Navigational Pedestrian Movement Model with Vision-driven Agents

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Abstract

This paper proposes a navigational pedestrian movement model based on vision-driven agents. In the paper, two different patterns of movement are discussed: natural movement and navigational movement. The natural movement model, which is based on Gibson's ecological theory of perception and Hillier's research, facilitates understanding of the relation between visual perception and movement; unfortunately, it has no origin-destination (OD) pairs. In contrast, the navigational movement model does not take the process of visual perception into account. The proposed navigational pedestrian movement model integrates these two movement models by replacing an attractive factor in the conventional natural movement model with a potential field of walls for navigational movement. Consequently, the results of simulations performed show that the proposed model generates a smoother and more plausible movement pattern that is affected by the visual field angle of agents. The problem and its solution according to visual field angle are also demonstrated through model tests. The proposed model demonstrates that an integrated approach can enrich pedestrian studies and enable understanding of the relation between visual perception and movement. It may also be developed as a simulation model for emergencies or wayfinding.

Keywords: pedestrian simulation; natural movement; navigational movement; agent-based model; vision-driven agents

1. Introduction

Much research has been conducted with the aim of understanding pedestrian movement in order to facilitate safe and comfortable walking environments in buildings and on urban streets. Predicting pedestrian movement can facilitate solutions to spatial usage problems such as wayfinding, congestion, and evacuation. Advancements in computer systems have also enhanced research on pedestrian modeling and simulating for several decades.

A number of pedestrian simulation models have been proposed. They can be categorized by scale (macro-, meso-, micro-), situation (crowd/evacuation, route choice/wayfinding), methodology (cellular automata, agent-based), simulation time (continuous, discrete), rules (potential field, social force, fluid dynamics, etc.), etc. (Batty 2001; Papadimitriou et al. 2009)

Considering the movement rules of previous models, such as social field and fluid dynamics models, in general, agents have the appearance of lifeless particles or unicellular organisms that respond only to their neighborhoods. This is especially true in potential field models. Movement is a basic ecological behavior generated by an interaction between an agent and its environment. Human movement is especially guided by visual perception. Gibson (1979) discussed the complementarity between human movement and visual perception. Although the models discussed above deal with the interaction with an environment, the agents in the models have no vision. The movement routes are calculated beforehand without regard to visual perception, or only the dynamic relations with other agents, such as their existence in neighborhoods or distance from them, which affect movement behavior. These approaches are focused on movement itself without regard to its complementary behavior with visual perception.

Pedestrian models with vision-driven agents also exist. In these models, an agent with partial visibility, because human eyes in the front of the head have visual limitations, decides on one of the routes using environmental configuration information within its visual field. Turner (2002) encoded this rule as an agent-based system, and named his model the natural movement model after reviewing Gibson's ecological perception theory and Hillier's research (1993). Lee (2013) subsequently reviewed and developed Turner's model. In the revised model, the spatial element steering a vision-driven agent was redefined from a floor- to a wall-based perspective. Their models are discussed in Section 2.
A natural movement model has a distinct feature in that the related agent has vision, but there is a need to consider that the agent has no destination. A natural movement model, as the meaning of "natural," shows the emergence phenomenon, in which the whole movement pattern (volume) generated by an interaction between a vision-driven agent and its environment only has good correlation with observed pedestrian data in the real world, although there is no destination control in the simulation model. However, movement without destination is rare in our daily lives. Although a natural movement model is distinct from a navigational movement model, both models appear to be supplementary to each other.

In this paper, the possibility of integrating both models is discussed and an integrated simulation model proposed. The visual parameters of agents are considered in the proposed model, but physical parameters, such as body size and moving speed, are normalized because the model focuses on navigational movement via visual perception. The meaning of the proposed model and the possibility for application are also discussed through simulations in several test spaces.

2. Related Work

2.1 Two Different Patterns of Movement

As stated above, pedestrian models can be viewed as two different patterns of movement: natural movement and navigational movement. Natural movement is the movement pattern in which a vision-driven agent makes a decision about the next direction or target point to move according to its visual perception. There is no need to receive other information outside of the agent's vision or complete spatial structure. In this case, movement is affected not by a specific destination but by the visual range of the agent's vision. Consequently, the overall route of an agent in the model is unpredictable, because the route choice of the agent is impromptu, stochastic, and Markov-chain based. The model enables us to see where the more attractive spaces guiding the agent's movements are. Natural movement patterns can be observed in locations such as exhibition halls, galleries, and shopping malls, where novice visitors have no specific destination or little information about the overall spatial structure. However, our ordinary movement with destinations is different from that of the model. Furthermore, applying a natural movement model without origin-destination (OD) pairs to an evacuation or wayfinding situation is difficult.

Navigational movement is a pattern of movements in which an agent with a destination makes a route decision using geometric clues about the environment. Most pedestrian simulation models with OD pairs can be viewed as navigational movement models. In this model, as a rule, the shortcut path to a destination is used for agent navigation because people tend to choose the shortest route possible. In general, people depend on a mental cognitive map for navigation. However, it is difficult to design artificial intelligence for every agent, because the computation needed in a multi-agent simulation is time consuming. Therefore, to reduce the simulation time, the shortest distance to a destination should be calculated prior to the agent being at every cell to which the agent can move. The distribution of the shortest distance to a destination is called the potential field or the floor field.

| Items/Model | Navigational Movement | Natural Movement |
|-------------|------------------------|------------------|
| Agent Vision | No                     | Yes              |
| OD Pairs    | Yes                    | No               |
| Spatial Memory of Agents | Yes (outside) | No            |
| Perception Range | Neighborhoods | Visual Field     |
| Movement Generator | Potential field | Configuration (Spatial Affordance) |
| Route Choice | Designated             | Stochastic       |
| Movement Result | Predictable           | Unpredictable    |
| Termination | According to Arrival    | Infinite Loop    |
| Self-organization Pattern | Arch-Formation at a bottleneck | Pediatric Volume |
| Main Goal of Analysis | Evacuation, etc. | Global Movement Pattern, etc. |

2.2 Potential Field Model

Many researchers have proposed using the potential field method to model agent-based microscopic navigational movement. In this model, the agent continues to move to one of its neighborhoods via the shortest distance to the destination (Hoogendoorn, 2002; Lightfoot and Milne, 2003; Meister, 2007). In some cases, there are two concepts of potential field: static potential field, and dynamic potential field. Static potential field contains geometric information at a cell in an environment, which describes the shortest distance to a destination by measuring how many steps are needed to reach the destination from the cell. A dynamic potential field contains information generated by agents that can change according to their movement. The factors associated with dynamic information could be occupation or trace of agents, such as an animal's pheromone, which guides an agent to a leader or a crowd, or geometrical relations between each other considering social attraction. The sum of the two types is used for a potential field to guide agent movement. However, this paper considers static potential field only because the visual perception process of an agent already means that dynamic behavior could be applied.

The problem in obtaining a potential field is calculating the shortest distance to a destination. If there are hindrances such as walls, the direct distance or vector between OD pairs cannot make an agent avoid those hindrances. Therefore, a potential field is typically obtained using part of a grid algorithm:
The distance calculation between cells begins at the neighborhood cells of the destination. The task is repeated on the next non-hindrance neighborhoods, and the values are accumulated until all cells are completed. The further a cell is from a destination, the higher its value. The movement rule in a navigational model is that an agent has only to move repeatedly toward one of the neighborhoods with a minimum value in order to reach the destination.

2.3 Natural Movement Model

The concept underlying natural movement is that human movement is generated by configuration or surface. Turner (2002) encoded natural movement as an agent-based system by reviewing the theories put forward by Hillier et al. (1993) and Gibson (1979). He stated that a rule of OD pairs may not always be demanded or follow the shortest path in daily movement. Citing related studies indicating that people tend to move based on the length of a line of sight or the minimum angle toward the destination, Turner discarded OD pairs and encoded the natural movement model using vision-driven agents who could decide their routes according to visible configuration. Consequently, he proposed a vision-based system called an exosomatic visual architecture (EVA), in which the visibility at every space is calculated prior to a simulation in order to reduce processing time. This results in the visual perception information lying outside the agents.

The rule of movement is a loop process in which an agent picks a target point within its field of view, and takes steps toward that point based on a Poisson distribution. The overall movement patterns, not the individual agent path, of the EVA model exhibit good correlation with the gate-count data surveyed in the real world, the Tate Britain Gallery; nevertheless, it does not have OD pairs. Although the model considered vision-driven agents and perceptual relations with the environment, Turner (2002) also noted that the agents could not return to an entrance.

Lee (2013) subsequently reviewed Turner’s model and proposed a new approach for a natural movement model. He indicated the problem of movement pattern of an agent at a micro-scale of the EVA model, in which an irregular pattern like Brownian motion can be found in the trail of the agent's movement. This is because an agent takes a random point on a visible floor that it is able to move on. Although Turner assumed that the element that supports natural movement is only a visible floor formed by walls, authors believe that one would have already perceived the walls before perception of the floor, and then the movable space is formed by the walls. Therefore, authors believe that vertical walls or boundaries are important architectural elements to guide human movement. From this perspective, the configuration of a wall, rather than a floor, can be replaced as a generator for natural movement. Lee hypothesized that boundaries or substances perceived by an agent, such as walls, could guide its natural movement. The new rule of the model is that a vector field from an agent position toward visible walls guides its movement. He called the model the wall vector field (WVF) model. In general, walls are continuous, resulting in the ability to obtain a smoother movement pattern through this rule than through the EVA model at micro-scale. The simulation results of the WVF model also show good correlation with the visitor data of the Tate Britain Gallery, which was used by Turner. However, because a WVF varies according to the agent's position and direction, it has to be calculated every time the simulation is run, unlike the EVA model. Lee (2014) suggested that smoother and more plausible natural movement at the micro-scale is also needed for the visual dynamics analysis (VDA) model. In the VDA model, it was necessary to implement a regular movement in order to analyze the dynamic visibility of agents engaged in natural movement.

3. Vision-Based Navigational Model

In a navigational movement model, agents typically use potential field for their route choice. The potential field values of neighborhoods around an agent contain information about the shortest route to a destination. An agent has only to select one cell with a minimum value in order to reach a destination. If another agent is already on the cell with the minimum value, it will stop or select a cell with a second value. There is no need to consider the visual perception of an agent. However, our movements do not rely solely on the condition of nearby surroundings; pedestrians obtain navigational information from all perceivable entities. This is because there must be an interrelation between pedestrian movement and visual perception. If such is the case, in the case of an environment with a spatial configuration only, it will be able to make vision-driven agents use a potential field of visible walls for their navigational movement. This paper proposes a navigational movement model that uses a visual perception process and the WVF of a natural movement model.

3.1 Natural Movement Afforded by Wall Vector

As stated above, a WVF was used as a natural movement model, in which the movement of a vision-driven agent is guided by the configuration of wall. The "configuration" in the model was modeled as vectors with direction and distance from an agent to walls. Humans have a partial visual field and tend to maintain the direction of their head while moving. Furthermore, although a wall in front of a pedestrian acts as a hindrance, its continuous feature can also be a mobility attractor. The experimental study on natural movement by Lee (2011) showed that most subjects in a virtual environment move along visible objects. Further, while moving, people are interested in a distant wall rather than a wall nearby. This is because
the walls in the distance can give us more information to move than those already experienced and close by. This is the same meaning as the studies showing that human movement is based on the length of line of sight, which raises the possibility of moving to another space. Pedestrian researchers in the field of space syntax theory use this perspective as the basis of their research (Hillier, 1984; Peponis et al., 1990; Dalton, 2003).

Therefore, the vector sum to the perceivable (visible) walls can be viewed as a generator guiding an agent's movement. Hence, the direction of the sum vector is a more important factor in guiding an agent's direction than the length. Although the length may be relevant to an agent's walking speed, it can be disregarded because walking speed is affected more by an agent's condition or external events. Thus, the next orientation ($\vec{a}_{(t+1)}$) of an agent that does a natural movement is the sum of the agent's current direction ($\vec{a}_{(t)}$) and the direction of the WVF ($\int a \times \vec{w}_d \cdot \, \mathrm{d}w$), which is the sum of the unit vectors to visible walls multiplied by an attractive value ($a$). This can be expressed as follows:

$$\vec{a}_{(t+1)} \cong \vec{a}_{(t)} + \int a \times \vec{w}_d \cdot \, \mathrm{d}w$$ (1)

In a natural movement model, the distance to the wall can be viewed as an attractive factor guiding an agent's movement, in a concept similar to the length of line of sight. Therefore, in the WVF model, the ratio of the distance to the difference between the maximum and minimum distance to visible walls is used as a normalized attractive value ($a$):

$$a = \left( \frac{|\vec{w}_d| - |\vec{w}_d|_{min}}{(|\vec{w}_d|_{max} - |\vec{w}_d|_{min})} \right)$$ (2)

However, unlike the EVA model, the WVF must be calculated every time because an agent's partial view, which has visual distance and visual field angle, varies according to its direction and other agents. Other agents may be visual hindrances when they are near, or act as social attractors when they are far away. This real-time visual perception process can enable an agent to avoid collisions with others, and exhibits a self-organization phenomenon such as a lane formation.

### 3.2 Potential Field as an Attractor

Potential field contains geometric information to a destination and can thus be thought of as a cognitive map outside of agents. It should be obtained prior to an agent being activated for simulation efficiency. If potential field can be obtained in a model before a simulation, vision-driven agents have only to use the value for their navigational movement. In the natural movement model using a WVF, an attractive factor is considered as a distance to a visible wall, because there are only distance relations between agents and walls. However, if walls have information about the distance to a destination, the attractive factor could be replaced by a potential field for a navigational model.

The smaller the potential field value a cell has, the more attractive it becomes as a guide for an agent to a destination. From equation (2), distance can be replaced by potential field value ($p$), but an inverse proportion should be applied because a smaller potential field value is more attractive. Fig.1. shows conceptual diagrams for two types of movement models by a WVF. Henceforth, authors call the WVF that uses potential field "a wall-potential vector field" for distinction.

$$a = 1 - \frac{(p - [p_v]_{min})}{([p_v]_{max} - [p_v]_{min})}$$ (3)

### 3.3 Navigational Movement by Vision-Driven Agents

Authors programmed a navigational movement model with vision-driven agents using NetLogo, an agent-based programming language and integrated modeling environment. In the model, vision-driven agents could detect their route and finally reach a destination. In the implementation of the proposed model, the algorithm of the potential field, partial visual field of the agent, movement rule, etc. were considered. An agent has parameters for orientation, visual field angle and visible distance, noise (looking around behavior), and walking speed. Vision-driven agents revise their direction via a wall-potential vector field, and then move forward at walking speed, similar to the process outlined in Fig.2. If an agent could directly detect a destination, there would be no need for a WVF in the choice of routes. In such a case, the agent would have only to move toward the destination.
4. Simulations

4.1 Comparison with a Model with Blind Agents

A conventional potential field model that does not consider agent visibility was programmed for comparison with the vision-driven agent model. In this "blind agents model," the route of the agent was designated, and the movement showed an inflexible pattern at the micro-scale because the agent only used the information about its neighborhoods. In contrast, the wall-potential vector field in the vision-driven agent model generated a continuous and natural movement. Fig.3. compares the simulation results for the two navigational models: vision-driven agents and blind agents. In the simulations, five agents start simultaneously at the same origin in the bottom left corner, and move to a destination in the top right corner.

Unlike the blind agent model, the vision-driven agents are always guided by the wall-potential vector field. Consequently, the agents seek other routes to the destination without hesitation, although the direction is not the shortest path. This continuous route detection behavior cannot represent arch-formation at a narrow gate, a bottleneck in a self-organization phenomenon.

However, in normal situations the natural movement patterns do not always follow the arch-formation rule behavior and press against each other. In such a case, people tend to wait their turn to enter or move around the gate. Fig.4. shows the movement patterns for two models with a narrow gate.

4.2 Variable of a Visual Field Angle

The navigational model by vision-driven agents is more focused on the relation between vision and movement than navigation itself. As stated in Section 3, a visual field angle can be an influential variable that affects movement. The visual range of an agent in the model is a critical factor, because it affects the wall-potential vector field. The visual field in the model is determined by three agent parameters: orientation ($\theta$), visual field angle ($\theta$), and visible distance ($l$).

The most influential parameter among them for route choice is visual field angle. A narrow visual field angle guides the agent directly forward only, whereas a wider
one opens the possibility for the agent to obtain more information from visible walls and thus become more likely to detect a shorter route.

In order to observe this scenario, authors designed a test model consisting of an outside corridor and a large junction in the middle of an environment (Fig. 5). In Fig. 5, it can be seen that there are four gates to enter the junction. The origin of the agents is the left end of the corridor, and their destination is the right end. The shortest path to the destination is through gates (1) and (4), but there are also alternate routes that can be taken to reach the destination in spite of detours. Figs. 5(a), (b), and (c) show the results for scenarios in which each of the thirty agents moves under the same visual field angle but enters the origin between long intervals of time. In Fig. 5(d), each of the thirty agents with a wide visual field angle enters at a short interval. All the simulation results are different because there is a noise factor, such as looking around. However, they are expected to show a similar movement pattern under the same condition. The noise angle was smaller than five degrees in these models.

Agents with a narrow visual field angle had a tendency to miss the shortest path. At gate (1), at a few steps from the gate, the line of sight of an agent cannot reach the inner walls toward the junction. Therefore, the wall-potential vector field was built by the front corridor walls so that movement was guided forward (Figs. 5(a), (b)). This phenomenon occurred in the case where an agent entered the junction through gate (2). Agents with a narrow visual field angle, after moving through gate (2), had a tendency to miss gate (4) and select gate (3), because gate (4) was out of their visual range (Fig. 5(a)). However, when the visual field angle was sufficiently wide to detect gate (4), agents were more inclined to enter gate (4) through the junction (Fig. 5(b)). Agents with a wider visual field angle tended to choose the shortest path, because the visible information was sufficient for them to do that (Fig. 5(c)). Then, if many agents with a sufficiently wider visual field angle moved simultaneously, would they all show a similar movement pattern? Fig. 5(d) shows that some agents missed the shortest path.

This is because other agents in front of those agents constituted a visual hindrance. They deprived the agents of the opportunity to detect information about the shortest path, resulting in some agents being obliged to select an alternate route.

Fig. 5 shows that it is necessary to have a wide vision in order to take a shortcut, especially when coming to a gate or junction. Otherwise, the shortest path will be overlooked and a circuitous route taken or wandering occurs. Further, the movement of others or congestion could be a dynamic visual hindrance obstructing navigational movement. The effect of vision on movement through the simulation by vision-driven agents can be understood.

The remaining question in the model is the question of which angle would be suitable for a simulation. The model also has some problems according to a fixed visual field angle. This is discussed in the ensuing section.

4.3 Consideration of Problems

The general visual field angle of human beings is less than 180 degrees. However, it seems to be more or less problematic when applying an acute visual angle to a model in a specific case. When an agent moves along a corridor, and to make matters worse, in the opposite direction from the destination, the wall-potential vector field by the corridor will maintain the moving direction of the agent, because the wall-potential vector field is symmetrical. A narrow visual field angle makes it difficult for an agent to change direction or escape from the corridor. If the visual field angle is sufficiently wide to detect the circumstances around an agent, more than 180 degrees or close to 360 degrees, the corridor problem will be solved. Although an obtuse angle appears to be inappropriate as a visual field angle, considering the human vision system, it could be acceptable because navigational behavior needs the action of looking around to detect one’s pathway. Fig. 6 shows the corridor problem. In the simulations, the agents left from the same position toward the same destination in the top right corner with the same orientation to the right side, but had different visual field angles.
Conversely, an overly wide visual field angle close to 360 degrees could give undesirable results in a space with symmetrical walls. In such a case, the agent would be bewildered by the WVF of all directions, and hover around the walls. Fig. 7. shows the problem according to the visual field angle.

Therefore, the model could generate more plausible movement if agents had a rule to adjust their visual field angle according to circumstances in order to select a reasonable route. However, distinguishing all problematic spatial types and adapting their visual field angle to the cases is time consuming. Furthermore, people look around or look at something while moving, so our visual system is not always fixed. Our visual field repeats extension and contraction, or people turn their heads. Although a visual field angle should be wide for the detection of routes, it is in a state of change even in a navigational situation. This allows the model to make an understandable approach in which the visual field angle of a moving agent could be variable. If an agent could periodically change its visual field angle at a random value within a certain range, the problem of the agent becoming trapped by a corridor or symmetrical walls would be avoided, although not perfectly. Consequently, this rule was considered for the model, and the agent visibility parameter (a maximum and a minimum visual field angle and visible distance) could also be specified.

4.4 Applications

Fig. 8. shows the result for 30 agents entering the bottom left corner at short intervals and moving to their destination in the top left corner. Their visual field angles are in the range of 90 to 270 degrees. The blind agents moving by the potential field of neighborhoods would stick to the shortest path. However, the vision-driven agents with a variable visual field angle selected alternate routes to the destination, although most of them had a tendency to follow the shortest path (Fig. 8.(a)). As stated in the adage, "the longest way round is the shortest way home," some agents were able to reach the destination before others that were struggling in congestion. This appears to be positive in that some agents could discover alternate routes in an emergency situation, but it could be negative in a wayfinding situation if there were too many agents who selected alternate routes. In Fig. 8.(a), there is a wall in the center to interrupt the smooth flow of agents. The wall acts as a visual hindrance. If the wall is removed, it is expected that the flow would be smoother and the number of detouring agents would decrease. Fig. 8.(b) shows that more agents took the shortest path after removal of the wall.

In the navigational model by vision-driven agents, the configuration of the environment appears to be more important to guide movement than the distance to a destination. Even though further enhancements are still needed, the model shows the possibility of being developed as a simulation model for emergencies or wayfinding.

5. Conclusion

This paper proposed a navigational model for vision-driven agents using a wall-potential vector field. The proposed model is part of efforts to integrate the natural movement model with the navigational model. Most conventional navigational models have no agent vision; as a result, the movement pattern is only designated by the potential field of neighborhoods. Considering the complementary relation between vision and movement, the models are insufficient for representing human behavior. Further, although previous natural movement
models were based on ecological behavior, agents could not be given a navigational task, because there were no OD pairs. Consequently, this paper proposed an integrated model that a vision-driven agent can use for navigational movement to a destination.

The movement pattern of the proposed model also appears smoother and more plausible than the blind agents model. The model showed that the visual field angle of an agent affects its movement pattern. Several test simulations were performed to understand the relation between vision and movement, and the model was also reviewed with relation to various problems. Some agents in the test model missed the shortest route according their visual field angle or a visible configuration, and sought alternate routes for their navigational movement. However, the results show that the model has the possibility to be developed as a simulation model for emergencies or wayfinding.

Studies on pedestrian modeling have mainly been in the field of traffic engineering. However, in such cases engineers are only interested in movement itself. Pedestrian modeling studies have also been carried out in the architectural field. However, only studies have been conducted and the concern was primarily on the ecological approach to a natural movement. From this perspective, the proposed model can be considered as the meaning to expand a natural movement model into a navigational model. This approach could enrich pedestrian studies, and help us better understand the relation between vision and movement. The model remains to be reviewed and enhanced by real world data for validity. Further, more complex human behaviors should be considered in a follow-up study.

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