Pedestrian Modeling as Generative Mechanism for the Design of Adaptive Built Environment

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Abstract. The investigation of the relationship between pedestrian modeling and the built environment is essential in the process of analyzing, evaluating and generating new architectural spaces that can satisfy circulation design conditions and respect the surrounding environment in the best possible way. In order to achieve the direct interaction between the users and the environment, current work attempts to examine how pedestrian models can be used as generative mechanisms for the production of adaptive spaces, which can be optimized according to human movement behavior needs. In this investigation, an existing computer program will be further developed in relation to its ability to inform the environment in an adaptive manner resulting the formation of spaces that can influence and can be influenced by pedestrian movement behavior and hence circulation systems. This can be done by creating new rules of interaction between components, for instance between pedestrians and the geometry of environment, and by taking into account pedestrian movement behavior conditions, as well as functional and morphological architectural design criteria.

Keywords: Pedestrian modeling; virtual forces; generative design; adaptive built environment.

INTRODUCTION

The integration of pedestrian modeling approaches with the design of built environment is important for the generation of spaces that can satisfy movement criteria of effective flow, efficient use of space, as well as aesthetical design criteria. As it has been already discussed in previous work by the author (Kontovourkis 2010), human movement behavior simulation involves the use of different modeling techniques largely used for the evaluation of human movement performance in the built environment. Attention has been given in models that simulate the behavior of a large number of interacting components (particles, agents, pedestrians, etc) in real time and in parallel based on simple rules of interaction. Such techniques might be divided in two main categories, in social interaction-communication and in way-finding (Kontovourkis 2010). Examples that attempt to investigate the above-mentioned relationship between pedestrian modeling and design of built environment can be found in both categories.

In the first category examples might include work done in the area of pedestrian modeling in order to
solve problems in micro-scale level and specifically in spaces within buildings. In such cases, works might propose new design of spaces where the movement of pedestrians is found to be problematic influencing the smooth transition and flow of pedestrians from one space to the other. Also, work might be found in cases where design needs to be improved in order to allow unobstructed movement of pedestrians, for instance in emergency situations. Various attempts to find connections and to generate spaces that can satisfy movement behavior scenarios can be found, for instance, in the work done by Helbing et al. (2001) for the design optimization of corridors' bottlenecks according to human movement conditions using pedestrian modeling and evolutionary design principles. Helbing et al. (1997a; 1997b; 2001) have also introduced an active walker model where pedestrians were programmed to influence their environment and vice versa.

Focusing on similar principles that combine pedestrian modelling and optimization processes, Turner et al. (2004) combined pedestrian modelling techniques based on visual perception together with evolutionary algorithms to solve problems related to the organization of rooms and spaces.

In each case, an extended version of pedestrian model has been used, which combines simulation of movement and design optimization strategies in order to investigate and improve existing spaces, to suggest solutions in problems of spatial arrangement, etc. In the process of generating new building environments using pedestrian simulation techniques, computer models are enriched by adding new computational rules and information that will connect their internal structure with the geometry of environment to be generated.

OVERVIEW
The paper is structured as follows: the second part demonstrates new rules and information added on the existing computer program allowing its use as design generator of adaptive spaces; the third part tests the program and its ability to generate new environments by introducing two design scenarios together with a discussion on results; the fourth part draws some general conclusions.

COMPUTER PROGRAM
The existing computer program is called ‘virtual force’ model since the interaction and movement of individual components (this word is used to describe all types of individual components involved in pedestrian modeling) is achieved by the application of forces that are acting on them motivating their movement behavior. Apart from individual components that represent pedestrians, other type of components include signs, obstacles, boundaries, etc. Interaction between different types can be used in order to investigate pedestrian movement behavior within given environment (Kontovourkis 2009; 2010).

In previous work, rules of behavior were divided in two main categories. The first category includes rules of interaction behavior between pedestrians and other types of individual components that produce a number of effects like repulsion, attraction, obstacle avoidance, and sign effect (attraction-direction force) (Williams and Kontovourkis, 2008) (Kontovourkis 2009; 2010). The second category includes rules of movement based on route choice behavior modeling, which allows pedestrians to select their route towards a particular destination using systems of signs and destinations (Kontovourkis 2009; 2010).

In all cases, types of individuals that represent geometrical components of the built environment were treated as static objects. Circulation diagrams were generated showing possible optimum paths that pedestrians were taking to reach various destinations. A number of other information was taken from these models, for instance occupation of areas by pedestrians during their movement towards a particular destination. Also, circulation diagrams were evaluated according to various movement behavior criteria including the effective flow and the efficient use of space, but the decisions on the formation of built environment was taken based on architect’s selection and choice. Such design strategy involves the use of pedestrian modeling techniques together with architect’s intervention.
This work tries to expand current program’s potential by introducing new computational rules and information that can be added on the existing program in order to develop a new digital design strategy for the generation of adaptive built environment. Apart from interaction and movement behavior that occur between different types of individual components, the new developments include interaction with geometrical components of the environment in a dynamic manner again using the concept of ‘virtual forces’. The pedestrian model is developed further to include the following behavioral rules that can lead to a number of new effects. For the purpose of current paper these behavioral rules are divided in three main categories:

• Behavioral rules between pedestrians and the geometry of environment
• Behavioral rules between different geometrical components of the environment
• Behavioral rules between components within pedestrians’ system of movement

**Pedestrians – Geometry of environment**

The first behavior that can be emerged is the one due to the movement of pedestrians in a given empty space. Such behavior leads to the production of spaces that are occupied by pedestrians. Following examples show computer-generated spaces due to the movement of two groups of pedestrians (red and blue) that interact in a given environment. The red group moves from bottom-left to top-right and the blue group moves from bottom-right to top-left [FIGURE 1].

Computer-generated spaces can be defined geometrically as cells, trails, networks of proximity, geometrical as cells, trails, networks of proximity,

**Figure 1**
Spatial arrangement generated by pedestrians’ movement behavior simulation in a given time interval. Left: Pedestrians’ area occupation, Right: Pedestrians’ network of proximity

**Figure 2**
Patterns produced by the interaction of pedestrians with boundaries. Images show pedestrians’ area occupation (three basic time steps)
etc. Quantitative and qualitative information taken from such investigation might include areas, positions, and statistical values related to the occupation of areas by individuals moving in a specific direction and in a given time interval.

The second behavior is the result of pedestrians’ interaction with given geometrical components of the environment. In this category, attempt is to re-formulate or to re-define new position of geometrical components based on their mutual interaction with pedestrians. Repulsive forces between pedestrians and geometrical components are used. In this case, components can represent boundaries or obstacles but can also take different names, forms and arrangements according to the problem under investigation. In both cases, in boundaries and in obstacles, the components that describe their geometries can be static or movable objects resulting changes of pedestrians’ and objects’ position according to the forces acting on them.

Examples show, first, a possible interaction of pedestrians with boundaries [FIGURE 2], and second, a possible interaction of pedestrians with obstacles [FIGURE 3].

As it has been already mentioned, such investigation can take different forms and expressions resulting the generation of various design outcomes, which are related to the selected geometry and arrangement of geometrical components as well as the pedestrians’ movement behavior.

This interaction suggests the generation of fluid spaces that are continuously re-created. Although, such study can provide an idea of the design process adopted for the generation of dynamic empty spaces in-between pedestrians’ systems of movement, it has been observed that there is not much flexibility of the system to re-formulate the direction of pedestrians’ movement in global level. This is achieved only in local level between individual components that represent pedestrians and other components that represent obstacles or various forms of boundary systems (repulsive behavior between two individual components, for instance pedestrians and obstacles or pedestrians and boundaries). The global control and dynamic interaction of pedestrians’ movement behavior with the geometry of environment might be achieved by re-parameterizing the way geometrical components of the environment behave in relation to the movement of pedestrians.

The previous investigation can be further developed by examining the dynamic interaction that occurs between various geometries of the environment as well as components that influence pedestrians’ movement systems. Following behavioral rules investigate dynamic interactivity that is occurred, first, in the geometry of environment, and second, in pedestrians’ movement systems.

**Geometry of environment**

Behavioral rules within the geometry of environment adopt concepts related to previous investigations, particularly concepts derived from repulsive or attractive effects (Kontovourkis 2009; 2010). Repulsion
or attraction forces are applied in order to achieve connectivity, separation, or proximity between different geometries.

In the following example, the interaction between boundaries, obstacles, and field area in a given environment is examined. The goal is to optimize the spatial organizational structure of geometrical components according to ‘virtual forces’ acting on them influencing their behavior and hence their position in space. Following figures show an attempt to generate patterns derived from these concepts using repulsive forces [FIGURE 4].

The global formulation of such systems is the fluid result of the interaction between individual components that consists the built environment with possible influence by individuals that represent pedestrians. It is a time-based re-formation of systems that re-adjust their position and morphology in space taking into account repulsive forces acting on pedestrians’ movement system and on the geometry of environment [FIGURE 5].

**Pedestrians’ systems of movement**

This approach, in comparison with the previous ones, concentrates on the global control of pedestrians’ movement behavior, which can be changed continuously over time due to the external interaction of pedestrian movement components (signs, destinations) with the environment.

As it has been already developed in previous work done by the author, signs influence the movement behavior of each pedestrian. The position of signs in space in relation to the position of destinations can formulate systems of movement according to specific scenarios. So far, the arrangement of signs and destinations were done based on architect’s selection and choice mainly in an iterative design process. Basic steps in this procedure includes the initial simulation, the evaluation of results according to given movement criteria, and the suggestions for new signs and destinations positioning that fulfills movement criteria in the best possible way.

In this paper, the procedure moves a step further, attempting to introduce methods for the direct interaction between components (for instance signs or destinations) that accelerate movement behavior. Behavioral rules between signs or destinations are

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**Figure 4**
Patterns produced by the interaction between geometrical components of the environment. Images show pedestrians’ network of proximity (three basic time steps)

**Figure 5**
Spatial arrangement as the result of dynamic interaction between pedestrians’ system of movement and the geometrical components of the environment in a given time interval.
applied aiming to control their position in space according to parameters of proximity, separation, etc. By achieving re-adjustment of movement components in space, their interaction with pedestrians can continuously change the way path systems are generated introducing an optimum relation between pedestrians and movement systems. As a result the 'best' design solution of circulation systems in a given built environment can be generated.

In general, current work attempts to enrich the existing pedestrian model by adding new behavioral rules. Simulated results and data derived from pedestrians’ movement behavior can dynamically inform and be informed by the environment generating an adaptive built environment. Again this can be achieved by investigating different effects based on forces acting on each type of individual component motivating its behavior according to the surrounding conditions of the built environment.

In order for the study to be completed, results from dynamic interactivity between different types of individuals are analyzed and used for further studies aiming at the optimization of design. Also, attention is given on the information derived from the position and area occupation of pedestrians in space.

Following section tests the new computational rules and information based on two scenarios of interaction between pedestrians and the built environment.

**DESIGN SCENARIOS**

This part examines the relation between pedestrian modeling and design of built environment through the generation of adaptive spaces that can satisfy pedestrian movement criteria and geometrical conditions of the environment. In order to achieve this, two scenarios are developed, evaluated and results are derived as regards the pedestrian modeling principles introduced in the previous part and the conditions of the built environment under investigation:

- The first scenario takes into account minimum conditions of the surrounding environment (pedestrian movement behavior)
- The second scenario takes into account maximum conditions of the surrounding environment (geometrical components)

Both scenarios are developed based on initial information derived from previous author’s work (Kontovourkis 2010). This is done mainly in order to examine relations, correlations and connections with previous work and to draw useful conclusions that can help on the application of computational techniques in architectural design. In order to test the potential of new computational rules to be used as generative mechanism, the hypothetical existing example of an imaginary public area of a city is taken, together with all initial information that formulate the design problem under investigation (Kontovourkis 2010).

Although, the example remains the same as regards the initial geometrical conditions, parameters that formulate the problem are modified and new ones are developed according to the current scenarios.

In order to have a clear understanding regarding the initial parameters of the given public area, following information derived from previous work is given (Kontovourkis 2010):

- The example might be categorized in macro-scale level where the design of circulation systems and the organization of functional areas are examined
- Circulation systems can help towards the generation of design solutions that aim to achieve space efficiency and at the same time to optimize spatial configuration
- The procedure involves the parallel use of pedestrian modeling and design following an iterative process starting from an initial pedestrian simulation, then evaluating the results and finally suggesting new design that is used as the starting point for further studies

The conditions of given environment as it was described in previous work by the author is given below (Kontovourkis 2010) [FIGURE 6]:
• Outline of public area including initial positioning of spaces or points of interest
• Points on the boundaries of public area are fixed representing entry and destination points
• Spaces within public area are initially distributed randomly
• Pedestrians move and interact with each other within the given area according to different needs and desires
• Pedestrians flow diagrams consists of different points of interest and movement scenarios
• Given movement scenarios are represented by route choice strings where each point represents a space or point of interest (spaces are organized in a sequence of movement steps with one entry and one destination point)
• Three groups of pedestrians (A, B, and C) move inside the given area, each of them related with three possible route choice strings
• Route choice strings and hence generated systems are divided in two categories: a. Main circulation system that represents movement of all pedestrian in the perimeter of functional areas, and b. Secondary circulation system that represents movement through spaces or points of interest

The current work attempts to apply new behavioral rules that have been developed in previous section. Such rules will allow an alternative investigation of the existing design problem different from the one examined in previous work (Kontovourkis 2010). In both cases (current and previous work), the aim is to create architectural spaces that can satisfy given movement scenarios.

**First scenario**

In the first scenario, design possibilities are the results of the interaction behavior between pedestrians in existing movement systems and new geometrical components of the environment like functional areas, field areas, boundaries, obstacles, etc. Initially, components of pedestrian movement behavior, for instance signs and points of interests (destinations), are positioned in the area under investigation. Such components are determined according to given movement scenarios (route choice strings). It is expected that pedestrians will interact with the geometry of environment resulting re-positioning or re-adjustment of functional areas, boundaries, obstacles, etc. Attempt is to generate an adaptive built environment based on those interactions. Following figures show patterns generated by this behavior [FIGURE 7; FIGURE 8]

**Second scenario**

In the second scenario, design possibilities are the results of the interaction behavior between existing geometrical components, for instance boundaries, and pedestrians’ movement systems in the given environment. It is assumed that results derived from previous design scenarios are used as the initial geometrical configuration. Based on the given geometry of environment, the movement behavior of

**Figure 6**

Pedestrians’ route choice strings. Left: Main circulation system, Right: Secondary circulation system (Kontovourkis 2010)
pedestrians under the influence of surrounding environmental conditions is investigated.

Results derived from both scenarios show design possibilities that can be emerged taking into account different parameters and behavioral rules. It is believed that through such investigation a number of unpredictable results are produced satisfying movement criteria as they are described in each case.

Focusing on macro-scale design investigation, current work examines how such pedestrian models can be used as generators of adaptive built environments. It has been found that such methodology can be used in the conceptual stage of design providing alternative design solutions that are generated using modeling and optimization processes. Behavioral rules and information derived from such studies can be examined and developed further in order to allow the use of similar principles in different levels of design.

**CONCLUSIONS**

In conclusion, the current program and the new behavioral rules have the potential to be used as generative mechanisms for the design of adaptive built environment. Obviously, new behavioral rules can be added, as well as scenarios can be further developed in order to continue the current investigation, which is in a preliminary phase. In parallel with the development of any new movement behavioral rules, the model can be useful in architectural design education and practice. It is believed that there is a potential towards this direction since the concepts, which relate pedestrians’ movement behavior with the design of built environment are essential aspects that need to be taken into account in any architectural design problem. Architects and students of architecture can further develop ideas of adaptive spaces and interactive relations by introducing such
concepts in their computer models involving different computational approaches.

**FUTURE PLANS**
Current work will continue towards the development of new computational rules in order to improve results presented in this paper. Also, analytical information derived from current movement behavior and interactivity between geometrical components will be investigated further. Finally, current methodology will be applied in actual design scenarios and results will be examined.

**REFERENCES**