A Microscopic Pedestrian Simulation Model with Theory of Mind (心の理論を考慮した微視的歩行者シミュレーションモデル)

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1 Introduction

Modeling and simulating pedestrian behavior have contributed to design congested public spaces and improve the efficacy of pedestrian flows for the last few decades. Recently, a paper intended to capture the game theoretic aspects among pedestrians which are conspicuous in collision avoidance behavior and in its negotiation process ([1]). Although their works were elaborate and had been well implemented for practical applications, collision avoidance behavior is simplified too much with classical game theory and there must be some fundamental and important perspectives that are missing by such over-simplification.

In this paper, we propose a microscopic pedestrian simulation model by adopting a universal modeling method in theoretical decision science. Also, we probe into pedestrians' mental attribution to infer the behavior of other pedestrians, which can be regarded to be Theory of Mind ([2]). Furthermore, we present how depth of inference levels affects the efficacy of a pedestrian flow as a whole with computer simulations.

2 The model

Our modeling procedure is composed of three parts. We first stipulate available transition of pedestrians and then define their movements as a sequence of decision making tasks. Then, we incorporate the idea of Theory of Mind to our model.

2.1 A pedestrian model

A pedestrian must be presented with some alternatives to choose from so that they can evaluate the value of utility for each of their options. Therefore, we discretize pedestrians' applicable direction and speed at a certain step and give a finite number of choices. The choice set of a pedestrian denoted by $\Omega_i(\tau)$ is composed of two sets; one is the choice set of direction denoted by $\Omega_i^\theta(\tau)$ and it is given as

$$\Omega_i^\theta(\tau) = \{\theta_i(\tau)|\, \theta_i(\tau) = \theta_i(\tau-1) + \frac{2m-n}{n}\,\varphi,\ m = 0, 1, \cdots, n\},$$

and the other is the choice set of speed denoted by Ω_i^{v} and it is stipulated as

$$\Omega_i^{\mathrm{v}} = \{v_i|\, v_i = \frac{k}{l}\, v_i^{\mathrm{d}},\ k = 0, 1, \cdots, l\}.$$

Then, the choice set $\Omega_i(\tau)$ is given as

$$\Omega_i(\tau) = \Omega_i^\theta(\tau) \times \Omega_i^{\mathrm{v}}.$$

Above configuration is summarized in Figure 1.

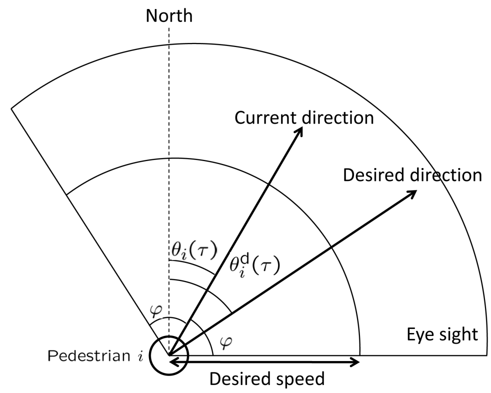

Fig. 1. Choice set of pedestrian i. The fan-shape is consistent with our experience as pedestrians.

2.2 Modeling pedestrian behavior with decision theory

We assume that pedestrian behavior can be divided into two factors and we name them goal-directed (GD) behavior and risk-oriented (RO) behavior. GD behavior reflect the fact that pedestrians basically attempt to minimize the time that is required to reach their goals and RO behavior reflect the fact that pedestrians hate physical contacts with other pedestrians or walls. To represent such behavior, we define the utility of a state $s_i(\tau+T)$ for pedestrian i who is in the state $s_i(\tau)$ in a simple form as

$$\begin{aligned} U(s_i, s_{-i}) &= \alpha T v_i(\tau)\cos(\theta_i(\tau) - \theta_i^{\mathrm{d}}(\tau)) \\ &+\beta \sum_{j:s_j(\tau)\in A_i(\tau)} f(|s_i(\tau+T) - s_j(\tau+T)|) \\ &+\gamma \sum_{\mathrm{wall}} f(\mathrm{dist}(s_i(\tau+T), \mathrm{wall})), \end{aligned}$$

where s_{-i} denotes the set of positions of pedestrians other than pedestrian i and the state $s_i(\tau+T)$ is completely stipulated by the choice set $\Omega_i(\tau)$. Also, $A_i(\tau)$ represents the set of pedestrians who are in the eye sight of pedestrian i at step τ and the anticipatory period which is denoted by T represents how distant future events a pedestrian focus on to decide his action. Furthermore, we specify the function f as $f(x) = -e^{-ax}$ so that we can ignore the interaction between a pedestrian and other pedestrians or walls when the value of x that corresponds to their distance is large enough.

Also, utilities must determine the transition probability and it is obtained by adopting the softmax function as

$$p_i(s_i(\tau+T)|s_i(\tau)) = \frac{\exp(\lambda E(U_i(s_i(\tau+T))))}{\sum_{s_i'(\tau+T)} \exp(\lambda E(U_i(s_i'(\tau+T))))}.$$

Here, λ is the inverse-temperature parameter and it controls how likely a pedestrian deviates from the rational choice for unexplained reasons. Note that we employ the expected utility for stipulating the transition probability.

2.3 Theory of Mind

The concept of Theory of Mind is considered in pedestrian behavior such that, "In a certain environment, a pedestrian makes belief about other pedestrians' future movements and decides his action based on the belief.". We assume types in pedestrian behavior and denote them as L(k) where k represents the k-th order strategic thinking. We assume that a pedestrian with type L(1) does not represent the behavior of other pedestrians, thus does not anticipate the action of others. In contrast, a pedestrian with type L(k) ($k \geq 2$) is assumed to evaluate and predict other pedestrians' actions to determine the behavior of his own. In practical, we assume that a pedestrian with type L(1) always chooses his desired direction and speed regardless of the existence of any interference. Also, for a pedestrian whose order type is equal to or higher than 2, his formed beliefs are completely reflected in his utility calculation. The utility of a pedestrian with type L(k) is calculated assuming that all other pedestrians in his eye sight have type L($k-1$), which is one level lower than his own.

3 Simulation results

In this section, we present simulation results which are intended to verify how the distribution of types in pedestrians affect the efficacy of the flows by evaluating average speed into the desired direction and frequency of collisions. The simulations in this section consider interactions among about forty pedestrians simultaneously. Also, we consider three types of order.

3.1 Bi-directional flow

We present simulation results for a bi-directional flow, in which some pedestrians are walking from left to right and others are walking from right to left along a road whose length is 10 [m] and width is 5 [m]. We present the results for some distributions which are denoted by $(p(\mathrm{L}(1)), p(\mathrm{L}(2)), p(\mathrm{L}(3)))$ in Figure 2 and show trajectories that corresponds to each distribution in Figure 3.

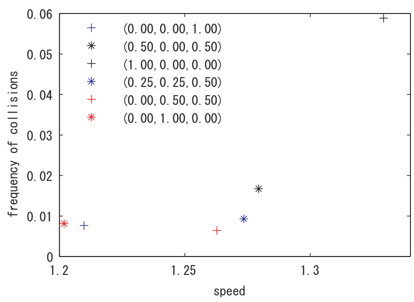

Fig. 2. Speed-collision relationship of a bi-directional flow. It is beneficial for pedestrians if the point is plotted in the bottom-right of the figure and we see that it is achieved with some mixtures of order types.

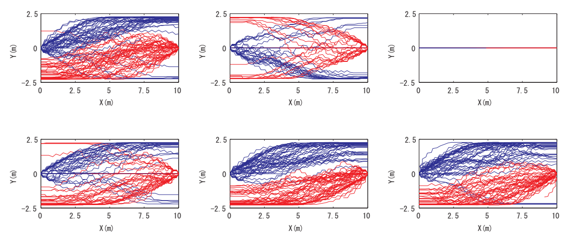

Fig. 3. Trajectories of pedestrian movements in a bi-directional flow. A pedestrian is added at $[0, 0]$ or $[10, 0]$ in every two successive steps by turns. Also, their goal point is set to be $[10, 0]$ or $[0, 0]$, respectively. Each figure from above left to right corresponds to each distribution in Figure 2 in order.

3.2 Flow at an intersection

We show the simulation result for the flows which are observed in an intersection, where two roads each of which is 10 [m] long and 5 [m] wide are crossing orthogonally. We first show the results in Figure 4 and then we plot the position of pedestrians at some particular time steps for the case of $(p(\mathrm{L}(1)), p(\mathrm{L}(2)), p(\mathrm{L}(3))) = (0.25, 0.00, 0.75)$ in Figure 5. In Figure 5, we see dynamical lane or cluster formation in pedestrian behavior.

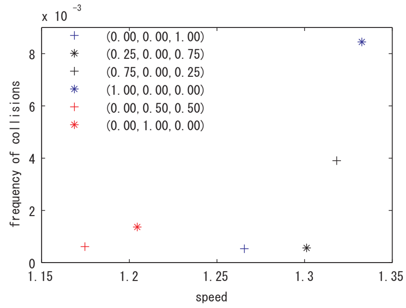

Fig. 4. Speed-collision relationship of a large scale orthogonal flow. As same as the previous example the best result is achieved with the distribution which is a certain mixture of pedestrians with different order types.

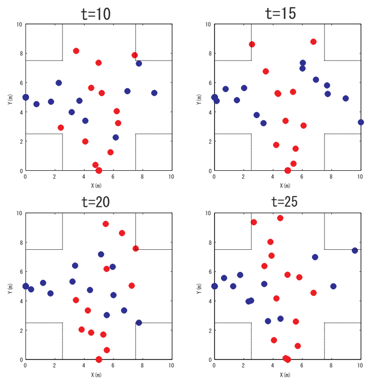

Fig. 5. Dynamical lane formation. Snapshots from a large scale orthogonal crossing at $t = 10, 15, 20, 25$ when $(p(\mathrm{L}(1)), p(\mathrm{L}(2)), p(\mathrm{L}(3))) = (0.25, 0.00, 0.75)$ are illustrated from above left to right in order. A pedestrian is added at $[5, 0]$ or $[0, 5]$ in every two successive steps by turns.

4 Conclusion

We proposed a microscopic pedestrian simulation model with a universal method in decision theory and incorporated the idea of Theory of Mind by introducing types of order in strategic thinking levels that are reflected in their behavior. Also, we applied our model to large scale pedestrian flows to test how the distribution of types of order affects the efficacy of pedestrian flows as a whole. Although our modeling procedure is one of the simplest ones than those of previous models, we could focus on collision avoidance behavior and its mental attribution, which have never been shed much light in past researches. Also, our results support the idea that high order strategies induce cooperative behavior since they contributed to the lane formation among pedestrians.

Bibliography

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