x_a, y_x \rangle$. Agent's action is thus represented by a vector $\overline{m}_a = \langle \delta_{x_a}, \delta_{y_a} \rangle$ where $|\overline{m}_a| = \sqrt{\delta_{x_a}^2 + \delta_{y_a}^2} < M$ where M is a parameter depending on the specific scenario

representing the maximum displacement per time unit.

More complex environments could be modeled, for instance by means of a set of relevant objects in the scene, like points of interest but also obstacles. These objects could be perceived by agents according to their position and perceptual capabilities, and they could thus have implications on their movement. Objects can (but they do not necessarily must be) in fact be considered as attractive or repulsive by them. The effect of the perception of objects and other pedestrians, however, is part of agents' behavioural specifications. For this specific application, however, the perceptive capability of an agent a are simply defined as the set of other pedestrians that are present at the time of the perception in a circular portion of space or radius r_p centered at the current coordinates of agent a. In particular, each agent $a \in A$ is provided with a perception distance per_a; the set of perceived agents is defined as $P_a = p_1, \ldots, p_i$ where $d(a, i) = \sqrt{(x_a - x_i)^2 + (y_a - y_i)^2} \leq per_a$.

Pedestrians are modeled as agents situated in an environment, each occupying about 40 cm^2, characterized by a state representing individual properties. Their behaviour has a goal driven component, a preferred direction; in this specific example it does not change over time and according to agent's position in space (agents want to get out of the corridor from one of the exits, wither North or South), but it generally changes according to the position of the agent, generating a path of movement from its starting point to its own destination. The preferred direction is thus generally the result of a stochastic function possibly depending on time and current position of the agent. The goal driven component of the agent behavioural specification, however, is just one the different elements of the agent architectures that must include elements properly capturing elements related to general proxemic tendencies and group influence (at least), and we also added a small random contribution to the overall movement of pedestrians, as suggested by [36]. The actual layering of the modules contributing to the overall is object of current and future work.

Fig. 4. Experiments on facing groups: several experiments were conducted on real pedestrian dynamics, some of which also considered the presence of groups of pedestrians, that were instructed on the fact that they had to behave as friends or relatives while moving during the experiment.

In the scenario, agents' goal driven behavioural component is instead rather simple: agents heading North (respectively South) have a deliberate contribution to their overall movement $\overline{m}_a^g = \langle 0, M \rangle$ (respectively $\overline{m}_a^g = \langle 0, -M \rangle$).

We realized a sample simulation scenario in a rapid prototyping framework[2] and we employed it to test the simple behavioural model that will be described in the following. In the realized simulator, the environment is responsible for updating the position of agents, actually triggering their action choice in a sequential way, in order to ensure fairness among agents. In particular, we set the turn duration to 100 ms and the maximum covered distance in one turn is 15 cm (i.e. the maximum velocity for a pedestrian is 1.5 m/s).

A. Basic Proxemic Rules

Every pedestrian is characterized by a culturally defined proxemic distance p; this value is in general related to the specific culture characterizing the individual, so the overall system is designed to be potentially heterogenous. In a normal situation, the pedestrian moves (according to his/her preferred direction) maintaining the minimum distance from the others above this threshold (rule *P1*). More precisely, for a given agent a this rule defines that the proxemic contribution to the overall agent movement $\overline{m}_a^p = 0$ if $\forall b \in P_a : d(a,b) \geq p$.

However, due to the overall system dynamics, the minimum distance between one pedestrian and another can drop below p. In this case, given a pedestrian a, we have that $\exists b \in P_a : d(a,b) < p$; the proxemic contribution to the overall movement of a will try to restore this condition (rule *P2*) (please notice that pedestrians might have different thresholds, so b might not be in a situation so that his/her *P2* rule is activated). In particular, given $p_1, \ldots, p_k \in P_a : d(a,p_i) < p$ for $1 \leq i \leq k$, given c the centroid of $pos_{p_1}, \ldots, pos_{p_k}$, the proxemic contribution to the overall agent movement $\overline{m}_a^p = -k_p \cdot \overline{c - pos_a}$, where k_a is a parameter determining the intensity of the proxemic influence on the overall behaviour.

These basic considerations, also schematized in Figure 3-A, lead to the definition of rules support a basic proxemic behaviour for pedestrian agents.

in which the environment is populated with two variable sized sets of pedestrians heading North and South; they are not characterized by any particular relationship binding them, with the exception of a shared goal, i.e. they are not a group but rather an unstructured set of pedestrians.

B. Group Dynamic Rules

In this situation, we simply extend the behavioural specification of agents by means of an additional contribution representing the tendency of group members to stay close to each other. First of all, every pedestrian may be thus part of a group, that is, a set of pedestrians that mutually recognize their belonging to the same group and that are willing to preserve the group unity. This is clearly a very simplified, heterarchical notion of group, and in particular it does not account for hierarchical relationships in groups (e.g. leader and followers), but we wanted to start defining basic rules for the simplest form of group.

Every pedestrian is thus also characterized by a culturally defined proxemic distance g determining the way the pedestrian interprets the minimum distance from any other group member. In particular, in a normal situation a pedestrian moves (according to hie/her preferred direction and also considering the basic proxemic rules) keeping the maximum distance from the other members of the group below g (Rule *G1*). More precisely, for a given agent a, member of a group G, this rule defines that the group dynamic contribution to the overall agent movement $\overline{m}_a^g = 0$ if $\forall b \in \big(P_a \cap (G - \{a\}) \big) : d(a,b) < g$.

However, due to the overall system dynamics, the maximum distance between one pedestrian and other members of his group can exceed g. In this case, the it will try to restore this condition by moving towards the group members he/she is able to perceive (rule *G2*). In particular, given $p_1, \ldots, p_k \in \big(P_a \cap (G - \{a\}) \big) : d(a,p_i) \geq g$ for $1 \leq i \leq k$, given c
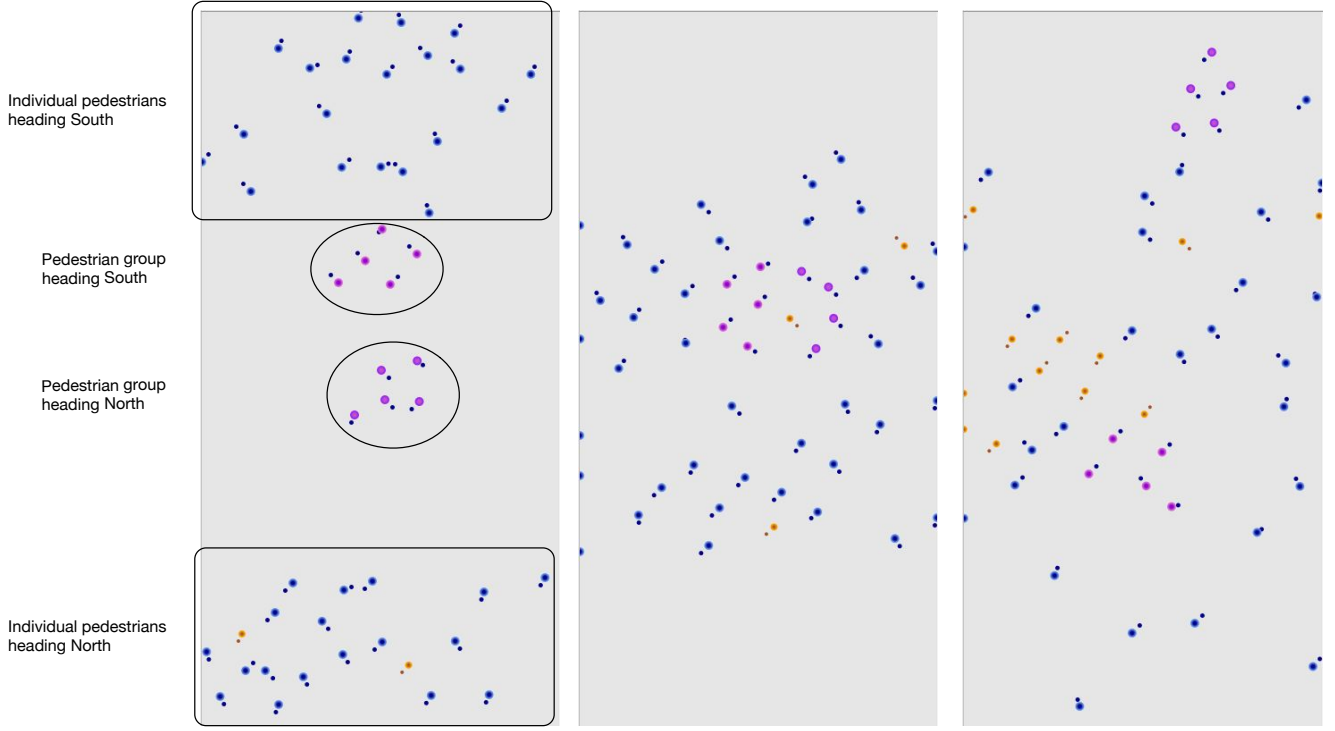
Fig. 5.   Screenshots of the prototype of the simulation system.

the centroid of $pos_{p_1}, \ldots, pos_{p_k}$, the proxemic contribution to the overall agent movement $\overline{m}_a^g = k_g \cdot \overline{c - pos_a}$, where k_a is a parameter determining the intensity of the group dynamic influence on the overall behaviour.

This basic idea of group influence on pedestrian dynamics, also schematized in Figure 3-B, lead to the extension of the basic proxemic behaviour for pedestrian agents of the previous example. We tested the newly defined rules in a similar scenario but including groups of pedestrians. In particular, two scenarios were analyzed. In the first one, we simply substituted 4 individual pedestrians in the previous scenario with a group of 4 pedestrians. The group was able to preserve its unity in all the tests we conducted, but the average travel time for the group members actually increased. Individuals, in other words, trade some of their potential speed to preserve the unity of the group. In a different scenario, we included 10 pedestrians and a group of 4 pedestrians heading North, 10 pedestrians and a group of 4 pedestrians heading South. In this circumstances, the two groups sometimes face and they are generally able to find a way to form two lanes, actually avoiding each other. However, the overall travel time for group members actually increases in many of the simulations we conducted.

In Figure 5 two screenshots the of the prototype of the simulation system that was briefly introduced here. Individual agents, those that are not part of a group, are depicted in blue, but those for which rule P2 is activated (they are afraid to be touched) turn to orange, to highlight the invasion of their personal space. Members of groups are depicted in violet and pink. The two screenshots show how two groups directly

facing each other must manage to "turn around" each other to preserve their unity but at the same time advance towards their destination.

C. Experimental results

We conducted several experiments with the above described model and simulator, altering the starting conditions to evaluate the plausibility of the generated dynamics and to calibrate the parameters to fit actual data available from the literature or acquired in the experiments. In particular, we focused on the influence of the proxemic distance p on the overall system dynamics. We started considering Hall's personal distance as a starting point for this model parameter. Hall reported ranges for the various proxemic distances, considering a close phase and a far phase for all the different perceived distances (described in Section II-A). In particular, we considered both an average value for the far phase of the personal distance (1m) and a low end value (75 cm) that is actually the border between the far and the close phases of the personal distance range. In general, the higher value allowed to achieve relatively results in scenarios characterized by a low density of pedestrians in the environment. For densities close and above one pedestrian per square meter, the lower value allowed to achieve a smoother flow.

A summary of the achieved results is shown in Figure 6. In particular, these data refer to the simulation of a 10 m long and 5 m wide corridor. We varied the number of agents altering the density in the environment; to keep constant the number of pedestrians in the corridor, the two ends were joined
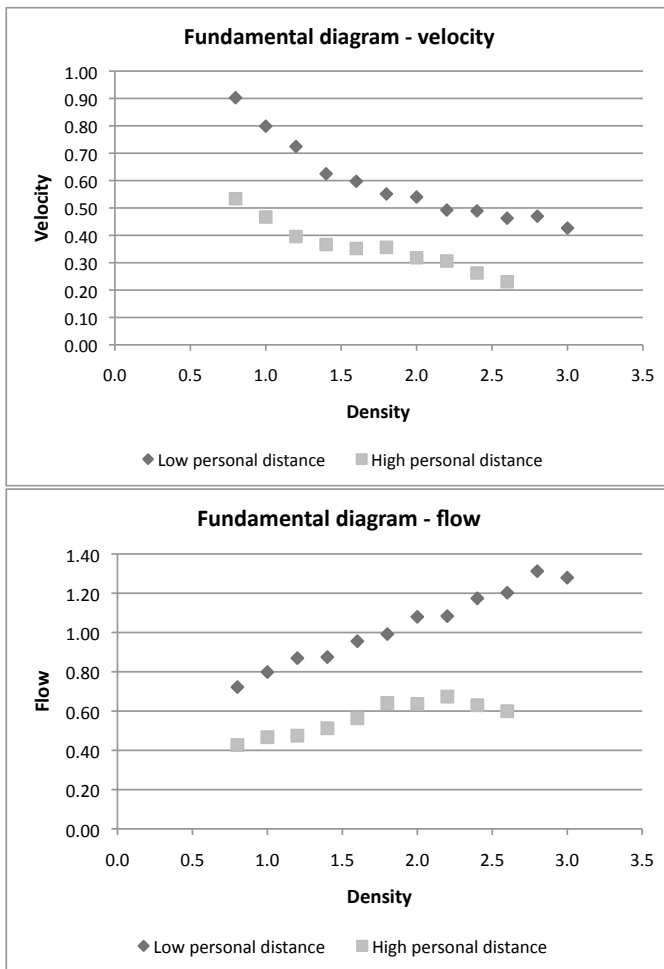
Fig. 6. Fundamental diagrams for the 10m long and 5m wide corridor scenario. The two data series respectively refer to different values for the proxemic distance, respectively the low end (75cm) and the average value (1m) of personal distance.

(i.e. pedestrians exiting from one end were actually re-entering the corridor from the other). For each run only complete pedestrian trips were considered (i.e. the first pedestrian exit event was discarded because related to a partial crossing of the corridor) and in some occasions several starting turns were also discarded to avoid transient starting conditions. The results of the simulations employing the low personal distance are consistent with empirical observations discussed in [7].

We are currently analyzing the implications of the presence of groups in the environment. The generated data, as well as the empirical observations, still do not lead to conclusive results: in most cases, especially in low density scenarios, group members are generally slower than single individuals but in high density scenarios they are sometimes able to outperform the average individual. This is probably due to the fact that the presence of the group has a greater influence on the possibility of other individuals to move, generating for instance a higher possibility of members on the back of the group to follow the "leaders".

V. CONCLUSIONS AND FUTURE WORKS

The paper has presented the research setting in which an innovative agent–based pedestrian an crowd modeling and simulation effort is set. Preliminary results of the first stage of the modeling phase were described. Future works are aimed, on one hand, at consolidating the preliminary results of this first scenarios (performing a calibration of the model and validation of the results, that is currently under way), but also extending the range of simulated scenarios characterized by relatively simple spatial structures for the environment (e.g. bends, junctions). On the other hand, we want to better formalize the agent behavioural model and its overall architecture, but also extending the notion of group, in order to capture phenomenologies that are particularly relevant in the context of Hajj (e.g. hierarchical groups, but also hierarchies of groups). Finally, we are also working at the integration of these models into an existing open source framework for 3D computing (Blender[3], also to be able to embed these models and simulations in real portions of the built environment defined with traditional CAD tools.

ACKNOWLEDGMENTS

REFERENCES

[1] M. Batty, "Agent based pedestrian modeling (editorial)," *Environment and Planning B: Planning and Design*, vol. 28, pp. 321–326, 2001.

[2] A. Willis, N. Gjersoe, C. Havard, J. Kerridge, and R. Kukla, "Human movement behaviour in urban spaces: Implications for the design and modelling of effective pedestrian environments," *Environment and Planning B*, vol. 31, no. 6, pp. 805–828, 2004.

[3] R. Axtell, "Why Agents? On the Varied Motivations for Agent Computing in the Social Sciences," *Center on Social and Economic Dynamics Working Paper*, vol. 17, 2000.

[4] S. Christley, X. Zhu, S. A. Newman, and M. S. Alber, "Multiscale agent-based simulation for chondrogenic pattern formation *n vitro*," *Cybernetics and Systems*, vol. 38, no. 7, pp. 707–727, 2007.

[5] M. Luck, P. McBurney, O. Sheory, and S. Willmott, Eds., *Agent Technology: Computing as Interaction*. University of Southampton, 2005.

[6] E. D. Kuligowski and S. M. V. Gwynne, *Pedestrian and Evacuation Dynamics 2008*. Springer, 2010, ch. The Need for Behavioral Theory in Evacuation Modeling, pp. 721–732.

[7] A. Schadschneider, W. Klingsch, H. Klüpfel, T. Kretz, C. Rogsch, and A. Seyfried, "Evacuation dynamics: Empirical results, modeling and applications," in *Encyclopedia of Complexity and Systems Science*, R. A. Meyers, Ed. Springer, 2009, pp. 3142–3176.

[8] E. T. Hall, *The Hidden Dimension*. Anchor Books, 1966.

[9] ——, "A system for the notation of proxemic behavior," *American Anthropologist*, vol. 65, no. 5, pp. 1003–1026, 1963. [Online]. Available: http://www.jstor.org/stable/668580

[10] U. Chattaraj, A. Seyfried, and P. Chakroborty, "Comparison of pedestrian fundamental diagram across cultures," *Advances in Complex Systems*, vol. 12, no. 3, pp. 393–405, 2009.

[11] E. Canetti and C. Stewart, *Crowds and power*. Farrar, Straus and Giroux, 1984.

[3]http://www.blender.org/

[12] S. Bandini, S. Manzoni, and S. Redaelli, "Towards an ontology for crowds description: A proposal based on description logic," in *ACRI*, ser. Lecture Notes in Computer Science, H. Umeo, S. Morishita, K. Nishinari, T. Komatsuzaki, and S. Bandini, Eds., vol. 5191. Springer, 2008, pp. 538–541.

[13] S. Bandini, L. Manenti, S. Manzoni, and F. Sartori, "A knowledge-based approach to crowd classification," in *Proceedings of the The 5th International Conference on Pedestrian and Evacuation Dynamics, March 8-10, 2010,*, 2010.

[14] M. Schreckenberg and S. D. Sharma, Eds., *Pedestrian and Evacuation Dynamics*. Springer–Verlag, 2001.

[15] D. Helbing, F. Schweitzer, J. Keltsch, and P. Molnár, "Active walker model for the formation of human and animal trail systems," *Physical Review E*, vol. 56, no. 3, pp. 2527–2539, January 1997.

[16] D. Helbing and P. Molnár, "Social force model for pedestrian dynamics," *Phys. Rev. E*, vol. 51, no. 5, pp. 4282–4286, May 1995.

[17] D. Helbing, "A fluid–dynamic model for the movement of pedestrians," *Complex Systems*, vol. 6, no. 5, pp. 391–415, 1992.

[18] S. Okazaki, "A study of pedestrian movement in architectural space, part 1: Pedestrian movement by the application of magnetic models," *Transactions of A.I.J.*, no. 283, pp. 111–119, 1979.

[19] M. Moussaïd, N. Perozo, S. Garnier, D. Helbing, and G. Theraulaz, "The walking behaviour of pedestrian social groups and its impact on crowd dynamics," *PLoS ONE*, vol. 5, no. 4, p. e10047, 04 2010. [Online]. Available: http://dx.doi.org/10.1371%2Fjournal.pone.0010047

[20] K. Nagel and M. Schreckenberg, "A cellular automaton model for freeway traffic," *Journal de Physique I France*, vol. 2, no. 2221, pp. 222–235, 1992.

[21] V. J. Blue and J. L. Adler, "Cellular automata microsimulation of bi-directional pedestrian flows," *Transportation Research Record*, vol. 1678, pp. 135–141, 2000.

[22] ——, "Modeling four-directional pedestrian flows," *Transportation Research Record*, vol. 1710, pp. 20–27, 2000.

[23] A. Schadschneider, A. Kirchner, and K. Nishinari, "Ca approach to collective phenomena in pedestrian dynamics." in *Cellular Automata, 5th International Conference on Cellular Automata for Research and Industry, ACRI 2002*, ser. Lecture Notes in Computer Science, S. Bandini, B. Chopard, and M. Tomassini, Eds., vol. 2493. Springer, 2002, pp. 239–248.

[24] K. Nishinari, Y. Suma, D. Yanagisawa, A. Tomoeda, A. Kimura, and R. Nishi, *Pedestrian and Evacuation Dynamics 2008*. Springer Berlin Heidelberg, 2008, ch. Toward Smooth Movement of Crowds, pp. 293–308.

[25] J. Was, "Crowd dynamics modeling in the light of proxemic theories," in *ICAISC (2)*, ser. Lecture Notes in Computer Science, L. Rutkowski, R. Scherer, R. Tadeusiewicz, L. A. Zadeh, and J. M. Zurada, Eds., vol. 6114. Springer, 2010, pp. 683–688.

[26] C. M. Henein and T. White, "Agent-based modelling of forces in crowds." in *Multi-Agent and Multi-Agent-Based Simulation, Joint Workshop MABS 2004, New York, NY, USA, July 19, 2004, Revised Selected Papers*, ser. Lecture Notes in Computer Science, P. Davidsson, B. Logan, and K. Takadama, Eds., vol. 3415. Springer–Verlag, 2005, pp. 173–184.

[27] J. Dijkstra, J. Jessurun, B. de Vries, and H. J. P. Timmermans, "Agent architecture for simulating pedestrians in the built environment," in *International Workshop on Agents in Traffic and Transportation*, 2006, pp. 8–15.

[28] C. Gloor, P. Stucki, and K. Nagel, "Hybrid techniques for pedestrian simulations," in *Cellular Automata, 6th International Conference on Cellular Automata for Research and Industry, ACRI 2004*, ser. Lecture Notes in Computer Science, P. M. A. Sloot, B. Chopard, and A. G. Hoekstra, Eds., vol. 3305. Springer–Verlag, 2004, pp. 581–590.

[29] M. C. Toyama, A. L. C. Bazzan, and R. da Silva, "An agent-based simulation of pedestrian dynamics: from lane formation to auditorium evacuation," in *5th International Joint Conference on Autonomous Agents and Multiagent Systems (AAMAS 2006)*, H. Nakashima, M. P. Wellman, G. Weiss, and P. Stone, Eds. ACM press, 2006, pp. 108–110.

[30] S. Bandini, M. L. Federici, and G. Vizzari, "Situated cellular agents approach to crowd modeling and simulation," *Cybernetics and Systems*, vol. 38, no. 7, pp. 729–753, 2007.

[31] S. R. Musse and D. Thalmann, "Hierarchical model for real time simulation of virtual human crowds," *IEEE Trans. Vis. Comput. Graph.*, vol. 7, no. 2, pp. 152–164, 2001.

[32] W. Shao and D. Terzopoulos, "Autonomous pedestrians," *Graphical Models*, vol. 69, no. 5-6, pp. 246–274, 2007.

[33] S. Paris and S. Donikian, "Activity-driven populace: A cognitive approach to crowd simulation," *IEEE Computer Graphics and Applications*, vol. 29, no. 4, pp. 34–43, 2009.

[34] Y. Murakami, T. Ishida, T. Kawasoe, and R. Hishiyama, "Scenario description for multi-agent simulation," in *AAMAS*. ACM, 2003, pp. 369–376.

[35] C. W. Reynolds, "Flocks, herds and schools: A distributed behavioral model," in *SIGGRAPH '87: Proceedings of the 14th annual conference on Computer graphics and interactive techniques*. New York, NY, USA: ACM, 1987, pp. 25–34.

[36] M. Batty, *Advanced Spatial Analysis: The CASA Book of GIS*. Esri Press, 2003, ch. Agent-based pedestrian modelling, pp. 81–106.