Simulating Human Behaviour in Built Environments

YAN Wei and KALAY Yehuda
Department of Architecture, University of California, Berkeley, USA

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Abstract: This paper addresses the problem of predicting and evaluating the impacts of the built environment on its human inhabitants. It presents a simulation system comprising a usability-based building model and an agent-based virtual user model. The building model represents both geometric information and usability properties of design elements, and is generated automatically from a standard CAD model. Virtual users are modelled as autonomous agents that emulate the appearance, perception, social traits and physical behaviour of real users (walking, sitting, meeting other virtual users, etc.). Their behaviour model is based upon theoretical and practical environment-behaviour studies, real world data from a field study, and Artificial Life research. By inserting the virtual users in the usability-enabled building model, and letting them "explore" it on their own volition, the system reveals the interrelationship between the environment and its users. The environment can then be modified, to see how different arrangements affect user behaviours.

1 INTRODUCTION

Human spatial behaviour, in the context of architectural design, is a term that describes the relationship between the built environment and its human inhabitants. 'Good' spatial behaviour is an indicator of successful architectural design, whereas 'bad' spatial behaviour can be an indicator of wasted resources and the cause for occupants' dissatisfaction. For example, in a study of New York City urban spaces, William Whyte (1980) found that some worked well for people, while most others did not. At lunchtime, a good plaza attracted many people sitting, sunbathing, picnicking, and talking (Figure 1 left). Others were not used much, except walking across (Figure 1 right). If designers of the plazas could predict the ensuing behaviour pattern in advance, they would design spaces that are better suited for their intended use. Simulating future human spatial behaviour is, therefore, an area of great interest to designers and clients.

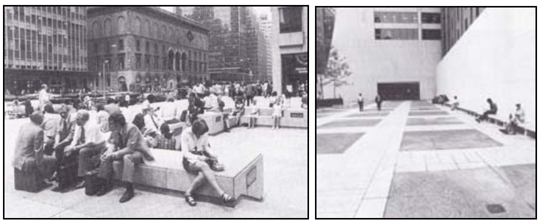


Figure 1 New York City plazas (Whyte 1980)

Most current environmental simulations, however, pay more attention to the physical qualities of built environments, such as lighting, energy use, and thermal comfort, than to human spatial behaviour. Existing human spatial behaviour simulations are often limited to some well-defined areas of human activities, where considerable empirical research helped develop the requisite cognitive models. These include pedestrian traffic simulation (e.g. Helbing et al. 2000; Haklay et al. 2001), and fire egress simulation (e.g. Stahl 1982; Ozel 1993). Such simulations are often aimed at testing the Level of Service—the amount of space people need to conduct certain activities, such as the width of walkways, corridors, and doors, under both normal and emergency situations. General human spatial behaviour simulation models have been developed by Archea (1977), Kaplan & Kaplan (1982) and others. They typically use discrete event simulation methods, where a generalized algorithm tracks minute-by-minute changes, geometry-based approaches, or neural-nets (O'Neill 1992).

Our approach, turning contrast, is general purpose: it is based on an agent-based artificial user model, which can be inserted in any environment. Earlier work by Steinfeld (1992) and Kalay & Irazábal (1995) proposed, but did not implement, the development of artificial—or 'virtual'—users. We have developed simulation methods and implemented both simulation and visualization of human behaviour in a public space. To allow the virtual users to recognize the environment in which they operate, we developed a usability-based building model, which possesses both geometric information and usability properties of design elements. It is generated automatically from a standard CAD model, which saves the need to re-enter a specific model for the simulation. The virtual users are modelled as autonomous agents that emulate the appearance, perception, social traits and physical behaviour of real users. These behaviours are based on a field study using automated video tracking techniques to generate statistics of users' behaviour in a public space (as discussed in Section 2). The conversion of a standard CAD model of the space into a usability-based building model is discussed in Section 3. The agent-based virtual user model is based on environment-behaviour theories, the field study, and Artificial Life algorithms (Section 4). A simulation engine that achieves similar behaviour patterns to those observed in reality is discussed in Section 5.

2 BEHAVIOUR TRACKING AND ANALYSING

To ensure the correspondence of the simulation to reality, our simulation is based on a large amount of quantitative, real-world behaviour data. The data was collected through our automated video tracking system that automatically tracked and analysed the behaviour pattern of users in a public space (Yan and Forsyth 2005). The tracking system consists of an algorithm to detect individual people in single video frames, and a data association technique for tracking people through successive frames. We applied the system to 8 hours of video data, which was recorded in Sproul Plaza at U.C. Berkeley, during 4 days, from 3PM to 5PM on each day, in summer 2003 (Figure 2).

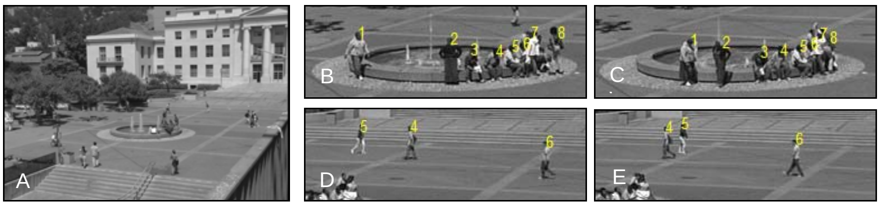


Figure 2 Plaza video (A). Tracking people at the fountain (B & C) and walking (D & E)

The target region is a roughly square space in the centre of the plaza. It contains distinctive paving, a fountain with low seating edge, large area of steps, and a few benches. The plaza is the birth-place of the Free Speech Movement of the 1960s, and has, therefore, been studied extensively by researchers.

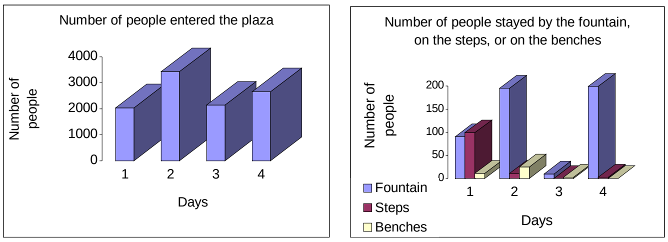
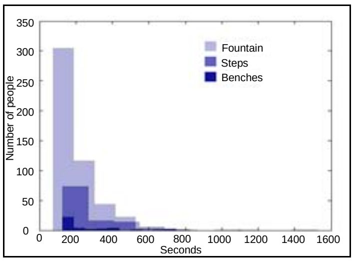


Figure 3 Left: Numbers of people who entered the plaza in different days. Right: Numbers of people sat at different places.

We compared the results obtained from the tracking system with those obtained from manual counting, for a small data set, and found the results to be well-correlated. We then applied the system to the large-scale data set and obtained substantial statistical measurements that include the total number of people who entered the space, the total number of people who sat by a fountain (Figure 3), distributions of duration at the fountain, the benches, and the steps (Figure 4), and people's walking paths (Figure 5). The measurements also include the probability that a person entering the plaza will choose to sit by the fountain, on the steps, or on the benches, respectively; the distribution of arrival rate per minute (which was found to be close to a Poisson distribution); and the probability of a person entering from one location and exiting at another.



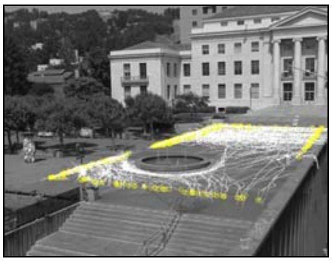


Figure 4 Distributions of duration. **Figure 5 Walking paths**

3 USABILITY-BASED BUILDING MODEL

A model of the built environment is, of course, key to behaviour simulations whose goal is to evaluate its effect on human spatial behaviour. However, built environments are relatively complicated, compared with environments of the kind used in Artificial Life simulations, where autonomous life-like agents fly in the sky or swim in the tank with certain motivations and according to certain behaviour rules. For example, Boids environments (Reynolds 1987) focus on simulating interaction among bird-like agents during flight, while avoiding obstacles. Similarly, the Artificial Fish (Tu 1996) environment consists of water current, seaweed and plankton. The fish are able to perceive their environments and act by avoiding collisions and pursuing a moving target. In contrast, built environments consist a large number of design elements, such as walls, doors, windows, stairs, columns, benches, fountains, lawns, paving, etc. A virtual user needs to perceive and understand them to behave properly, e.g. walk through a door, stand by a fountain, and sit on a bench.

We developed a systematic approach to modelling the environment and created a usability-based building model. Unlike traditional CAD models, our model possesses both graphical/geometric information of design elements and non-graphical information about the usability properties of these elements. The environmental information is structured in a way that makes it perceivable and interpretable by the virtual users. To be more practical, the building model is not created from scratch. Instead, it is built on top of existing CAD models that come from everyday architectural design practices. Such building models already contain complete graphical information but lack the non-graphical information concerning usability of design elements, and therefore cannot be directly understood by virtual users. We have developed a method to automatically convert standard CAD models (e.g. in DXF format), to usability-based models that are ready for the human behaviour simulation.

3.1 Geometry Modelling

We created a model of Sproul Plaza in layer-based DXF format, and converted it into a 3D VRML model (Figure 6). To prepare for the translation from the DXF model to the usability-based model, we used a regularized naming convention for the layers, and made sure each design component was placed in its appropriate layer. For example, LowWall-FountainSide is the name of a design component of type LowWall, and its ID is FountainSide. We also marked the components' z-depths according to their actual spatial relationships, e.g. fountain-side is on top of the ground.

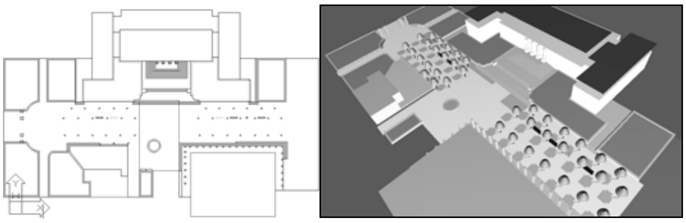


Figure 6 The plaza's DXF model (left) and VRML model (right)

3.2 Usability Modelling

Our modelling tool converts the DXF into Scalable Vector Graphics format (SVG), which is a subset of XML for graphical presentation. SVG is semantically rich: the graphical information is always associated with meaningful textual information. Its element-tree can be traversed to search for a specific node, which can be checked for attributes such as usability. In our approach, as the geometries in the DXF format are converted into SVG elements, their architectural semantics are inserted into the SVG element-tree according to their layer names. Custom tags of the architectural components with their attributes, in extended architectural name-space, appear in the data structure. For example, the fountain-side element is defined by its element type, followed by its geometry element:

```
<arch:LowWall id='FountainSide'/>
<circle cx='85.5' cy='90.75' r='3.75' style='&DesignElementStyle;'/>
```

Most of the activities in our simulation take place in the plaza's centre area—the target region. Virtual users must know where they are and what they can do at any given location. For example, a user by the fountain can sit on a small area of the low wall. We subdivide this large space object into many small objects, in the form of a grid of cells. Each cell in the grid is an object that possesses several layers of properties. They can include information such as whether the cell is sittable, whether it is in the sun or in the shade, whether it is occupied by a user, etc. Every user occupies one grid cell at any given time. Given the potentially large number of cells in a plaza, we balanced computational efficiency against the physical reality by using 750mm sized cells, and 1 second time steps.

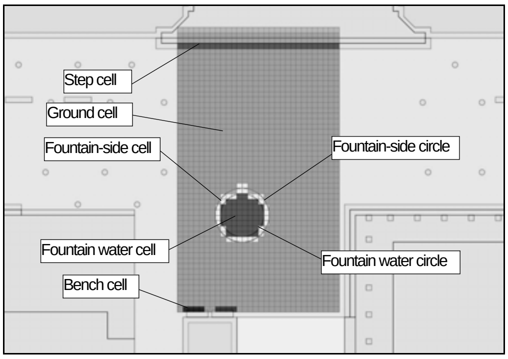


Figure 7 Discrete space model. Cells are marked correctly with colour codes

Each cell can have a number of design element types. For example, it can be fountain-side and ground, at the same time. We applied the Painter algorithm (see Hearn and Baker 1997) to classify cells according to their top-most underlying design element. In the above example, the cell is designated fountain-side, which is the top-most level's type (see Figure 7). Each cell's usability property is then added to the element's attribute list. For example, usability of type 'sit' is defined for a cell of type fountain-side:

```
<arch:LowWall archID='FountainSide' x='9' y='39' id='516' usability='sit'/>
<use xlink:href='#cell_6' transform='translate(84.0,94.5)'/>
```

This discrete space model becomes our usability-based model, which allows virtual users to access and understand the space's properties, beyond mere geometry. It is not tied to any particular CAD software. Rather, it is designed as a reusable tool for working with traditional geometric models and Building Information Models.

4 AGENT-BASED VIRTUAL USER MODEL

The virtual users are modelled as autonomous agents that emulate the appearance, perception, social traits and physical behaviour of real users. User modelling consists of geometry modelling, perception modelling, and behaviour modelling.

4.1 Geometry Modelling

A 3D VRML model is used to represent virtual users as mannequins, with articulated body geometry, texture mapping and animation, and conforms to the international standard of human modelling—Humanoid Animation Specification (H-Anim, 1.1). It is used to represent realistic close-up models of virtual users, their walking and sitting animations (Ballreich 1997, Babski 1998; Figure 8 left).

This model, however, is computationally too expensive for visualizing groups of people. Therefore, we created a simpler human model, based on low-level limb movements that are encapsulated within the H-Anim model, such as the arms' and legs' movements for walking. These stick-figures have the same high-level movements as the close-up models (walking, running, and sitting), without the overhead of fully flashed-out bodies. By augmenting the VRML model with Java programming, we created real-time motion controls to start or stop walking, running, sitting down, sitting still, standing up, and standing still. The control makes it possible to create a sequence of motions using a script, e.g. walk to location X, sit for n minutes, and walk to location Y. Turning is calculated automatically so that there is no need to specify it: whenever a virtual user starts a journey in a new direction, it will turn along the direction smoothly and go forward, just like a real user. Transitional movements such as sitting down and standing up are inserted into motion sequence automatically. For example, if a virtual user first walks and then sits, a transition of sitting down is inserted between walking and sitting.

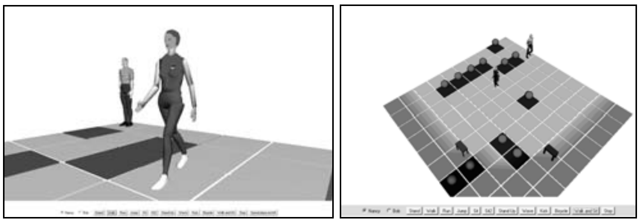


Figure 8 Left: 'Nancy' and 'Bob' demonstrating walking and standing behaviours respectively. Right: Nancy and Bob finding benches using A* search algorithm

4.2 Perception Modelling

Perception modelling defines the users' ability to access and interpret the environment model. It is the combination of four components: (1) "seeing," i.e. accessing the relevant parts of the environment model within a circular area in front of a user in real-time, and translating them into terms that correspond to the virtual user's cognitive model, for such purposes as avoiding collisions and recognizing an acquaintance or an object; (2) "knowing" the entire environment in advance to help make basic decision of what to do and how to behave, much like a frequent visitor has knowledge of the location and orientation of benches, so they can seek them out in order to sit on one; (3) "finding" paths using A* algorithm, which is widely used for searching the shortest path in games (Figure 8 right). We optimised A* in our simulation to reduce the search space from the total number of cells to a subset of cells within a rectangle with a user's starting and target points as corners; and (4) "counting" the duration of a specific behaviour, such as sitting, to make a decision about what to do next: continue sitting or walk away.

4.3 Behaviour Modelling

Behaviour modelling is the most critical issue underlying the simulation because it must mimic closely how humans behave in similar socio/spatial environments, given similar goals. Accordingly, our behaviour modelling is based on three important and firm sources. The first source includes theoretical and practical environment-behaviour studies, such as those by Lewin (1936), Moore (1987), Stokols (1977), Hall (1966), Whyte (1980), Gehl (1987), etc. The common characteristics of these theories provided us with the basic relationship between environment and behaviour. The relationship can be expressed as: B = f (G, R, E), where G, R, and E stand for the goals, behaviour rules, and the built environment, respectively. Goals are high-level objectives, the results of intra-personal processes. Rules are the results of physiological and psychological processes, influenced by social and cultural dimensions. The built environment is comprised of design elements.

The second source of data was the field study, which provided important and substantial statistical measurements about users' behaviour, e.g. users' goals and overall behaviour patterns. The third source of data is Artificial Life research, which provided primitive group behaviour algorithms. Built from simple behaviour rules for individual users, the group behaviour algorithms are used for simulating spatial interactions among individuals during their movements.

Using these three sources, we developed an agent-based approach, where the behaviour of virtual users (which include walking through the plaza, sitting by the fountain, on the benches, or on the steps, or standing while meeting acquaintances, etc.), is determined through a hierarchical structure of rules, resulted directly from the following aspects:

- **Artificial Life approach.** Primary movement control is inspired by Artificial Life's flocking algorithm (Reynolds 1987). Three simple rules define the heading direction of a so called Boid and result in a complex behaviour pattern that mimics birds' flocking. The three rules are: (1) separation - steering to avoid crowding flockmates; (2) alignment - steering towards the average heading of flockmates; and (3) cohesion - steering to move toward the average position of flockmates. When applied to user simulation, the algorithm is modified with consideration of human social environmental factors.
- **Social spaces.** Environment-behaviour studies helped to apply Artificial Life's flocking algorithm to users' behaviour simulation in public spaces: (1) separation - people tend to keep certain distances from one another (Gehl 1987, Hall 1966; see Figure 9); (2) alignment - pedestrians tend to accelerate or slow down to match the motion of others (Whyte 1980), and align in two-way traffic (Gehl 1987); (3) cohesion - they try to stay in the main pedestrian flow or move into it (Whyte 1980). They gather with and move about with others and seek to place themselves near others (Gehl 1987).

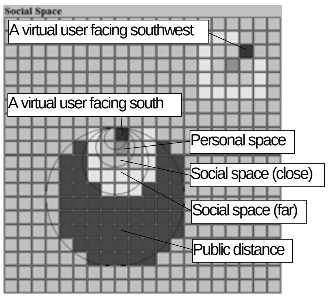


Figure 9 Social spaces

- **Environmental effects.** The field study provided the goals and overall behaviour patterns, including: (1) arrival rates to set up the frequency of inserting virtual users into the plaza from different entrances; (2) target distribution based on users walking paths; (3) probabilities of users choosing to sit; (4) seating preferences based on people's choices among the fountain, the benches, and the steps; and (5) distribution of duration with means and standard deviations of duration at different seating places.

- **Randomisation.** To add more realism to behaviour simulation, we applied random events, including Poisson distribution for arrival rates, normal distribution for duration of sitting and standing, and uniform distribution for meeting acquaintances (standing still), appearance of virtual users, starting and ending points at entrances or exits, etc.

5 SIMULATION AND RESULTS

We built a simulation engine that integrates the building model and the virtual user model into 2D simulation, on top of which we created 3D visualization.

5.1 2D Simulation

The simulation engine first loads the plaza SVG model and parses the model's graphical and usability properties, then creates a virtual user group—a list that allows an unlimited number of users to be added into, and upon completion of a journey removed from the list. The engine runs the simulation step by step, and at each time step (one second) it adds users from the entrances and moves all the users by one step. Adding users from multiple entrances at the same time is a multi-thread process, and it is controlled by the statistics of goals and overall behaviour pattern. The engine passes the environment properties to the virtual users so that the users know, for example, where they can walk and where they can sit. Then the engine starts another thread, which lets the virtual users move following behaviour rules, e.g. shortest path, group movement rules, and social spaces. The simulation engine uses Batik SVG toolkit with Java2D rendering engine, and Document Object Model (DOM) to traverse the element tree (see Watt, A. et al. 2003 for details of Batik).

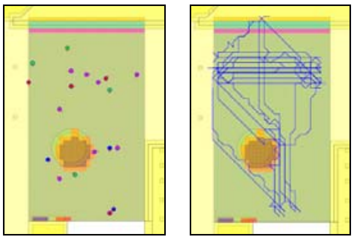


Figure 10 Left: 2D animation. Right: behaviour data - paths

The simulation results include (1) a 2D animation of virtual users movements, including walking and standing in the plaza, sitting at different places, and meeting other users, etc. (Figure 10 left); and (2) a behaviour data set that records all users' behaviour information associated with their paths, including the coordinates along paths, arrival time, motions, sitting directions, and duration of stay (Figure 10 right).

5.2 3D Visualization

By inserting 3D virtual users to the 3D plaza model and letting the users move following the recorded behaviour data, we realized behaviour visualization—animations in which the virtual users exhibit similar traits to those observed in reality (walking, sitting, meeting other virtual users, etc.; see Figure 11 left).

To experiment how design alternatives affect users' behaviour, we ran a simulation for a new plaza that is similar to Sproul Plaza but missing the fountain (Figure 11 right). As the result turned out, users were just walking across or standing for short time, and no one stayed in the centre of the plaza for very long. The result seems obvious in this simple experiment. Our point, however, is that the simulation can produce an immediate picture of how environmental settings affect people's behaviour.

Figure 11 Left: virtual users walking in the plaza and sitting and standing by the fountain. Right: virtual users walking in a plaza without a fountain

6 CONCLUSION

By inserting virtual users in a model of the designed environment, and letting them "explore" it on their own volition, our system reveals the interrelationship between the environment and its users.

The contributions of our approach include: 1) It is more design-oriented than other behaviour simulations. It utilizes CAD models and automates the conversion from CAD models to usability models and therefore requires minimal additional effort in preparing building data for behaviour simulation. 2) The application of computer vision (video tracking) to obtain large amounts of quantitative data for behaviour simulation has proven to be effective. 3) The model places the emphasis on comprehensive environmental behaviour rules, which are derived from solid sources and integrated into the behaviour model. By producing immediate visible results of users' behaviour, the simulation can assist evaluation and comparison of design alternatives, and can help designers gain a better understanding of behaviour and incorporate behaviour knowledge into design process. It can assist architectural education by helping students gain intuition about how different environmental settings impact users' behaviour. 4) While previous behaviour simulations tended to focus on emergency conditions, our model simulates users' daily behaviour and their environmental preferences under normal conditions, which are the main concerns of architects' daily design tasks.

We expect the result of this research to change how architects and environmental behaviour experts will approach the design and evaluation of built environments.

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