Improving Pedestrian Micro-Simulations with Event Steps

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Summary. Microscopic pedestrian models describe individual pedestrian behavior and the interaction of pedestrians with other pedestrians and obstacles. Continuous time models generally calculate the acceleration of pedestrians due to repulsive or attractive interactions using for instance distances to other pedestrians and obstacles within a two-dimensional influence area. Two problems that usually arise with these types of models when simulating very large crowds are extreme accelerations that occur due to very short distances to other pedestrians and obstacles and large computational times to assess and to calculate the accelerations for individual pedestrians. This paper presents a hybrid pedestrian management algorithm that combines a traditional optimized time-based simulation and an event-driven simulation. This way, the task of assessing the surroundings and the task of dealing with interactions on very short distances are each treated in an optimized way leading to more reliable accelerations in high densities as well as shorter calculation times.

1 Introduction

Although the computational power available in a personal computer grew several orders of magnitude in the last decades, performing micro-simulations involving several thousands of pedestrians still requires a significant amount of time. This may effectively hinder the application of these models in a design process in which an architect wants to assess several layouts of public areas or large buildings. In the next section we will show that most simulation models, among which the NOMAD model [1], apply general approaches to search pedestrians' surroundings to identify other pedestrians and obstacles. This search is one of the most time consuming parts of micro-simulation models computations and it has to be performed each simulation step. In this contribution we propose an optimized spatial search to improve the quality and the efficiency of the NOMAD model.

2 The NOMAD Model

NOMAD is a normative model proposed by Hoogendoorn and Bovy [1]. Being a microscopic simulation model, it has a discrete time step. The movement of a pedestrian p in terms of velocity and acceleration can be described as a system of differential equations. Let $\mathbf{r}_p(t)$, $\mathbf{v}_p(t)$ and $\mathbf{a}_p(t)$ respectively denote the location, the velocity and the acceleration at time instant t, then the following is valid:

$$\frac{d}{dt}\mathbf{r}_p(t) = \mathbf{v}_p(t) \tag{1}$$

$$\frac{d}{dt}\mathbf{v}_p(t) = \mathbf{a}_p(t) \tag{2}$$

The acceleration is the result of different factors affecting the speed of pedestrian p, namely the desire to stay as close as possible to a desired trajectory leading towards the pedestrian's destination, avoiding other pedestrians, avoiding obstacles, the physical forces when pedestrians collide and some random component or noise:

$$\mathbf{a}_p(t) = \frac{\mathbf{v}_p^0(t) - \mathbf{v}_p(t)}{T_p} - A_p \sum\nolimits_q e^{-\frac{\mathbf{d}_{pq}(t)}{R_p^p}} - A_p^o \sum\nolimits_o e^{-\frac{\mathbf{d}_{po}(t)}{R_p^o}} + \mathbf{b}_p(t) + \boldsymbol{\varepsilon}_p(t) \tag{3}$$

where:

$\mathbf{v}_p^0$	: desired velocity
$\mathbf{d}_{pq}$	: vector pointing from pedestrian p towards pedestrian q
$\mathbf{d}_{po}$	: vector pointing from pedestrian p towards obstacle o
T_p	: acceleration time of pedestrian p
A_p	: interaction strength between pedestrian p and other pedestrians
A_p^o	: interaction strength between pedestrian p and obstacles o
R_p	: interaction distance between pedestrian p and other pedestrians
R_p^o	: interaction distance between pedestrian p and obstacles o
$\mathbf{b}_p(t)$	: physical acceleration due to contact forces
$\boldsymbol{\varepsilon}_p(t)$	: random term

A pedestrian is only affected by the pedestrians and obstacles present within his influence area. The latter can be represented by different forms (isotropic influence areas, anisotropic influence areas, etc.).

The physical forces $\mathbf{b}_p(t)$ are calculated as follows [2, 3] (Eq. (4) describes normal forces, while Eq. (5) describes tangential forces):

$$\mathbf{b}_p^{(n)}(t) = \kappa_p \delta_{pq}(t) \tag{4}$$

where:

$\mathbf{b}_p^{(n)}$	: physical acceleration in direction of centers of p and q
κ	: restitution coefficient
$\delta_{pq}(t)$	: deformation of pedestrians p and q

$$\mathbf{b}_p^{(t)}(t) = \upsilon_p \left| v_p^{(t)}(t) - v_q^{(t)}(t) \right| \delta_{pq}(t) \tag{5}$$

where:

$\mathbf{b}_p^{(t)}$	: tangential physical acceleration in direction of centers of p and q
υ	: tangential viscosity factor
$v_p^{(t)}(t)$	: tangential speed of pedestrian p
$v_q^{(t)}(t)$	: tangential speed of pedestrian q
$\delta_{pq}(t)$	: deformation of pedestrians p and q

3 Improving Efficiency of Micro-Simulation Models

The simulation model NOMAD is capable of reproducing emergent spatial patterns. However, two problems are potentially encountered due to the formulation of the acceleration term in Eq. (3):

- The physical forces that arise when pedestrians are very close to each other or close to obstacles can be very large in extreme densities due to large deformations of pedestrians.
- The computation times to calculate the distance vectors $\mathbf{d}_{pq}(t)$ and $\mathbf{d}_{po}(t)$ at every simulation step can grow excessively, impairing the total time needed to run a simulation, especially when many pedestrians are present in dense situations.

There are several ways to solve these problems, such as using dedicated data representation structures to reduce look-up times for pedestrians in the direct vicinity of pedestrian p. However, this only partially eliminates the problem, since it is still dependent on the size of the pedestrian population. Another way is to use isotropic (circular) influence areas. Usually, it is possible to implement a simplified query algorithm for this geometry that does not take the heading of the pedestrian into consideration to assess the distances. Again, this is not a complete solution, because such an area may produce unrealistic behavioral results, and it still requires a query at every simulation step.

The second problem of possibly high interaction forces can be tackled by using another formulation such as an exponential spring model for the physical forces:

$$\mathbf{b}_p^{(n)}(t) = c_1 e^{c_2 \delta_{pq}(t)} \tag{6}$$

Physical accelerations progress in a manner that could prevent too large accelerations to occur (in case of small deformations). It would not solve the problem when density is very high and large deformations will occur. The most effective way to prevent high deformations is to reduce the time step dt. A sufficiently small dt prevents pedestrians to deform too much (due to numerical issues) since the acceleration terms are calculated more frequently.

However, a small dt increases the simulation time substantially, which has already been identified as a problem in the previous section.

4 Hybrid Pedestrian Management

In a simulation, in each time step the walking behavior is calculated for each individual pedestrian present on the walking area. In this contribution we call pedestrian management the part of the simulation model responsible to calculate this walking behavior. Hybrid pedestrian management, presented in this contribution, is a combination of a time based simulation step and an event based simulation step, where most models are restricted to a time based simulation step. A time based simulation step considers discrete (constant) time steps, during which every pedestrian moves the distance calculated considering the constant speed in the time step (Fig. 1a).

To overcome the high physical forces in high densities, the hybrid management will distinguish the pedestrians that are very close to each other (categorized as pedestrians "in-collision"). These pedestrians are handled as colliding particles in an event-based simulation [4] (Fig. 1b), while for the other pedestrians the traditional time-based simulation is applied. The latter are further distinguished in two categories: those being sufficiently far away from other pedestrians and obstacles in order not to collide during the next time step ("in-range") and those being even further away from pedestrians and obstacles guaranteeing that their influence area will be not interfered ("isolated"). This way of distinguishing three degrees of isolation allows the hybrid management to optimize the amount of pedestrians that have to calculate the repulsion terms caused by physical contact.

4.1 Event Step

The hybrid way of handling collisions that may occur during a simulation step is to subdivide the simulation step into *smaller collision event steps of variable time lengths*. The smallest distance that any pedestrian "in-collision" can walk before he collides with another pedestrian or an obstacle will determine the next event step. If the time for the next collision event is smaller than the simulation time step, the pedestrians involved are moved until they collide, while other pedestrians in the event step will move according to this event step. The process is then repeated for the next smallest event time step. This process stops when the added length of the realized event steps including the next calculated event step is larger than the simulation time step. At this moment the last collision event is not realized and the residual time (see Eq. (7)) will be used to move the pedestrians to their final positions in this step without collisions:

$$R_{step}(t) = \sum_{i=1}^{n} E^{i}_{step}(t) - S_{step} \tag{7}$$

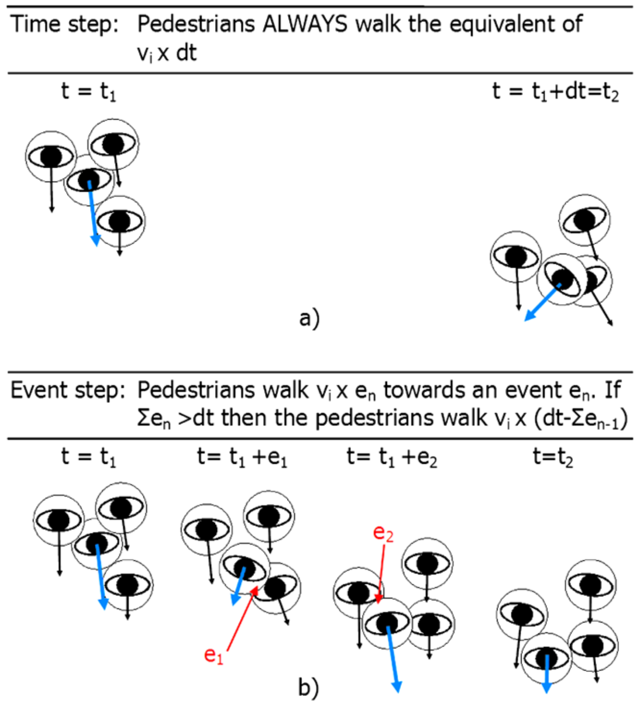

Fig. 1. a) and b) Comparison between a simulation time step and an event step.

where:

$R_{step}(t)$: residual time step
$E^i_{step}(t)$: event time step
S_{step} : simulation time step

To handle the collisions that occur at each event step we assume that there a pedestrian has a maximum deformation in the normal direction (δ_{max}). With this assumption an event becomes a collision when at least one pedestrian has $\delta_p(t) = \delta_{max}$. With the introduction of this condition the hybrid management makes sure that the collision forces will never be larger then a certain calibrated value independent of the value of dt.

4.2 Optimized Time Based Simulation Step

The time based simulation step is an optimized step in which the necessity to assess the influence areas by the pedestrians is minimized. Preferably, all pedestrians are calculated using the optimized time based simulation step and only those pedestrians that are too close to other pedestrians or walls will perform the event step. The main parameter in the time based optimization is the isolation time parameter ($T^{ip}(t)$) which is calculated for each pedestrian during his initialization phase. The isolation time of a pedestrian indicates the amount of time a pedestrian can walk without interfering with other pedestrians or obstacles, since the nearest pedestrian or obstacle is too far away to risk appearing in his influence area. When the isolation time has expired, the hybrid management will recalculate it and the process restarts. These pedestrians are said to be "isolated" from other pedestrians whilst their isolation time did not expire. By definition an "isolated" pedestrian does not need to look for other pedestrians in the current time step. To calculate his walking behavior the repulsion terms due to pedestrians and obstacles as well as the physical forces from Eq. (3) do not need to be recalculated. His acceleration can be then described by Eq. (8):

$$\mathbf{a}_p(t) = \frac{\mathbf{v}_p^0(t) - \mathbf{v}_p(t)}{\mathrm{T}_p} + \boldsymbol{\varepsilon}_p(t) \tag{8}$$

To calculate the lower boundary of $T^{ip}(t)$ for a pedestrian p the hybrid management calculates the distances between him and all pedestrians around him and assumes that each pedestrian is in direct collision route regardless of the real walking directions. Fig. 2 shows the above mentioned worst case situation.

To be sure that pedestrian q will not reach the influence area of pedestrian p, the hybrid management uses the maximum speeds (V_{max}) and maximum body radii (R_{max}) for both pedestrians. It also must assume all possible direc-

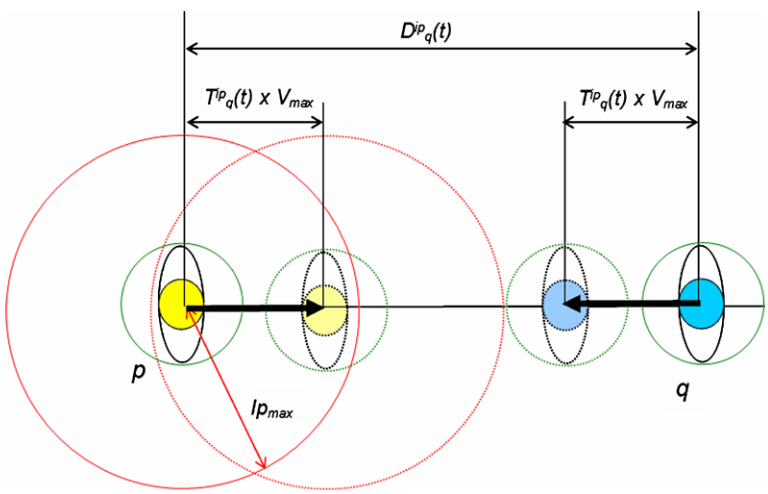

Fig. 2. Pedestrian q entering the influence area of pedestrian p assuming a conflicting trajectory.

tion changes by both pedestrians. Therefore it uses a circle with radius Ip_{max} to calculate $T_q^{ip}(t)$ and not the real influence area shape. From Fig. 2 we can derive the expressions for the distance between two pedestrians in terms of the maximum constants and $T_q^{ip}(t)$ and the expression for $T_q^{ip}(t)$ (Eq. (10)).

$$D_q^{ip}(t) = 2 \cdot \left(T_q^{ip}(t) \cdot V_{\max}\right) + Ip_{\max} + R_{\max} \tag{9}$$

$$T_q^{ip}(t) = \left(\frac{D_q^{ip}(t) - Ip_{\max} - R_{\max}}{2 \cdot V_{\max}}\right) \tag{10}$$

The isolation parameter time $T^{ip}(t)$ for a pedestrian is obtained as the minimum of all $T_q^{ip}(t)$ that are calculated according to Eq. (11):

$$T^{ip}(t) = \min\left(\frac{D_q^{ip}(t) - Ip_{\max} - R_{\max}}{2 \cdot V_{\max}}\right) \forall q \neq p \tag{11}$$

If the value obtained in Eq. (11) is larger than the simulation step dt, then the pedestrian is "isolated" from other pedestrians. For obstacles, a similar approach is implemented.

A pedestrian p is "in-range" if the nearest pedestrian q is sufficiently distant to guarantee that no collision will occur, but too close to guarantee that pedestrian q will not fall within pedestrian p's influence area. In this case the acceleration of pedestrian p takes into account all terms of the acceleration formula in Eq. (3) except the physical term since by definition there is no chance of collision with any pedestrian (Eq. (12)).

$$\mathbf{a}_p(t) = \frac{\mathbf{v}_p^0(t) - \mathbf{v}_p(t)}{T_p} - A_p^p \sum\nolimits_{q\in P} e^{-\frac{\mathbf{d}_{pq}(t)}{R_p^p}} - A_p^o \sum\nolimits_{o\in O} e^{-\frac{\mathbf{d}_{po}(t)}{R_p^o}} + \boldsymbol{\varepsilon}_p(t) \tag{12}$$

To calculate the in-range time ($T_{rp}(t)$) that a pedestrian is guaranteed to be free of collisions from other pedestrians we apply the same assumptions used for the isolation time: maximum parameter values and a straight collision path. We can deduce the value of $T_{rp}^q(t)$ that is the in-range time that pedestrian q would take to collide with pedestrian p in a straight trajectory with full speed:

$$T_q^{rp}(t) = \left(\frac{D_q^{rp}(t) - 2 \cdot R_{\max}}{2 \cdot V_{\max}}\right) \tag{13}$$

The maximum time during which pedestrian p will certainly not collide with other pedestrians is shown in Eq. (14). We define:

$$T^{rp}(t) = \min\left(\frac{D_q^{rp}(t) - 2 \cdot R_{\max}}{2 \cdot V_{\max}}\right) \forall q \neq p \tag{14}$$

$$T^{ip}(t) \leq dt \tag{15}$$

If the value obtained in Eq. (14) is larger than the simulation step dt and his $T_{ip}(t)$ is smaller than dt then the pedestrian is "in-range" from other pedestrians. For obstacles, again a similar approach is used.

If a pedestrian is neither "isolated" nor in "in-range", than his nearest pedestrian (or obstacle) is so close that there is a theoretical possibility that they may collide. In this case this pedestrian is "in-collision" and will perform the event step.

5 Conclusions and Future Work

In this contribution we presented a new hybrid pedestrian management approach that combines an optimized time-based simulation step and an event-based simulation step. This hybrid pedestrian manager differentiates pedestrians in micro-simulations according to three isolation degrees: "isolated", "in-range" and "in-collision". With this, the hybrid management is able to optimize the time to compute pedestrians' accelerations and prevent unrealistic repulsive accelerations in very dense situations. This hybrid manager is expected to improve calculation times and accuracy of accelerations during high densities in spatially distributed micro-simulations. The next step in this research is to implement and calibrate the hybrid model including the event step and compare the quality and the performance of the results with the traditional management model.

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