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Theory of mind in a microscopic pedestrian simulation model

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Abstract: In this paper, we propose a microscopic pedestrian simulation model which focuses on pedestrians' anticipatory behavior in collision avoidance. While it is obviously recognized that inferring other pedestrians' behavior is playing a crucial role when they intend to avoid collision, few models seriously tackled with this mental attribution. Our model assumes that each pedestrian has theory of mind, which refers to the capacity to make accurate judgments about beliefs, desires and intentions of other people, and he decides his action based on his current state in cognitive hierarchy. We also present various simulation results to understand how our anticipatory behavior affects pedestrians' behavior as a whole.

Keywords: Pedestrian Simulation, Decision Making, Theory of Mind

I Introduction

A number of researches analyzing microscopic pedestrians' behavior with computer simulations have been conducted after we experienced vast improvement on computational ability. Such microscopic simulation models adopt physical forces [1], cellular automaton models ([2], [3]) or decision making processes [4]. In these papers, authors' cardinal concerns were how accurate their models could simulate realistic pedestrian behavior in our daily lives, which are obviously important from a practical perspective, and they did not pay much attention to collision avoidance behavior although the game theoretic aspects which occur when we face other pedestrians on a road are fundamental to pedestrians' characteristics, thus should be investigated further. Recent relevant papers which treat collision avoidance game theoretically include [5] and [6].

Although adopting game theory to pedestrians' collision avoidance is insightful, classical game theoretic approaches do not immediately tell pedestrians how they should behave in a certain environment. What a pedestrian do to make reasonable decisions in ever changing environment is that he successively infers and makes belief about the movements of other pedestrians and then decides his response based on that belief. Thus it is natural to incorporate the concept of theory of mind [7], which refers to the ability to make accurate guessing about the beliefs, desires and intentions of other people.

In this paper, we model pedestrian behavior with decision making approaches incorporating theory of mind. We also present various simulation results and discuss anticipatory behavior of pedestrians.

II The model

In this section, we first describe the microscopic pedestrian model we have developed and then discuss how we apply the idea of theory of mind to collision avoidance in our model. Our model assumes that pedestrians' transition are fully specified by utilities calculated on each available state. Such assumption and procedure are one of the most common and powerful approaches in past researches of human decision making.

1 Pedestrians' admissible directions and speeds

Due to computational constraints, we need to discretize pedestrians' applicable directions and speeds at a certain moment. We adopt the same model as in [6], which is described in Figure 1, except for some parameter configuration. Here, θ_i^d and θ_i are desired and current direction,

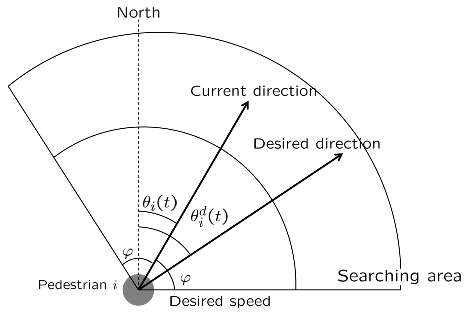

Figure 1: Choice set of pedestrian i

respectively.

At every moment after a certain time called scan interval, pedestrian i decides his new direction within the choice set Θ_i, that are

$$\Theta_i(t) = \{\theta_i(t) |\, \theta_i(t-1) + \frac{2m-n}{n}\,\varphi,\ m = 0, 1, \cdots, n\}$$

where φ restricts the admissible change in direction. Also pedestrian i chooses his speed v_i from the choice set V_i, that are

$$V_i = \{v_i |\, v_i = \frac{k}{l}\, v_i^d,\ k = 0, 1, \cdots, l\}$$

where v_i^d is the desired speed of pedestrian i.

2 Specifying actual direction and speed

We assume that pedestrian behavior can be divided into two factors, that are goal-directed (GD) behavior and risk-oriented (RO) behavior. GD behavior reflects the fact that pedestrians basically attempt to minimize the time required to reach their goals and RO behavior reflects the fact that pedestrians hate physical contacts with other pedestrians or walls. To represent such behavior, we define the utility of pedestrian i in a simple form as

$$\begin{aligned} U(s_i(t+1)) =& \alpha v_i(t) \cos(\theta_i(t) - \theta_i^d(t)) \\ &+ \beta f(|s_i(t+1) - s_j(t+1)|) \\ &+ \gamma f(\mathrm{dist}(s_i(t+1), \mathrm{wall})), \end{aligned} \tag{1}$$

where $s_i(t)$ denotes pedestrian i's position at step t.

In the first term of the equation (1) which represents GD behavior, a pedestrian chooses his direction and speed so as to maximize the distance traveled into his desired direction in anticipatory period. For the function f in the second and the third term, we specify it as

$$f(x) = -e^{-ax}. \tag{2}$$

Applying this f in our utility function, we can ignore interaction between a pedestrian and other pedestrians or walls when their distance is large enough. On the other hand, as the distance becomes smaller, RO behavior to avoid collision becomes dominant and the corresponding value of utility decreases. Also the parameter a should be tuned so that the value of utility be close enough to zero at any distance where pedestrians do not perceive to be uncomfortable due to the existence of other pedestrians or walls.

3 Transition of pedestrians

After every scan interval, pedestrian i moves to another state following the algorithms described below.

1) Given the current state $s_i(t)$, pedestrian i calculates the utility for every admissible state $s_i'(t+1)$ after anticipatory period.

2) Pedestrian i calculate the probability of moving to another state $s_i(t+1)$ from $s_i(t)$ as

$$p(s_i(t+1)|s_i(t)) = \frac{\exp(\lambda' U(s_i(t+1)))}{\sum_{s_i'(t+1)} \exp(\lambda' U(s_i'(t+1)))}.$$

3) Pedestrian i moves according to the probability distribution calculated above.

To determine probability of choosing strategies from the value of utility, three forms, exponential (logit), power and normal (probit) have been used in previous researches in decision making. Among these, exponential form which we adopt is considered to be the most preferable experimentally. The parameter λ' controls how likely pedestrian i deviates from the rational choice for unexplained reasons. Also it is known that there is positive correlation between the value of λ' and pedestrian's rationality. We put $\lambda = \lambda'/100$ in what follows.

4 Theory of mind

Theory of mind, namely attribution of mental states, was originally studied in chimpanzees [7] and is now broadly used in researches that investigate our psychological concepts for imputing mental states to others and ourselves. Also there are some recent mathematical models of theory of mind, [8] and [9], from which we gained inspiration for this research.

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 that belief. The utility we mentioned in the last section is calculated with this formed belief.

We model the first- and the second-order type of theory in pedestrian behavior denoted as L1 and L2, respectively as the same manner as in [9]. We assume that pedestrians with type L1 do not represent other pedestrians' behavior, thus do not anticipate others' actions. In contrast, L2 pedestrians are assumed to model other pedestrians' planning processes to predict their future behavior. In practical, a pedestrian with type L1 always chooses his desired direction and speed. Also the utility of a pedestrian with type L2 is calculated assuming that all other pedestrians in his eye sight are having type L1. These L1 and L2 types refer to "going" and "giving way" behavior mentioned in [6].

While we can consider pedestrian types with higher-order contents such as L3, L4, $\cdots$, we only adopt two types L1 and L2 in this paper. We discuss this topic in detail later in concluding remarks. Also for simplicity, we assume that a pedestrian is type L1 with probability p and type L2 with probability $1-p$. This assumption is natural in congested situations such as intersections, stations or buildings where intermittent changes of environment hinders pedestrians' rational decision makings while it would not apply in cases when interference between only two pedestrians, in other words low density situations, are concerned.

III Simulation

In this section, we present various simulation results for algorithms shown in Section II.

1 Parameter configuration

First of all, let us explain general parameter configuration in our model. Note that we get the parameter values presented below after conducting various simulations.

α and β represent how each pedestrian balances between one's weights on GD and RO behavior. Here the proportion of β to α and γ to β are important, thus we put $\alpha = 1$, $\beta = 2.7 \pm 0.2$ and $\gamma = 1.5$. Someone who is in haste has low value of β and more inclined to GD behavior than to RO behavior, and vice versa. a determines the steepness of the function f in (2) and reflects the distance where a pedestrian begins to feel uneasy due to the existence of other pedestrians or walls and RO behavior starts to hinder GD behavior. We put $a = 2.0$ and $a = 10.0$ in the case of interaction with other pedestrians and walls, respectively. λ reflects pedestrians' rationality as we mentioned earlier and pedestrians become more rational as the value of it increases. Since our aim is to simulate the role of theory of mind in settings that contain intermittent interaction where changing environment makes it difficult for pedestrians to make rational choices, we put $\lambda = 1.0$. Other parameters are basically determined according to [6] and summarized in Table 1.

Table 1: Parameter settings

Scan intervals	0.2 s
Radius of a pedestrian	0.2 m
Searching area	Fan-shape with 5 m radius and $\pm\pi/3$ in range
Desired speed (v_i^d)	1.35 ± 0.2 m/s
Set of directions (φ, n)	$\pi/3$, 12 (every 10°)

Here we present two typical examples in which interaction with other pedestrians are not concerned (Figure 2) or are concerned only within two pedestrians (Figure 3, with a steady pedestrian at [4.0, 1.5] represented by a red circle), only to confirm that above parameter settings work. In both examples, the starting point and the goal are [0, 1,5] and [8.0, 1.5], respectively and we plot trajectories of a hundred pedestrians on the road. Since we defined transition of pedestrians probabilistically and added fluctuation in the value of β and desired speed, we are able to observe trajectories peculiar to each pedestrian.

2 One directional flow

In this section we present simulation results to show how the difference in the value of p affects pedestrian behavior as a whole.

First let us explain the simulation settings. Fifty pedestrians are assigned to walk along the road whose width is

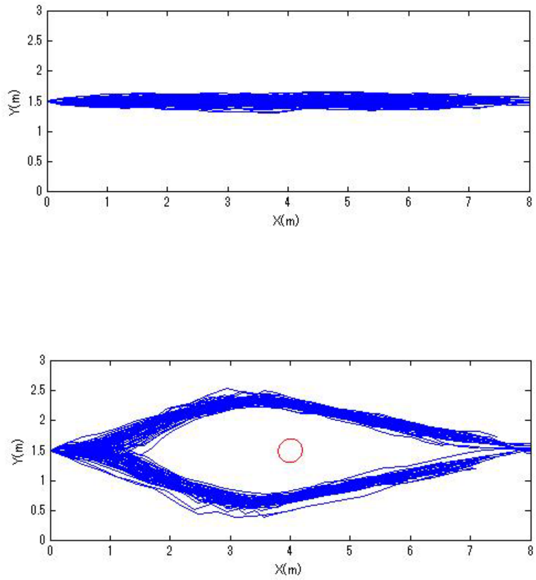

Figure 3: One directional trajectories with an obstacle

5m, starting at [0, 2.5] for fifty seconds. Other parameter configuration is same as that of Table 1. One directional flow simulation we adopt here are simple yet provide profound data about fundamental behavior of pedestrians and used in previous researches. All the data we employ for plots below are averages of the results for five times.

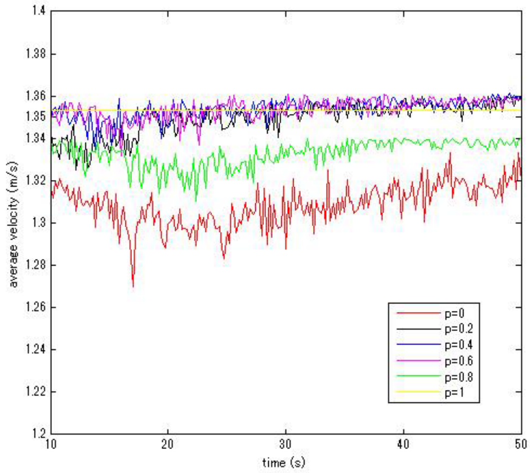

Figure 4: Velocities

We plot velocity of pedestrians after ten seconds in Figure 4 and frequency of collision which is the number of collision divided by the number of nodes among pedestrians in Figure 5 for some values of p. From these figures we see that the value of p close to 0 or 1 are unfavorable for pedestrians. To examine this effect we obtain the average of velocity and frequency of collision for all time steps and plot them in Figure 6. It is implied that the best value of p lies between $p = 0.2$ and $p = 0.5$.

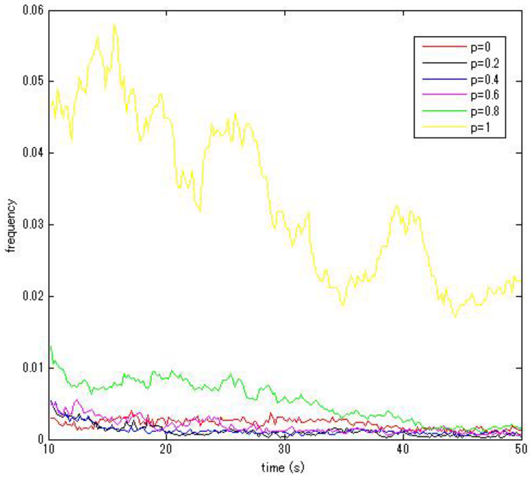

Figure 5: Frequency of collision

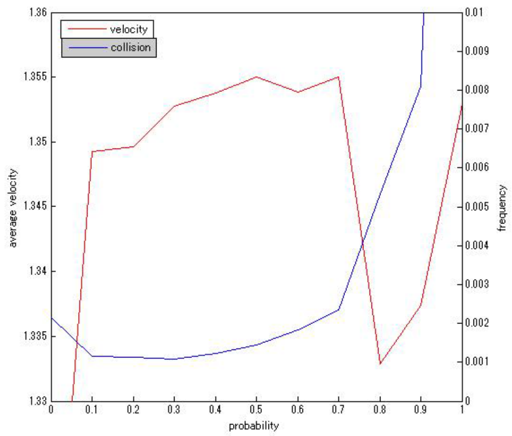

Figure 6: Average of velocity and frequency of collision

IV Concluding remarks

We proposed a microscopic pedestrian simulation model incorporating the concept of theory of mind which we strongly believe is fundamental to pedestrian behavior. We also presented numerical examples for simulated data to show that our model exhibits different behavior due to variation in pedestrians' mental attribution represented by types.

In this paper, we only adopted two types of theory in pedestrians, the first-order and the second-order, although we can consider higher order contents. Such higher-order types would lead to infinite repetition of anticipatory behavior and become unrealistic, while it could be worth considering since we never surely know how pedestrians are capable of using sophisticated strategies. If we take latest perspectives from researches on cognitive hierarchy into account, L3 and probably L4 are worth adopting while contents higher than L5 seem not to be required because such contents are likely to be mapping from states to actions acquired by experience rather than computation in the brain.

Also, although we assumed types in pedestrians are determined probabilistically with p in this paper, exploring a rule that regulates transition in types is valuable since we know by our experience that we choose our types observing the behavior of other pedestrians during a few steps before we make decisions.

These two main interesting topics would be investigated further in our future works.

Acknowledgements

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References

[1] D. Helbing and P. Molnar (1995), "Social force model for pedestrian dynamics", Physical Review E, Vol. 51, No. 4, pp. 4282–4286.

[2] V. J. Blue and J. L. Adler (2000), "Modeling four–directional pedestrian flows", Transportation Research Record, No. 1710, pp. 20–27.

[3] A. Kirchner, H. Klupfel and K. Nishinari et al. (2004), "Discretization effects and the influence of walking speed in cellular automaton models for pedestrian dynamics", Journal of Statistical Mechanics: Theory and Experiment, P10011.

[4] Th. Robin, G. Antonini, M. Bierlaire et al. (2009), "Specification, estimation and validation of a pedestrian walking behavior model", Transportation Research Part B, Vol. 43, No. 1, pp. 36–56.

[5] M. Asano, T. Iryo and M. Kuwahara (2009), "A pedestrian model considering anticipatory behavior for capacity evaluation", in: Transportation and Traffic Theory 2009, Springer, New York, pp. 559–581.

[6] M. Asano, T. Iryo and M. Kuwahara (2010), "Microscopic pedestrian simulation model combined with a tactical model for route choice behavior", Transportation Research Part C, Vol. 18, pp. 842–855.

[7] D. Premack and G. Woodruff (1978), "Does the chimpanzee have theory of mind?", Behavioral Brain Science, Vol. 1, pp. 515–526.

[8] W. Yoshida, R. Dolan and K. Friston (2008), "Game theory of mind", PLoS Computational Biology, Vol. 4, No. 12, pp. 1–14.

[9] C. Baker, N. Goodman and J. Tenenbaum (2008), "Theory-based social goal inference", Proceedings of the thirtieth annual conference of the cognitive science society, pp. 1447–1455.