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The Nomad model: theory, developments and applications

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Abstract

This paper presents details of the developments of the Nomad model after being introduced more than 12 years ago. The model is derived from a normative theory of pedestrian behavior making it unique under microscopic models. Nomad has been successfully applied in several cases indicating that it fulfils requirements for accuracy, scope and computational efficiency. In this paper we introduce the components of the model by relating them with behavioral assumptions providing an explanatory character to Nomad . The link between the model and the pedestrian theory is the main contribution and could improve the development of pedestrian models in general.

1. Introduction

Microscopic pedestrian models have been developed and used for many decades and come in many flavors. Some such as Cellular Automata, focus on simplicity to enhance computational efficiency. Others, such as Social Force Models, create more complex descriptions of pedestrian behaviors that promote more accurate movement of individuals. Nomad is a microscopic model developed under a more ambitious aim of proposing a pedestrian walking theory that couples the development of the model and assumptions on walking behavior.

Nomad pedestrian theory proposed by Hoogendoorn and Bovy (2002) is derived from a minimal effort principle. In the theory the walking effort is expanded to the more generic concept of walking cost and activity utility. Pedestrians gain utility when performing activities and 'pay' a cost when walking. Nomad pedestrians are maximizing the balance between both, thus it is a normative theory (*pedestrian economicus*).

This paper presents the theoretical and mathematical foundations of the Nomad pedestrian model. The model described in this paper reproduces the commuter behavior of purposeful pedestrians going straight to a goal. However, the Nomad model is not limited to commuters and is also applied to waiting behaviors. The derivation of the model can be found in Hoogendoorn and Bovy (2002) and some of the extensions in Campanella et al. (2009). Here, we emphasise the connection between the model and the behavioral assumptions (put explicit under the labels H#).

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2. Nomad three level pedestrian model

The Nomad model is based on the three level pedestrian theory approach. These levels break the important aspects of pedestrians behavior into clearly distinct tasks reducing the model complexity. The *strategic level* incorporates the tasks that must be completed before the trip starts (the plan), the *tactical* models the choices and decisions including changes in the original plan during the trip and the *operational level* describes the walking behavior or how pedestrians navigate to accomplish the plan. (Fig. 1(a))

2.1. The plan (strategic level)

The plan consists of the schedule (ordered list) of the activities and the corresponding routes linking the origin, activity areas and destination. According to the Nomad theory the planned trip has the highest possible utility that a pedestrian can gain from performing the intermediate activities, reaching the destination and discounting the walking costs. Thus, the trip is an optimal schedule of activities and the ordering of activities and the choice of the routes are performed simultaneously. The choice of an activity area (a suitable location) is dependent on four factors: the base utility (C_{base}) that represents a subjective value of performing the activity in the area ('this restaurant is very good'), the service cost ($C_{service}$) that depends on the expected service time (longer service times generate more costs), the expected waiting time ($C_{waiting}$) due to the presence of other pedestrians in that area (longer waiting generates more costs) and the cost of reaching the area ($U_{walking}$). The chosen activity area is the one with the maximum U_{net}^*:

$$U_{net}^* = \arg \max \left(U_{base} - C_{service} - C_{waiting} - C_{walking} \right) \tag{1}$$

The route choice model was developed by Hoogendoorn and Bovy (2004) using the minimum cost principle. The costs of walking reflect preferences of pedestrians when walking unhindered by other pedestrians. There are several costs that can be taken into consideration, travel distance, minimum distance to obstacles, travel time, subjective preferences such as closeness to shopping windows (lower costs for nearby areas).

The end result of the route choice calculation for a particular destination is a cost map that presents the walking cost for each position in the walking area to reach the destination. The optimal route is obtained by always joining the current position to the closest position with the lowest cost. This is repeated until the destination that has the overall lowest cost is reached. Fig. 1(b) shows an illustration of a cost map and three desired routes. The colored rings represent regular intervals of costs in descending values towards the direction of the destination (in yellow). From the cost map we derive an equivalent desired velocity map with vectors pointing along the desired route.
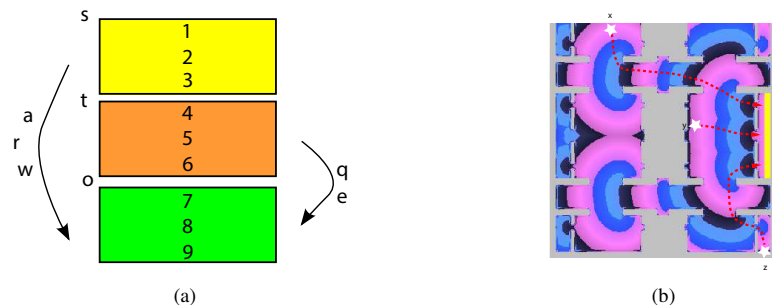

Fig. 1. (a) The three level model; (b) Three optimal routes starting from three origins leading to the same destination accessible via three doors.

2.2. Changes in the plan (tactical level)

There are many reasons why pedestrians make choices during the trip, the need to reschedule the plan because the original route is congested and an alternative route is less costly, an alternative activity area has significant less pedestrians waiting to perform the activity than the original, the travel time was higher than anticipated and pedestrians may need to drop one or more activities not to miss a mandatory activity such as boarding a train. Also pedestrians may have to choose between queues, escalators and stairs. Choices always follow the utility maximisation principle.

3. Nomad walker model (operational)

The Nomad model has two distinct parts, the controllable and non-controllable models. The controllable acceleration $\vec{a}_c$ is the part resulting from pedestrian actions. This is the model that describes the pedestrian behavior. The non-controllable $\vec{a}_p$ also referred to as physical acceleration is imposed on the pedestrians by physical contact with other pedestrians and obstacles. Equation 3 shows the Nomad walker model adding both accelerations:

$$\vec{a}(t) = \vec{a}_c(t) + \vec{a}_p(t) + \vec{\epsilon}(t) \tag{2}$$

The noise term $\vec{\epsilon}(t)$ accounts for everything that is not covered by the model and including natural fluctuations of the walking behavior (intra-pedestrian heterogeneity). Nomad pedestrians follow a utility optimisation strategy of always minimizing the costs of walking, they are thus:

H1: Optimal feedback-oriented controllers and
H2: minimise predicted discounted costs resulting from walking. In its basic version Nomad distinguishes three walking costs:

H3: straying from the desired route,
H4: the vicinity of obstacles and
H5: the vicinity of other pedestrians.

In the model this corresponds to: $\vec{a}(t) = \vec{a}_s(t) + \vec{a}_o(t) + \vec{a}_r(t) + \vec{a}_p(t) + \vec{\epsilon}(t)$. Where $\vec{a}_s$ is the path straying component, $\vec{a}_o$ is the obstacle interaction component and $\vec{a}_r$ is the pedestrian interaction component.

3.1. Straying component $\vec{a}_s$ (H3)

Section 2.1 showed that the optimality assumption results in desired velocities leading to the optimal route towards the destination. According to Buchmueller and Weidmann (2006) pedestrians prefer to walk according to their free speeds that are optimum in terms of energy consumption (fig. 2(a)). Therefore, deviations from free speeds represent walking costs. The Nomad model proposes an exponential equation for the velocity that penalises deviations below and above the free speeds and away from the optimal route:

$$v(t) = v_0(1 - e^{-t/\tau}) \quad \therefore \quad \vec{a}_s(t) = \frac{d\vec{v}(t)}{dt} = \frac{\vec{v_0} - \vec{v}}{\tau} \tag{3}$$

Where, τ is the constant acceleration time and v_0 is the free speed. The acceleration time τ mostly affects the intensity that pedestrians want to stay close to the optimal route. Pedestrians with very small τ ($\sim 0.0s$) will walk closely to their desired path with speeds around their free speeds. It will require very large interaction accelerations (section 3.3) to make these pedestrians deviate from other pedestrians representing uncooperative (aggressive) pedestrians.

3.2. Obstacle interaction component $\vec{a}_o$ (H4)

Pedestrians maintain a shy-away distance to obstacles (Buchmueller and Weidmann (2006)). However, there are situations in which pedestrians may need to stay closer to obstacles when waiting or passing turnstiles. Therefore, an exponential formulation would not be convenient we use a linear function instead (equation 4). For simplicity the distances between the pedestrians and the obstacles are calculated considering circular pedestrians (see fig. 2(b)).

$$\vec{a}_o(t) = -\vec{e}_n \cdot a_W \sum_{o \in O} \begin{cases} 1 & \text{if } 0 < d \leq ds/2 \\ 1 - (d - ds)/ds & \text{if } ds/2 < d \leq ds \\ 0 & \text{if } d > ds \end{cases} \tag{4}$$

$\vec{e}_n$ is the unity vector in the normal direction pointing to the closest point of the obstacle, a_W is the balancing parameter between this component and the others and ds is the shy-away distance.
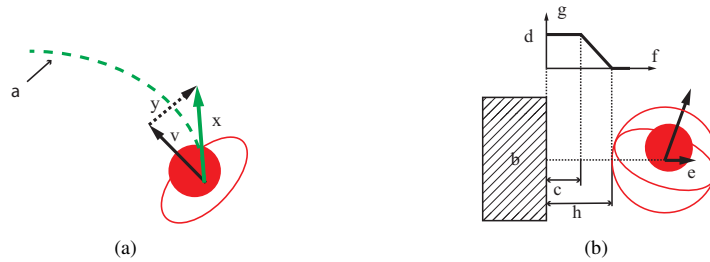
Fig. 2. The straying and obstacle interaction components. (a) Straying; (b) Obstacle.

3.3. Pedestrian interaction component $\vec{a_r}$ (H5)

When pedestrians perceive opponents that potentially could collide in the close future they (may) apply avoiding manoeuvres. The reaction to these opponents is based in assumptions about their reactions. When opponents are not paying attention (distracted behavior) or display a 'dominant' behavior (aggressive behavior) they are non-cooperative. Hoogendoorn and Bovy (2002) show that under some conditions, cooperative models are similar to non-cooperative models. The Nomad model presented in this paper uses a non-cooperative strategy that simplifies the derivation but because all pedestrians apply the avoiding manoeuvres the overall behavior is cooperative.

H6: Walkers anticipate on the behavior of other pedestrians by predicting their walking behavior according to non-cooperative or cooperative strategies.

Pedestrians anticipate the movement of others and themselves with the aim of minimizing their future cost of walking. The anticipation time can extend from zero (no-anticipation) to a positive value (in seconds). In Nomad this is modeled by using anticipated positions instead of current positions in the pedestrian perception. The anticipated positions are extrapolated from the current speeds of the opponents (and for themselves) for a time determined by the *anticipation time* (t_A): $\vec{r_A} = \vec{r} + \vec{v}t_A$, where $\vec{r_A}$ is the anticipated position of pedestrians.
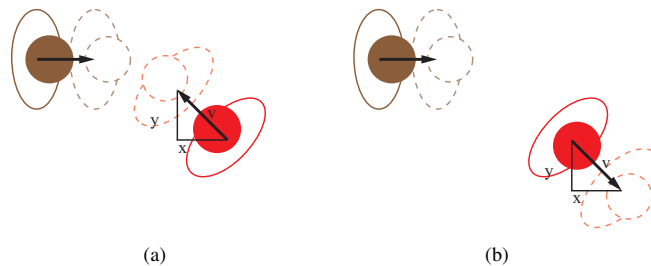

Fig. 3. For avoidance purposes the leftward pedestrian considers the anticipated dashed positions. (a) Approaching; (b) Distancing.

If the anticipated distances are larger than the real distances pedestrians are moving away from each other (case (b) in Fig. 3). In these cases their interaction will be vanishing in the future while for case a the interaction will increase. The anticipation is only used for interactions with pedestrians that are in the front. Pedestrians do not guess the speed of pedestrians that are behind them.

3.4. Influence area (H7 and H8)

Pedestrian perception is largely based in vision, but the other senses also play a role. Therefore, pedestrians also perceive what is happening behind them but only in close range. Nomad pedestrians have thus a limited area of interaction that is named the *influence area* that identifies which obstacles and pedestrians affect the pedestrian interaction behavior.

H7: Pedestrians have limited predicting possibilities, reflected by discounting utility of their actions over time and space, implying that they mainly consider pedestrians in their direct environment.

H8: Pedestrians are anisotropic particles that react mainly to stimuli in front of them.

The 'elliptic' shape of the influence area is obtained by multiplying the projected distance between pedestrians in the velocity direction $\vec{d_x}$ by a factor c_0^+ that is smaller than 1. $\vec{d_f}$ and $\vec{d_b}$ are the perceived distances respectively in the front and in the back, $\vec{dx}$ and $\vec{dy}$ are the projected distances in the velocity and orthogonal directions:

$$\vec{d_f} = \sqrt{\left(c_0^+ \vec{dx_f}\right)^2 + \vec{dy_f}^2} \qquad \text{and} \qquad \vec{d_b} = \sqrt{\left(c_0^- \vec{dx_b}\right)^2 + \vec{dy_b}^2} \tag{5}$$
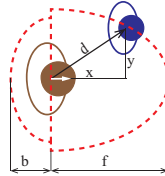

Fig. 4. The influence area that determines the interaction zone extending to the front and to the back of the pedestrian.

3.5. Interaction acceleration

For interaction purposes the costs of proximity are inverse to the distance between pedestrians. The closer they are to each other the more intensively pedestrians want to increase their relative distances. This is the equivalent to say that pedestrians will apply larger avoiding accelerations due to pedestrians that are closer. These accelerations push them away from each other ($\vec{a_{rn}}(t)$ in the normal direction see fig. 5(a)). In Nomad this is modeled by an exponential function that amplifies the close-by accelerations (Moussaïd et al. (2009)).

$$\vec{a_{rn}}(t) = -a_0 e^{-d_A/r_0} \cdot \vec{e}_n \tag{6}$$

The interaction strength a_0 is the balancing parameter between the interacting component and the other components. The larger a_0 the more important this component is. The interaction distance r_0 relates the distance between the pedestrians and the intensity of the interaction acceleration. Diminishing values of r_0 ($\sim 0.0m$) diminish the distances required to generate large interaction accelerations. Diminishing r_0 diminish the space between pedestrians in crowded situations. $\vec{e}_n$ is the unity vector in the normal direction pointing to the other pedestrian.

3.6. Extra lateral interaction

When two pedestrians walk towards each other in an almost parallel path they perform a strong lateral avoidance manoeuvre. The interaction acceleration $\vec{a_{rn}}(t)$ is not enough to create such large lateral accelerations when trajectories are aligned in a collision path. This occurs because the angle of the resulting $\vec{a_{rn}}(t)$ is aligned and mostly opposed to the velocity (fig. 5(b)). The extreme case of perfectly aligned 180° ongoing paths the interaction component would display a non-realistic behavior of decelerating the pedestrians until they stop. To improve such situations a lateral interaction component with an exponential formulation is introduced for pedestrians walking towards each other:

$$\vec{a_{rl}}(t) = -a_1 e^{-(d_A dy_A)/r_1} \cdot \vec{e}_y \tag{7}$$

The term $(d_A dy_A)$ makes sure that only when pedestrians are close to each other and with small lateral displacement the lateral acceleration will be significant. The total interaction acceleration component is the sum of both interactions: $\vec{a_r} = \vec{a_{rn}} + \vec{a_{rl}}$. When pedestrians interact with several pedestrians they react more intensively than for a single pedestrian by adding the interaction of each pedestrian inside (P) and in the frontal part (P_{front}) of the influence area:

$$\vec{a_r}(t) = -a_0 \sum_{p \in P} e^{-d_{Ap}/r_0} \cdot \vec{e}_{np} - a_1 \sum_{p \in P_{front}} e^{-(d_{Ap} dy_{Ap})/r_1} \cdot \vec{e}_{yp} \tag{8}$$

Fig. 5. The two interaction accelerations applied by the left pedestrian due to the opposing pedestrian. (a) Normal interaction; (b) extra lateral acceleration.

3.7. Physical acceleration $\vec{a_p}$ (H9)

For normal congested situations a particle based collision model is enough to estimate the elastic and orthogonal friction accelerations: $\vec{a_p}(t) = \vec{a_{p_n}}(t) + \vec{a_{p_t}}(t)$.

H9a: Pedestrians are soft particles, represented as circles and obstacles are rigid bodies with no deformation.
H9b: Collisions do not occur instantaneously, develop large elastic accelerations in direction of the centres of pedestrians and friction forces in the orthogonal direction.

$$\vec{a_{p_n}}(t) = -k_0 \delta_{pq} \cdot \vec{e}_n \qquad \text{and} \qquad \vec{a_{p_t}}(t) = k_1 \delta_{pq} \left(\vec{v}_{tq} - \vec{v}_{tp} \right) \tag{9}$$

Where δ_{pq} is the deformation of pedestrians p and q, k_0 is the elastic spring coefficient, k_1 is the orthogonal friction factor, $\vec{v}_t$ is the projection of the velocity vector into the orthogonal direction and $\vec{e}_n$ is the unity vector in the normal direction pointing to the other pedestrian.
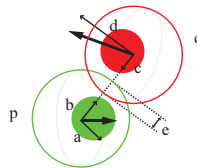

Fig. 6. The graphic representation of a collision between two Nomad pedestrians.

4. Conclusion

In this paper we presented how the components of the Nomad model were derived from the normative pedestrian theory. We also explicitly related the components to behavioral assumptions taken from empirical facts. These presented an updated overview of the Nomad model and indicated how components of microscopic models can be derived under a behavioral approach. Future work is necessary to develop the Nomad model for other types of pedestrian purposes such as leisure and shopping behaviors.

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