Crowd Modeling and Simulation
Towards 3D Visualization

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Abstract: The paper introduces a Multi Agent Systems (MAS) approach to crowd modelling and simulation, based on the Situated Cellular Agents (SCA) model. This is a special class of Multilayered Multi Agent Situated System (MMASS), exploiting basic elements of Cellular Automata. In particular SCA model provides an explicit spatial representation and the definition of adjacency geometries, but also a concept of autonomous agent, provided with an internal architecture, an individual state and behaviour. The latter provides different means of space-mediated interaction among agents: synchronous, between adjacent agents, and asynchronous among at-a-distance entities. Heterogeneous entities may be modelled through the specification of different agent types, defining different behaviours and perceptive capabilities. After a brief description of the model, its application to simple crowd behaviours will be given, and an application providing the integration of a bidimensional simulator based on this model and a 3D modelling application (3D Studio) will also be described. The adoption of this kind of system allows the specification and simulation of an architectural design with reference to the behaviour of entities that will act in it. The system is also able to easily produce a realistic visualization of the simulation, in order to facilitate the evaluation of the design and the communication with involved decision-makers. In fact, while experts often require only abstract and analytical results deriving from a quantitative analysis of simulation results, other people involved in the decision-making process related to the design may be helped by qualitative aspects better represented by other forms of graphical visualization.
Designing different kinds of environmental structures, at different detail levels, from the corridors or emergency exits of a building to the whole transportation system on urban or regional scale, requires some kind of simulation system, in order to evaluate strategies and designs before their actual implementation. There are different approaches to simulation, based on various theoretical models, ranging from analytical ones (Helbing [1991]) to those based on Cellular Automata (Wolfram [1986]). Rather than tackling simulation scenarios in a global way, defining centralized solution mechanisms that manage different aspects of the modelled system, they can be suitably reformulated in terms of local interacting entities, which try to achieve their own goals (explicitly specified or implicitly emerging from their collective behaviour), by means of coordination or competition schemes. The solution, global system behaviour, emerges as an effect of agents' individual local behavior (Ferber and Drogoul [1992]). In this framework, approaches based on Multi Agent System (MAS) principles (Ferber [1991]) that propose to focus on interaction aspects of agent groups and crowds have been defined. These works have shown that intelligent group behavior and solution to complex problems can be obtained as the result of interactions between agents characterized by a simple internal model (Drogoul [1995]). A MAS could thus represent a mean of modelling those self-organizing systems that carry out the planning operation to obtain the solution of the design problem.

MASs could even be useful in another kind of iterative design process, centered on simulation (Caneparo and Robiglio [2003]). The latter could provide a first phase in which the designer makes some preliminary choices about the environment, the entities that inhabit it and their behaviour, then a cycle of simulations is performed and the design can be evaluated (by the expert, maybe assisted by some semi-automatic mechanism provided by the system itself). If necessary the design can be then suitably modified by the designer, possibly supported by the system. Then this simulation, evaluation and adaptation cycle could be iterated until the design produces results that are considered acceptable.

The acceptance of the design is generally based on some kind of quantitative analysis of the simulation results performed by experts, but especially in this area there are often a many stakeholders involved in the decision-making process that are not able to understand this kind of information. Where tables, graphs and analytical approaches may not be effective, a realistic visualization of simulation dynamics can integrate them and allow non-experts to better understand effects of the design.
The aim of this paper is to describe the Situated Cellular Automata (SCA) model, a particular class of Multilayered Multi Agent Situated Systems (MMASS Bandini et al. [2002]), that has been designed for situations in which an explicit representation of the spatial structure of the environment is a crucial factor. This structure can be regular or irregular and agents' behaviour is strongly influenced by their position, as it is determined as a consequence of synchronous interaction with other adjacent entities (i.e. reaction) or according to the perception of signals asynchronously emitted by at-a-distance agents (i.e. field diffusion). Synchronous reaction can represent a direct cooperation between neighbours, and operates in a way that is very similar to CA’s transition rule. Remote interaction, implemented through the field emission-diffusion-perception mechanism represents instead a mean of modelling the concept of locality. The latter is generally obtained in CA-based approaches through extensions of the basic model (see, e.g., long-range neighborhood extensions in White and Engelen [1997] or Evans [2003]). The model allows thus to represent heterogeneity in the spatial structure, in agent behaviour and interaction.

The following Section briefly describes the SCA model, focusing on agent interaction, while Section 3 describes how to exploit it in order to represent crowd behaviours. Later two sample applications will be shown, respectively in indoor and outdoor situations. Conclusions and future developments will end the paper.

2. **SCA AT A GLANCE**

The Situated Cellular Agents (SCA) model defines MAS that are situated in environments whose structure is defined as an undirected graph of sites. This Space may represent an abstraction of a physical space, but also a conceptual one, for instance the adjacency relations in “logical” domains, such as the space of collaborations between roles in a business unit or the fact that different entities share an interest with reference to some kind of topic.

A SCA agent is defined by the 3-tuple \( \langle s, p, \tau \rangle \) where \( s \in \Sigma \_s \) denotes the current agent state and can assume one of the values specified by its type, \( p \in P \) is the site of the Space where the agent is situated, and \( \tau \) is the agent type. The latter allows the definition of heterogeneous agents (i.e. agents of different type), and the related perceptive capabilities and behavioural specification. An agent type \( \tau \) is thus defined by the 3-tuple \( \langle \Sigma, \text{Perception}_\tau, \text{Action}_\tau \rangle \), where: \( \Sigma \) defines the set of states that agents of type \( \tau \) can assume and \( \text{Perception}_\tau : \Sigma \rightarrow \{N \times W\} \times \ldots \times \{N \times W\} \) is a function associating to each agent state a vector of pairs representing the
receptiveness coefficient and sensitivity thresholds for that kind of field. This function defines the perceptive capabilities for the related agent type; field diffusion and perception mechanism will be better described in Section 2.1. \textit{Action}, represents instead the behavioural specification for agents of type $\tau$, and will be further described in Section 2.2.

Agent may interact in two different ways, both dependant on the environment and on the position of the involved entities. In particular two or more agents may interact if they are adjacent in their \textit{Space} they agree to synchronously change their state with a \textit{reaction} operation. A field emission-diffusion-perception mechanism allows instead communication among non-adjacent agents. An agent emits a field that is, it generates a signal defining its parameters (i.e. intensity value, diffusion function, and so on), and this signal propagates throughout the space according to its diffusion function. The \textit{Perception}, function, characterizing each agent type $\tau$, defines the other side of an asynchronous interaction among agents: that is, the possible reception of signals conveyed through a field diffused in the environment, if the sensitivity of the agent to the field is such that it can perceive it. This means that a field can be neglected by an agent of type $\tau$ if its value at the site where the agent is situated is less than the agent sensitivity threshold computed by the \textit{Perception} function.

Field perception constitutes a fundamental aspect of the perception-deliberation-action mechanism that specifies MMASS \textit{agent behavior}. This mechanism describes agents as characterized by a set of possible actions, and a mechanism for the selection of the action to be undertaken based on the internal state and the position of the agents themselves. The set of possible actions (i.e. \textit{Action},) specifies whether and how agents of type $\tau$ change their state and/or position, how they interact with other agents, and how neighboring agents can influence them. In the following more details of agent interaction and behaviour will be given. The suitable definitions field types, field sources and triggered behaviours for various agent types may allow to model effects of \textit{attraction} and \textit{repulsion} guiding agent movement in the environment. In this way it is possible to obtain agent movement without the need of providing each agent with an internal representation of the environment on which search algorithms and pathfinding techniques can be applied. Moreover, as agents are field sources, dynamic aspects of the environment such as their density in specific areas (i.e. crowding) may be modelled and considered by agents in the choices related to their movement (e.g. avoid or seek groups).
2.1 At-a-distance agent interaction

Each SCA agent is provided with a set of sensors that allow its interaction with the environment and other agents. At the same time, agents are influenced by the perception of those signals and can assume the role of source of given fields acting within the spatial structure.

Each field is characterized by the set of values that it can assume during its propagation throughout the space, a diffusion function, and field comparison and field composition functions that define field manipulation. Formally, a field \( f \in F \) is defined by \( \{ W_f, \text{Diffusion}_f, \text{Compare}_f, \text{Compose}_f \} \) where \( W_f \) denotes the set of values that the field can assume; \( \text{Diffusion}_f : P \times W_f \times P \rightarrow W_f \) is the diffusion function of the field computing the value of a field on a given space site taking into account in which site and with which value it has been generated (since the structure of a Space is generally not regular and paths of different length can connect each pair of sites, \( \text{Diffusion}_f \) may return a number of values depending on the number of paths connecting the source site with each other site). \( \text{Compose}_f : (W_f)^\times \rightarrow W_f \) indicates how field values have to be combined (for instance, in order to obtain the unique value of a field type at a site), and \( \text{Compare}_f : W_f \times W_f \rightarrow \{ \text{true, false} \} \) is the function that compares field values. For instance, in order to verify whether an agent can perceive a field, its value on the site it is placed on (modified according to the sensitivity coefficient of the agent type) and the agent sensitivity threshold are compared by this function (more details on agent perception will be given in the following subsection).

An agent interaction mechanism, regardless the specific kind of involved sense (e.g. sight, hearing capabilities of a man) can be defined through the specification of:

- **field sources** that can correspond to agents (that may model objects). For instance, fields can be emitted by agents to indicate their availability to fulfill given tasks (e.g. a door, a guide in a museum, a phone booth);

- **functions** to define diffusion, specifying how field values have to be modulated (e.g. when an agent moves far from a group of agents its view must be reduced and it is no more visible when he goes out from a room);

- **field sensors and perception functions** associated to each agent, allowing the representation of different and dynamic agent perceptive abilities, that can be dependent on agent state, goals, and context (e.g. agent sensitivity to the presence of a fire exit must be higher in an emergency situation, but its sight may be impaired by the smoke).
2.2 Agent behaviour

SCA agents are entities that are situated in an environment and that, according to their state, perceive their local environment (perception) and select an operation from a set of possible actions (deliberation) in order to move, modify their state, and interact with other agents (action).

A formal specification of agent perception mechanism and function can be found in (Bandini et al. [2002]). Field perception for each agent type and each field can be defined through the specification of the set of fields that agents are able to perceive (i.e. maximal agent capabilities, e.g. deaf agents can not perceive sound fields); a sensitivity threshold that indicates, according to agent state, the minimum field value that the agent is able to perceive (e.g. when they are involved in a conversation, agents are less sensitive to surrounding noises); a sensitivity coefficient that modulates field values according to agent state (e.g. when an agent is in a hurry, it is more sensitive to exit and elevator signs). The perception mechanism is summarized in Figure 1: the first part is related to the physical possibility to perceive a signal in a certain situation, while the second one refers to the semantic value that the agent assigns to the perception in the current circumstances. With reference to the previous example, related to the perception of a human agent in a fire emergency situation, the first part of the mechanism is used to specify that smoke reduces agent possibility to perceive visual signals, and this can be modelled as a change in agent state upon the perception of smoke. The reaction to this perception may also make
the agent more sensitive to signals related to emergency exits (i.e. rise the related sensitivity coefficient). The global effect can be fine tuned through a suitable definition of coefficients and thresholds, but the model can represent physical impairment (or improvement) related to perception and increased attention related to semantic aspects.

Agent behaviour can be specified using the L*MASS (Bandini et al. [2001]) language that defines the following primitives:

- reaction($s, a_1, ..., a_n, s'$): this primitive defined for agent $a$ situated in the site $p$ allows it to synchronously interact with agents $a_1, ..., a_n$ situated in $p_1, ..., p_n$ adjacent to $p$, that have agreed to take part in the interaction; the effect of this interaction is the change of its state from $s$ to $s'$;

- emit($s, f, p$): the emit primitive allows an agent to start the diffusion of field $f$ on $p$, that is the site it is placed on;

- trigger($s, f_i, s'$): this primitive specifies that an agent must change its state from $s$ to $s'$ when it perceives a field $f_i$;

- transport($p, f_i, q$): the transport primitive allows to define agent movement from site $p$ to site $q$ (between whom an adjacency relation must be present) upon reception of field $f_i$.

For all these primitive, additional conditions (i.e. sort of guards on the execution of the related operation) on agent state, perceived fields and adjacent sites can be specified. In some cases these two parameters can be insufficient, as they are just related to a single site, therefore these conditions can include the intensity of fields present in adjacent sites. For instance, in order to specify a transport operation, this is necessary to model the behaviour of an agent wishing to move to the adjacent site with the highest intensity of a certain field. In order to specify that a certain agent of type $\tau_a$ can attract agents of type $\tau_b$, one must respectively define a field type $F_{a\rightarrow b}$, specifying required parameters, insert a specific emit action in Action$_{\tau_a}$ and a transport operation in Action$_{\tau_b}$ indicating that the related agent of type $\tau_b$ should move towards the adjacent site with the highest value for field type $F_{a\rightarrow b}$. More precisely the transport action would be specified as follows:

\begin{verbatim}
action: transport(p, fa->b, q)
condit: position(p), empty(q), near(p,q), perceive(fa->b),best(q)
effect: position(q), empty(p)
\end{verbatim}

where $p$ and $q$ are sites, position($p$) specifies that the related agent is placed in $p$, empty($q$) indicates that site $q$ is not occupied by other agents, near($p,q$) specifies that
the arguments are adjacent sites (i.e. connected by an edge in the spatial structure) and \( \text{perceive}(f_{a\rightarrow b}) \) indicates that the agent is able to perceive a field \( f_{a\rightarrow b} \in F_{a\rightarrow b} \). The additional condition \( \text{best}(q) \) is verified when for all sites \( r \) adjacent to \( p \) and currently empty, the intensity of field type \( F_{a\rightarrow b} \) is lower or equal than is site \( q \). Repulsion requires the same operations, with a difference in the transport action, whose destination is the site with the lowest value for the repelling field type. More complex conditions for the transport operation can cause interesting effects, such as an agent that keeps at a certain distance from the source of a specific field type, following thus its movement but avoiding contact. The definition of different field sources and types (or, equivalently, the inclusion of an indication of the related source in the information related to fields) allows the definition of different way-points, intermediate goals in a script that specifies a path in the environment. An agent may be perceptive to the first field type and move towards its source. When the perceived field intensity reaches a certain level (i.e. when the distance has reduced under a certain degree) the agent may change its goal, becoming perceptive to the field emitted by the next way-point. In order to obtain more complex behaviours, for instance related to agents interests, goals, and more autonomous behaviours requires a more composite field definition, that should encapsulate more information than their simple intensity, and different agent actions. A formal description of the introduced modelling elements can be found in Bandini et al. [2004a].

3. CROWD MODELLING AND SCA

As previously specified in Section 2, the SCA model provides a discrete representation of the environment, an abstraction of the actual spatial structure in which the simulation takes place. In order to specify a situation exploiting the concepts defined by the model, the first step is to describe the simulation scenario in terms of a discrete and possibly irregular network of nodes. Figure 2 shows the 3D representation of a museum room and the related abstraction with a grid structure. Black squares are occupied by walls, grey ones represents artworks, while agents are represented with black circles. The decision on the granularity of the tessellation depends on the features of the scenario and especially on the goal of the simulation: for instance, if the main aim is to evaluate the design of a corridor in an evacuation situation, the spatial abstraction should reflect the actual dimensions of a human body and its space occupancy.
The second step is to describe the behaviour of the different entities placed in the environment, in order to obtain a realistic system dynamic. With reference to the same figure, we could model artworks and doors as sources of fields that can have an attractive effect on agents placed in the environment, according to their own internal state and goals. In fact agents may be perceptive to fields emitted by artworks placed at a distance lower than a specified threshold, and be attracted for a specific time interval, but only if they still have not already observed it. They may also be perceptive to doors and passageways, with a different priority. For instance they may decide to move from one room to another (according to a specific order among rooms), following the field emitted by the related door, after they have observed every artwork present in the room.

The placement of field sources must be specified with considering the diffusion function related to field types: in order to obtain a realistic behaviour of agents they should not be able to perceive the presence of an artwork if they are not able to see it. This consideration indicates that the diffusion of some signals can exploit the actual 3D model of the environment for the diffusion of specific field types, while for other ones (e.g. audible signals) the bidimensional abstraction can be enough to obtain believable system behaviour.

The definition of fields and diffusion functions, with reference to the representation of the environment, is just one side of behaviour modelling. The other is related to the specification of the reaction to the perception of a certain signal, in the form of actions undertaken by agents. Different entities may react in a completely different way to the perception of the same field, and even the same agent can perform different actions according to its own state. For instance, in order to specify that an agent should follow a specific path, the related way-points could be associated to field sources. The agent could be sensitive to the field emitted by the closest way-point and moving towards it, becoming sensitive to the next one once its distance becomes
lower than a certain threshold. Moreover the way-points could be exploited by different agent types related to different paths. In other words the order of the points to visit could be defined in the behaviour specification related to a specific agent type, and sources could be just relevant points indicating their presence through the emission of a presence field.

In the same way effects of attraction and repulsion can be defined in order to fine tune the behaviour of various entities roaming in the environment according to its infrastructure. Anyway agent movement can also be based on the behaviour of other active entities. In other words agents may be at the same time affected by fields but also sources of signals affecting other entities. For instance, a specific agent may be the source of a presence field that is considered attractive by a specific agent type. In this way crowds can concentrate around a leader and follow him/her in a procession (see Figure 3). In a similar way lanes and queues can be obtained specifying that every agent is only sensitive to the signals emitted by the preceding one, and having leaders that guide the crowd, following specified paths.

4. SAMPLE SIMULATIONS

One of the applications developed to implement SCA based simulations exploits a simulator based on a bidimensional spatial structure representation.
and an existing commercial 3D modelling instrument (3D Studio MAX). The simulator has been developed as experimentation and exploitation of a long term project for a platform for MMASS based simulations (Bandini et al. [2004b]). This software is based on the Java platform and its goal is to implement basic elements and mechanisms of the MMASS model in order to allow a user to rapidly use these components to build a simulation.

This simulator produces results that can undergo a quantitative analysis whose results can be easily understood by experts of the application area. In different situations it can be useful, for sake of communication with non-experts, to obtain a more effective visualization of simulation dynamics. To do so, the bidimensional simulator produces a log-file provided with a fixed-record structure, in which every record is related to a node of the spatial structure or the position of an agent with reference to this structure. Initially, the simulator prints the structure of the environment, then the starting position of each agent. For every iteration of the simulation the new position of every agent is also printed. This file is parsed by a 3D Studio Max script which generates a plane and walls related to the spatial structure, nodes related to sites, and bipeds related to agents. Splines are then generated starting from the discrete positions assumed by various agents, and represent bipeds' movement. This process introduces modifications to trajectories defined by the bidimensional simulator whose sense is to give a more realistic movement to agents' avatars. This application was tested in an abstract indoor situation, related to an evacuation scenario (see Figure 4).

Agents placed in this room are attracted by the door, which is source of a field that generates a gradient that can be ‘climbed’ by the entities placed in the room that are able to perceive it.

The perceptive capabilities, and especially agent behaviour, is object of current developments in collaboration with sociologists and psychologists: in fact it is possible to model psychological data and knowledge in order to define specific fields (e.g. presence signals that can model crowding) and transport actions for various agent types. For instance very lucid agents could favor sites where there are signs of an exit (whatever it is) and the crowd density is low. For instance this can be obtained introducing a presence field, which is emitted by every agent, whose Compose function simply sums the intensity of signals emitted by various agents. Other agents instead may head towards the closest exit, completely disregarding overcrowding situations or simply stand still. These considerations can be suitably represented by conditions specified for every transport operation in the behavioural specification of an agent type.
Figure 4. A screenshot of the animation produced by the 3D modelling tool in an indoor scenario.

Figure 5. A sketch of the bidimensional spatial structure editor.
The interaction mechanism between the simulator and the 3D modelling tool is currently being modified in order to allow an easy integration with existing models of the environment. By doing so, it will be possible to draw the bidimensional abstraction of the space directly on images obtained by the 3D modelling tool. Figure 5 shows a top view of a Scala Square in Milan, and a lattice of nodes has been generated in order to define a spatial structure suitable for adoption in a SCA model.

Figure 6. A screenshot of the animation produced by the 3D modelling tool in an outdoor scenario (the 3D model of Scala Square appears courtesy of Geosim systems)

Some nodes are related to portions of space that can be occupied by agents, while other ones are already occupied by static objects. This instrument allows the definition of a graph structure, inserting and deleting nodes and edges, starting from scratch or modifying predefined structures like regular lattices. The development of this kind tool for the specification of the environment is currently on-going and will allow an easy adoption of these models and instruments even in a realistic outdoor scenario.

As a preliminary result, some sample animations related to the area of Scala Square were produced: a screenshot of these animations is shown in Figure 6. Agents related to passers-by, heading for different ways out of the square,

1 The 3D model of Scala Square appears courtesy of Geosim systems.
only walk on “legal” spaces (i.e. sidewalks and zebra crossings), avoiding each others and, if needed, waiting for other agents to move out of their way. Their trajectory, as previously specified, is actually smoothened by a script that parses the simulation log and produces agents’ trajectories in the 3D modelling tool.

5. CONCLUSION AND FUTURE DEVELOPMENTS

This paper has presented the application of the SCA model to crowd modelling, simulation and visualization. The model provides the possibility to explicitly define a spatial structure of the environment in which the simulation takes place. Relevant objects are modelled as sources of fields, signals that diffuse in the environment and can be perceived by agents. The reaction to the perception of these fields is defined by agent type, which also specifies perceptive capabilities with reference to their state. The interaction model defined by the SCA model provides the possibility to obtain agents able to act and interact in an environment according to their context, in terms of spatial relationships among agents and local perception of signals. In this way it is possible to obtain agents that are more autonomous, meaning by that that they do not need an internal representation of the environment, on which traditional search algorithms or pathfinding techniques must be applied, but are instead guided by signals perceived in the environment. Moreover dynamical aspects of the environment can be modelled (e.g. the crowding of an area) through the field emission-diffusion-perception mechanism, and agents can adapt their behaviour to these additional contextual conditions. For instance agents may thus try to avoid or seek crowded areas, according to the behavioural specification that has been adopted for the simulation.

Currently the SCA model is being applied to simulation supporting localization (Bandini et al. [2003]), design of environments, but it is also being considered as an instrument for urban and environmental planning. The applications that were described in this paper provide the integration of a simulator and a 3D modelling tool, but the design of an integrated simulator and 3D engine for the development of real-time dynamic (and possibly interactive) applications exploiting elements of the model is currently under-way.

REFERENCES


