GEOMETRIC, COGNITIVE AND BEHAVIORAL MODELING OF ENVIRONMENTAL USERS

Integrating an agent-based model and a statistical model into a user model

WEI YAN
Texas A&M University, USA

and

YEHUDA E KALAY
University of California-Berkeley, USA

Abstract. This paper describes our user model (Virtual User) for behavior simulation. The model simulates the goals, social traits, perception, and physical behaviors of users in built environments. It includes three major components: geometric modeling and motion control; cognitive modeling that enables Virtual Users to understand the environment model; and behavioral modeling that seamlessly integrates sources of theoretical and practical environment-behavior studies, statistics from a field study, and an Artificial Life approach. By inserting the Virtual Users into our environment model and letting them "explore" it on their own volition, our system reveals the interrelationship between the environment and its users.

1. Introduction

Environmental behavior simulation can be used to predict and evaluate the impact of environments on human behavior and it is of great interest to designers and clients. User modeling (as well as environment modeling) is key to such simulations. We have developed a user model, which we call a Virtual User, defining the goals, social traits, perception, and physical behaviors of each user in a simulated environment. Virtual Users are modeled as autonomous agents, which have the ability to 'understand' their environment and behave accordingly. Compared with existing user simulations, our model represents a new approach of integrating an agent-based model and a statistical behavior model into a coherent user model, Section 2.

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The Virtual User model includes three major components: (1) geometric modeling and motion control, (2) cognitive modeling, and (3) behavioral modeling, Figure 1.

Geometry modeling represents Virtual Users as mannequins, with articulated body geometry, texture mapping and animation. To achieve autonomy, a good strategy for our purpose is to encapsulate basic motions (walking, running, and sitting, etc.) within the user models and enable script control of series of motions. Virtual Users' autonomous movements can then be controlled through high-level behavior rules (detailed in Section 3).

Cognitive modeling defines the Virtual Users' accessibility to the environment model. Perceiving and understanding environments are the prerequisite for Virtual Users to behave properly. However, simply providing all the information of the environment models to each user will not solve the dynamic problems that are not predictable in advance, such as encountering another moving user so that they can avoid collision. Our solution to perception is the combination of four components: "seeing" their local environment, "knowing" the global environment, "finding" paths to destinations, and "counting" duration of a specific behavior (detailed in Section 4).

Behavior modeling 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 behavior modeling stems from three important and firm sources in different research areas: theoretical and practical environment-behavior studies, real world data from a field study, and an Artificial Life approach. A seamless integration of these sources into a working solution results in behavior simulation that is close to reality (detailed in Section 5).

We have conducted a case study with a campus plaza – Sproul Plaza at the University of California at Berkeley, which contains distinctive paving, a fountain with low seating edge, large area of steps, and a few benches, Figure 2. We first used video tracking in the plaza and obtained a large number of statistical data about people's behavior (Yan and Forsyth 2005) and then integrated the statistical data into our user modeling. By inserting the Virtual Users in our usability-based building model and letting them "explore" it on their own volition, our system reveals the interrelationship between the environment and its users (detailed in Section 6).

2. Existing User Models and Our Approach

Human spatial behavior simulations that exist are often limited to some well-defined areas of human activities where there has been considerable empirical research that can help develop the requisite cognitive models

(Kalay 2004). Some of the areas for which such cognitive models have been developed are pedestrian simulation and fire egress simulation.

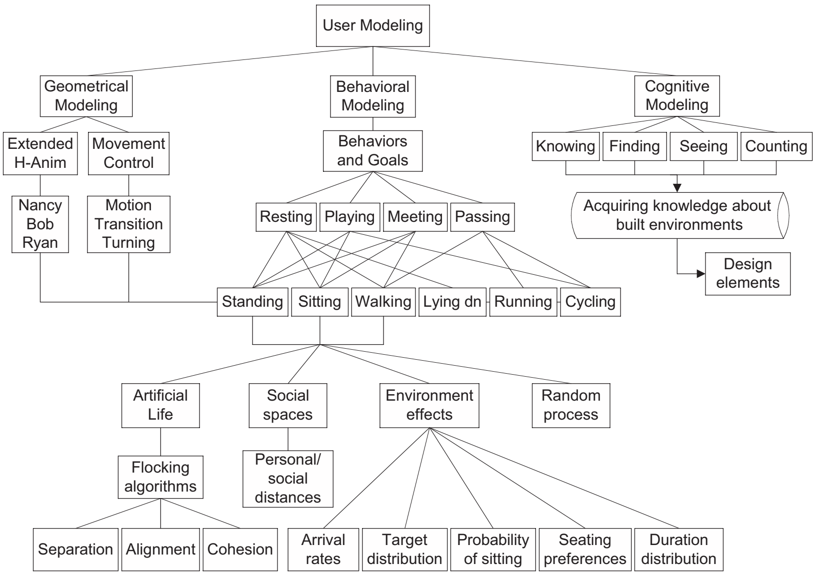


Figure 1. User modeling components: geometric modeling and motion control, cognitive modeling, and behavioral modeling.

Figure 2. Sproul Plaza at the University of California at Berkeley.

These simulations are often aimed at testing the Level of Service (Fruin 1971)—the amount of space people need to conduct certain activities, such as walking through corridors and doors, under normal or emergency situations. General human spatial behavior simulation models have been developed by Archea (1977), Glaser and Cavallin-Calanche (1999), and Kaplan and Kaplan (1982). They typically use discrete event simulation methods, where a generalized algorithm tracks minute-by-minute changes, geometry-based approaches (Glaser and Cavallin-Calanche 1999), or neural-nets (O'Neill 1992).

Batty (2001) has given a good review of recent pedestrian behavior modeling that employs agent-based models. These models take a very different view of probability than that used in more traditional transport and traffic models. Most transportation projects model movement patterns at a much higher scale than that of walking and they are not applicable at the kinds of fine scale that are associated with pedestrian movement. The advantages and feasibilities of using agent-based behavior simulation model include the following (Batty 2001): computer programming has become more object-oriented with individual events and artifacts being treated as classes whose behavior can be explicitly simulated; and new ways of articulating social systems by using ideas from complexity theory have developed over the past years, e.g. by Gilbert and Doran (1994). Some agent models have plans giving distinct purpose to their trips that drive them to complete some tasks, such as shopping (Haklay et al. 2001; Kerridge et al. 2001). Some other models are derived from various analogies in fluid dynamics and particle systems and also embracing key ideas from the theory of self-organization. All models emphasize the way pedestrians interact with one another and with the environment they walk in (e.g. Helbing et al. 1997). The general rules these models use are walking rules for interpersonal and obstacle avoidance and shortest path (e.g. Helbing et al. 2001).

Stahl (1982) and Ozel (1993) developed fire egress models, simulating the behavior in emergency. Ozel's model uses actions (such as "go to exit") and goal modifiers (such as "alarm sounds") libraries to define the behavior rules. These libraries, in turn, use the fire event, the building configuration, and the characteristics of the people as the determinants of their rules.

For various purposes, such as industrial product design, entertainment, and medicine, researchers have created many human models. Developed at the University of Pennsylvania beginning in 1984, Jack is a human model used in industry and government, showing car manufacturers whether their designs can accommodate a person of a certain size, or construction companies whether a particular task might leave employees injured and unproductive. Jack is good at testing ergonomics of a product design, while our Virtual Users are specifically created for evaluating environments. Thalman et al. have built virtual humans and an Informed Environment that creates a database dedicated to urban life simulation. Using a set of manipulation tools, the database permits integration of what they call "urban knowledge" in order to simulate more realistic behavior. Moreover, for various types of mobile entities, they can compute paths to move through the city according to area rules. By using data derived from the environment, virtual humans are able to acquire urban behavior (Thalmann et al. 1999). Therakomen (2001)'s simulation uses agent-based model (Artificial Life) that is also used in our user model.

However, these simulations lack components that we think are essential to environmental behavior simulation: the integration of an agent-based model, which employs human social/personal space rules, and a statistical behavior model, which provides goal distribution and overall behavior patterns, into a coherent user model (as well as a systematic approach for creating usability-based environment model, which is described in Yan and Kalay 2005).

Based on Steinfeld (1992) and Kalay and Irazábal (1995)'s proposals toward an artificial or Virtual User, we first proposed and then developed a new computational model that simulates a built environment, its occupants and their behavior. We have developed methodologies and algorithms to build the simulation that consists of a usability-based building model and an agent-based user model. The building model is a discrete spatial model that represents the building objects. It possesses both geometric information of design elements and non-geometric information about the usability properties of these elements. The relationship between design elements and their intended users, which was implicitly understood by the designer, now becomes explicit to the Virtual Users through this usability-based modeling.

The agent-based user model is a computer model that defines behavioral rules for each individual to simulate both individual and group behavioral patterns including encountering, congregating, avoiding, interacting, etc. The behavior rules are derived from previous literature of human spatial behavior, a field study, and Artificial Life research. The agent-based user models are autonomous models. They emulate the realistic appearance, movement, and perception of individual users under normal conditions. They have adjustable profiles that consist of physical and social variables. The simulation of group behavior is pursued simultaneously with the simulation of individual behavior, and is achieved automatically by aggregating individual behavior without extra efforts. The methods of this simulation are described in the following sections.

3. Geometric Modeling of Virtual Users

Geometric modeling includes 2D and 3D modeling. 2D modeling is used for behavioral simulation and 3D modeling is used for behavioral visualisation.

3.1. 2D MODELING

The Virtual User’s 2D model is a fairly abstract symbol used for user model design and checking purposes in the simulation phase. The Virtual User (as well as our environment model) utilises Scalable Vector Graphics (SVG) format – a graphical presentation of XML – for the purpose of presenting both geometrical and non-geometrical information. As shown in Figure 3, its graphical view is made of a filled circle and a short line indicating the facing direction of a Virtual User.

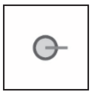


Figure 3. Virtual User’s 2D model.

Its textual view represents non-geometrical information of Virtual Users’ traits, as shown in Table 1.

TABLE 1. Content of the Virtual User’s model in SVG format.

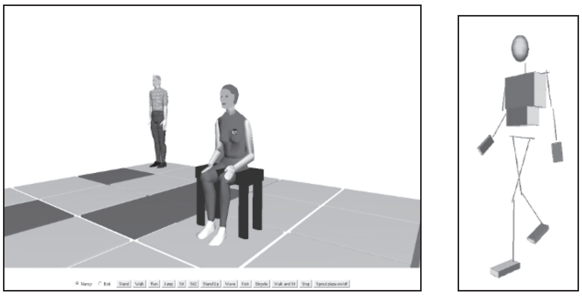
```
<svg>
        <title>Plaza User</title>
        <g id='geom' style='stroke:blue;stroke-width:0.1;fill:#00ff00;'
transform='translate(0,0) rotate(0,0,0)'>
        <circle r='.375'/>
        <line x1='0' y1='0' x2='0.75' y2='0' style='stroke:red;stroke-width:0.1;'>
        </g>
        <traits
                id='vuser'
                ………

                prob_1_5='1.58'
                ………
                time_sit_fountain_mean='190'
                time_sit_fountain_std='124'
                ………
                >
        </traits>
</svg>
```

In the above table, a Virtual User’s geometry is defined by a circle and a line with transformation data. The user’s traits are defined based on our field study – a large number of statistical data obtained by video tracking (Yan and Forsyth 2005), including probabilities of users’ choices of sitting by the fountain, on the steps, or on the benches, respectively; their duration of stay; their walking paths, etc. For example, “prob_1_5” in the table means the probability of a user comes from Lower Plaza and chooses to go to the fountain, and its value is 1.58 %; and "time_sit_fountain_mean" is the average time that users spent sitting by the fountain and its value is 190 second. The standard deviation of sitting duration by the fountain is 124 second.

3.2. 3D MODELING AND MOTION CONTROL

The Virtual User's 3D model (as well as the environment's 3D model) utilises VRML for seamless integration of the two models in visualisation.

The user's 3D VRML model represents Virtual Users as mannequins, with articulated body geometry, texture mapping and animation, and conforms to the international standard of human modeling—Humanoid Animation Specification (H-Anim, 1.1, by Human Animation Working Group). It is used to represent realistic close-up models of Virtual Users, their walking and sitting animations, Figure 4(a), (Ballreich 1997; Babski 1998; and Lewis 1997).



(a) (b)

Figure 4. (a) Nancy and Bob demonstrating sitting and standing behaviors respectively, (b) Ryan demonstrating sitting behavior.

This model, however, is computationally too expensive for visualizing groups of people. Therefore, we created a simpler human model called Ryan, 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 fleshed-out bodies, Figure 4(b).

Our simulation has shown that the Ryan model has the minimal level of details needed to depict behavior patterns: we can see clearly how people use the public space using these models. The Nancy and Bob models with higher level of details require considerable computational resources. By using them, we can achieve a more realistic visualisation that is similar or even better than that in the video used in our field study, which has been shown in Figure 2.

The H-Anim models use prototype design concept (PROTO in VRML). In H-Anim models, human's joints (e.g. a shoulder) and segments (e.g. an upper arm) are defined as PROTOs with field types, data types, field names, and default values (see Ames et al. 1997 for details of PROTO in VRML). Virtual User model extends the Humanoid PROTO in H-Anim model by adding clothes colors for distinguishing individual Virtual Users and motion control variables for triggering behaviors such as standing, walking, running, standing up, and sitting down.

By augmenting the VRML model with Java programming, we created a real-time motion control 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. 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.

Each Virtual User model occupies a cell in the discrete space model and has 8 directions: north, south, west, east, northeast, northwest, southeast, and southwest. 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.

4. Cognitive Modeling of Virtual Users

Cognitive modeling defines the users' ability to access and interpret the environment model. Perceiving and understanding environments are the prerequisite for Virtual Users to behave properly. However, simply providing all the information of the environment models to each user will not solve the dynamic problems that are not predictable in advance, such as encountering another moving user so that they can avoid collision. Our solution to perception is the combination of four components: "seeing" their local environment, "knowing" the global environment, "finding" paths to destinations, and "counting" the duration of a specific behavior.

4.1. KNOWING

"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 good knowledge of the space. The Virtual Users enter the plaza with knowledge of all the design elements, e.g. the starting points and the targets, which are entrances or openings of the plaza. They know each cell's design element type, be it ground, steps, fountain-side, fountain water, benches, etc. They know the location and orientation of all seats, so they can seek them out in order to sit on one. They also know the cells that are obstacles they need to avoid on their journeys such as the fountain and the benches. They need to calculate the shortest paths to go to their destinations using a search algorithm.

4.2. FINDING

"Finding" paths to destinations. People are naturally very conscious of their choice of routes because it is generally tiring to walk. If the target is in sight, they tend to steer directly toward it, sometimes crossing the plazas diagonally. Observations show that almost everyone follows the shortest routes across plazas; only users who push bicycles or baby carriages make detours (Gehl 1987). For the Virtual Users, we employed A* algorithm for searching the shortest path. A* algorithm is widely used in games (Russell and Norvig 1995). We optimized A* in our simulation to reduce the search space from the total number of cells to a subset of cells. Given starting point, target point, and original empty cells and obstacles, the algorithm first returns a subset of the empty cells and obstacles. The subset is defined as a rectangular area with starting and target points as corners. That way the search space is very much reduced and the performance of searching is speeded up significantly. In most cases a Virtual User can find a path in this subset of the search space. In case a shortest path can't be found in the subspace, the original search space will be used. See Section 5.5.1 for a sample of path finding using A* algorithm.

4.3. SEEING

"Seeing," i.e. accessing the relevant parts of the environment model within circular areas (social spaces) 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. Once a Virtual User obtained a path, it will start to walk on each cell along the path. During its journey, the Virtual User needs to avoid hitting others and to keep reasonable inter-personal distance. It will stick to the path unless someone else comes close. At each step the Virtual User checks its social spaces. If others are found within the spaces, the Virtual User will adjust its path. In case of meeting acquaintances, a user will stand still (and talk with them for a while). All of these kinds of knowledge are obtained in real time. (Social spaces are detailed in Section 5.2.)

4.4. COUNTING

"Counting" the duration of a specific behavior, such as sitting, to make a decision about what to do next: continue sitting if the duration has not exceeded a preset maximum duration based on our statistics (from the field study), or walk away.

5. Behavioral Modeling of Virtual Users

Behavioral modeling 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 behavioral modeling is based on three important and firm sources. The first source includes theoretical and practical environment-behavior 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 behavior. The relationship can be expressed as: $B = f(G, R, E)$, where G, R, and E stand for the goals, behavior 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 factors. The built environment is comprised of design elements.

The second source of data is our field study using video tracking, which provided important and substantial statistical measurements about users' behavior, e.g. users' goals and overall behavior patterns (Yan and Forsyth 2005).

The third source of data is Artificial Life research, which provided primitive group behavior algorithms. Built from simple behavior rules for individual users, the group behavior algorithms are used for simulating spatial interactions among individuals during their movements.

Using these three sources, we developed an agent-based approach, where the behavior 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, Figure 5, which resulted directly from the following aspects.

5.1. ARTIFICIAL LIFE APPROACH

The Virtual Users' 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 behavior pattern that mimics birds' flocking. The three rules are:

(a) **Separation** - steering to avoid crowding local flockmates, Figure 6, left;
(b) **Alignment** - steering towards the average heading of local flockmates, Figure 6, middle; and
(c) **Cohesion** - steering to move toward the average position of local flockmates, Figure 6, right.

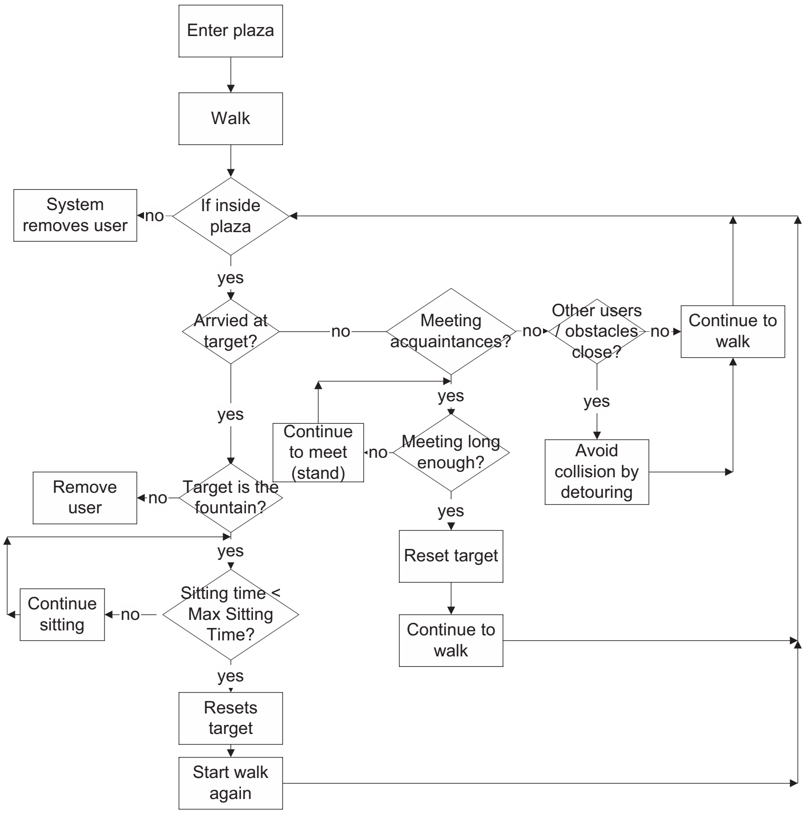


Figure 5. Hierarchical structure of Virtual Users' behavior rules.

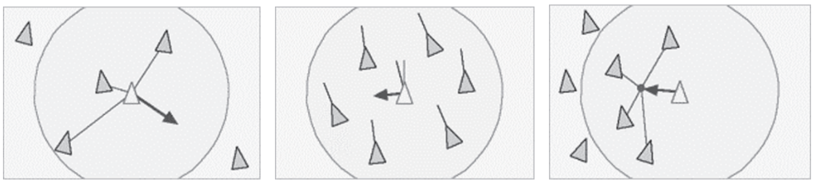


Figure 6. Boids' flocking algorithm. Reynolds (1999).

5.2. SOCIAL SPACES

Environment-behavior studies validated and helped apply Artificial Life's flocking algorithm to users' behavior simulation in public spaces. When applied to user simulation, Artificial Life's flocking algorithm is modified with consideration of human social environmental factors.

5.2.1. Separation

On plazas, the closeness is gratuitous (Whyte 1980), which means people want to keep certain distances from each other. They try to avoid collision with other people of the same or different directions on their paths. They also defer to someone of higher priority if in conflict with priority determined by age or gender (Gehl 1987). Different kinds of distances among people, discovered by Hall (1966), are used to determine the minimal distance between users:

(a) **Intimate Distance**: (6 ~ 18 inches)
(b) **Personal Distance**: close phase (1.5 ~ 2.5 feet), far phase (2.5 ~ 4 feet)
(c) **Social Distances**: close phase (4 ~ 7 feet), far phase (7 ~12 feet)
(d) **Public Distances**: close phase (20 ~ 25 feet), far phase (25 or more)

For a graphical illustration about the distances, Figure 7.

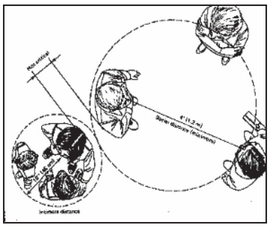


Figure 7. Personal-space bubbles. Source: Deasy (1985).

5.2.2. Alignment

Whyte (1980) observed the following pedestrian behavior in public spaces: people walking quickly, walking slowly, skipping up steps, weaving in and out on crossing patterns, accelerating and retarding to match the moves of the others.

Gehl (1987) also found that pedestrians align in two-way traffic. The upper limit for two-way pedestrian traffic is 10 –15 pedestrians per minute per meter street width. If the number increases, the tendency of dividing into two parallel opposite streams occurs. People start to keep to right, and freedom of movement is more or less lost. In a bi-directional pathway, passing on the right-hand side (which forces alignment) is a rule in countries such as US, etc. and left-hand side in UK, etc.

5.2.3. Cohesion

What attract people most are other people and their activities. People 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. New activities begin in the vicinity of events that are already in progress (Gehl 1987). This is the so-called self-congestion behavior.

From the above comparison we believe that it is reasonable to apply the Artificial Life's flocking algorithms to simulating users' movement in a plaza, with consideration of human's social and spatial factors, and the environmental effects (which will be discussed in the next section). Using Hall's proxemics findings, we created social spaces for a Virtual User by grouping the cells in front of a user into different spaces, Figure 8. As a Virtual User changes its direction, the spaces change as well. The corresponding parameters used are shown in Table 2. The spaces used that affect Virtual Users' movement are personal space, social space's close phase, and social space's far phase. Public distance is not affecting users' movement because other persons' present can be seen only peripherally in this distance (Hall 1966).

When users move in the plaza, at each step they will check whether there are other users or design elements are invading their social/personal spaces and if so, they will behave accordingly, e.g. to stop and stand to talk if meeting acquaintances, or detour if meeting strangers or obstacles.

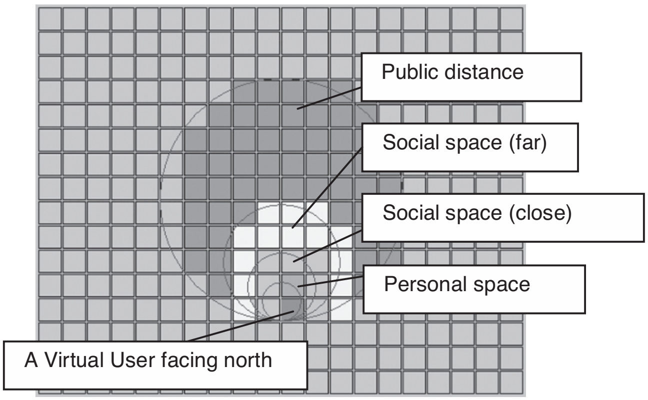


Figure 8. Virtual users' social spaces. Each cell in the grid of the usability-based building model is an object that possesses several layers of usability properties.

TABLE 2. Parameters of users' social spaces (Java implementation).

```
//distances of personal/social spaces
size = tile.size / scale; //750 mm
int personalDistance = 1200; //mm, 4 feet
int socialDistanceCloser = 2100; //mm, closer social distance, 7 feet
int socialDistanceFarther = 3600; //mm, farther social distance, 12 feet
int publicDistance = 7500; //mm, 25 feet;
```

5.3. ENVIRONMENTAL EFFECTS

Our field study provided the model with users' goals and quantitative measurements of overall behavior patterns, including:

(a) **Entering rates** to set up the frequency of inserting Virtual Users into the plaza from different entrances, based on (1) total number of people who entered our observation region in the plaza during the time interval of our field study; and (2) Poisson distribution. Poisson distribution is commonly used to model the number of random occurrences of some phenomenon in a specified unit of space or time. (For more details of Poisson distribution, see Spiegel 1992). Thus it is a good choice to use Poisson distribution to model the users' entering rate. We have also found that the distribution of the arrival rate per minute during the time interval is close to a Poisson distribution.

(b) **Target distribution** based on numbers of users walking in different routes and their probabilities. We applied the probabilities of a user entering from one entry and exiting from another or heading to a seat.

(c) **Probabilities of users choosing to sit** based on numbers of people who entered the plaza chose to sit vs. to walk crossing the plaza.

(d) **Seating preferences** based on people's choices among fountain, benches, and steps.

(e) **Distribution of duration** with means and standard deviations of duration at different seating places.

5.4. RANDOMIZATION

To add more realism to behavior simulation, we applied random processes to model users' behavior patterns.

(a) **Poisson distribution** is used to set up the rate that users enter the plaza. It is also confirmed by our field study.

(b) **Normal distribution** is used for duration of sitting and standing.

(c) **Uniform distribution** is used in the following processes:
   - Random appearance (clothes colors) to differentiate Virtual Users in visualisation.
   - Random starting or ending points at entering or exiting areas.
   - Probability of meeting acquaintances (a Virtual User will stand still then).

5.5. SAMPLE SCENARIOS

Combining all the four components: Artificial Life algorithms, social spaces, environmental effects, and randomization, we built a user model to simulate individual and group behaviors. The implementation details will be discussed in Section 6.

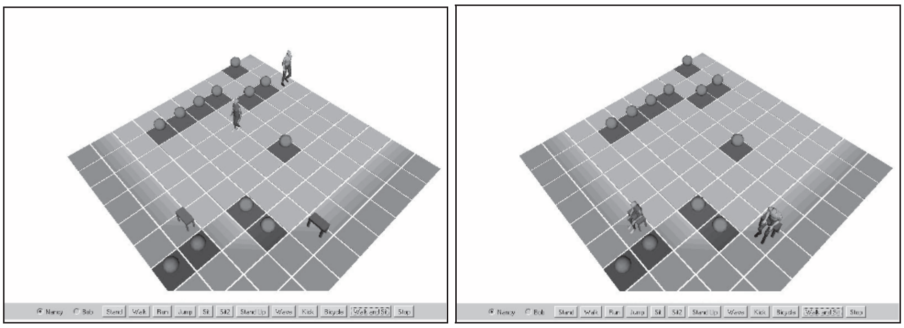
The following two scenarios are intended to test how the behavior simulation works. They reveal that many behavior patterns can be simulated. For testing purposes, we used only two Virtual Users: Bob and Nancy.

5.5.1. Finding benches in a plaza

Nancy and Bob use the shortest path search algorithm (A*) to find benches to sit on. Greenery is treated as an obstacle they must circumnavigate. Nancy has priority over Bob to get her nearest bench. So when a given bench is identified as the nearest seat from both Nancy's and Bob's points of view, Nancy will get it and Bob will look for another seat, even if it is further than the first one. The graphical user interface allows designers to move the benches and let Nancy and Bob find them, Figure 9.

5.5.2. To sit in the sun or in the shade?

For each cell of the space we calculated dynamically whether it is in the sun or in the shade, based on the plaza's geographic location, the sun's azimuth and altitude at a given time, and objects such as trees and buildings that may cast a shadow on the ground. Virtual Users can 'know' a tile's sun/shade disposition, and choose whether to sit on a bench located on that cell or not. Figure 10 shows that Nancy prefers a seat in the sun rather than a seat in the shade, even though the one in the shade may have been closer to her point of departure.



(a) (b)

Figure 9. (a) Nancy and Bob started to walk to the benches using A* search algorithm, (b) Nancy and Bob found the benches and sat.

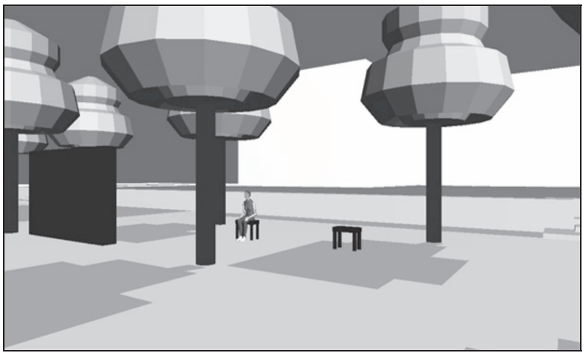


Figure 10. Nancy prefers a seat in the sun to a seat in the shade.

6. Applying the User Model to Behavior Simulation

We applied the user model to our behavior simulation in the run time through a simulation engine.

The simulation engine first loads the building model and parses the model's graphical and usability properties, then creates a Virtual User group—a list that allows an unlimited number of user models 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. The Virtual Users acquire environmental knowledge through the cognitive processes (knowing, seeing, finding, and counting) so that the users know, for example, where they can walk and where they can sit. Then the engine lets the Virtual Users move following behavior 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 design element tree of the building model (see Watt et al. 2003 for details of Batik SVG toolkit).

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 11(a), and (2) a behavior data set that records all users' behavior information associated with their paths, including the coordinates along paths, arrival time, motions (walking, sitting, or standing), sitting directions, and duration of stay, Figure 11(b).

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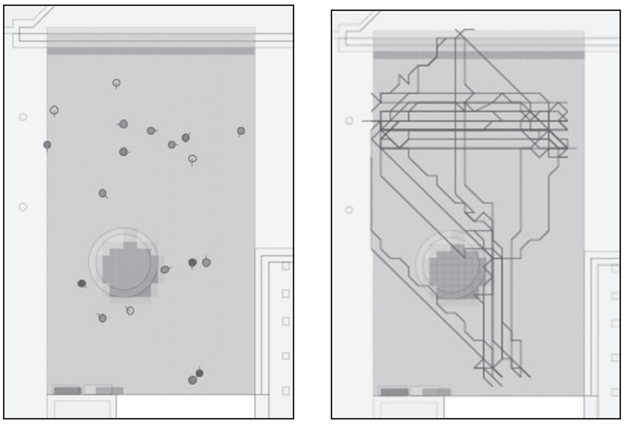

(a) (b)

Figure 11. (a) 2D animation of Virtual Users' movements. (b) Virtual Users' paths drawn using dark lines.

Finally, by inserting 3D models of Virtual User into a 3D model of the plaza and letting the users move following the behavior data recorded in the simulation, we realized behavior visualisation—animations in which Virtual Users exhibit similar traits to those observed in reality: walking, sitting, meeting other Virtual Users, etc., Figure 12.

7. Conclusion

Our model supports fast creation of realistic user simulation because the Virtual Users are re-usable, autonomous constructs, and their behaviors are driven by adjustable variables of users' characteristics and spatial configurations.

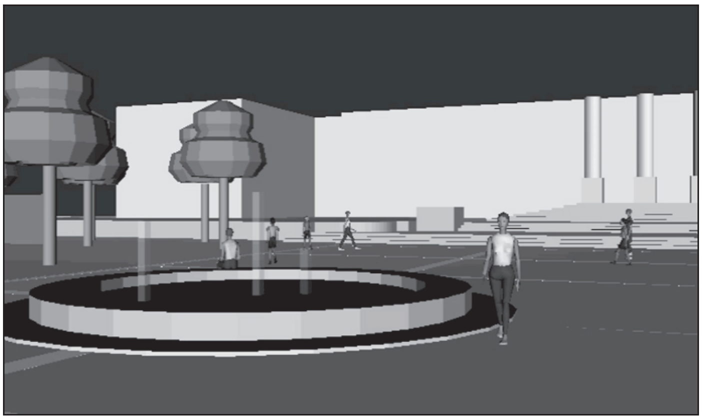

Figure 12. 3D visualisation: Virtual Users exhibit similar traits to those observed in reality (walking, sitting, meeting other Virtual Users, etc.).

We expect, with our Virtual User simulation, human behavior analysis as one of the most important aspects in building design can be integrated into designers' daily design practices seamlessly. The evaluation of human spatial behavior can be made easier and visible before the building is built. This will encourage designers to pay more attention to users and therefore innovative buildings concerning more about the needs of people can be designed and built.

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