Towards TransiTUM: A generic framework for multiscale coupling of pedestrian simulation models based on transition zones

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Abstract

Existing pedestrian dynamics models differ in computational effort and their ability to authentically describe human movement behaviour. Hybrid approaches combine different models to speed up simulation time and to improve the results of the simulation. Current hybrid approaches can only combine a specific set of models. It is not possible to independently change the coupled models from the hybrid approach. Furthermore, transition of pedestrians between the different models is only possible at specific entry points. TransiTUM overcomes these issues and can combine any model if provided a certain set of parameters, which are common in pedestrian dynamics (e.g., pedestrians' positions, velocities). In this paper, the coupling of mesoscopic and microscopic scales is presented.

1. Introduction

Pedestrian dynamics simulations can be divided into three different types (microscopic, mesoscopic and macroscopic) by their spatial resolution. In macroscopic models the scenario is reduced to a network of nodes and edges. The calculation itself is based on aggregated parameters of human crowds and not on the behaviour of individual pedestrians (Shiwakoti and Nakatsuji, 2005). Therefore, these kinds of pedestrian dynamics models are computationally efficient for the price of low spatial resolution. Many macroscopic models draw from the theory of fluid mechanics. For example, Henderson (1974) adopted the gas kinetic Bolzmann transport equation to describe the motion of crowds. The Lighthill-Whitham-Richards (LWR) model (Lighthill and Whitham, 1955a,b; Richards, 1956) and its variants (Hughes, 2003; Kachroo, 2009) are based on the continuity equation of fluid dynamics. These approaches are often simplified to one spatial dimension to reduce the complexity of the problem (Colombo and Rosini, 2005; Hartmann and Sivers, 2013). The second important kind of macroscopic simulations is the network flow model. These models calculate the smallest amount of time pedestrians need to exit a given network scenario (Burkard et al., 1993; Tjandra, 2003).

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Mesoscopic models, which are carried out by cellular automata (Blue and Adler, 2001), have typically a finer spatial resolution associated with increasing computational effort. Therefore, the complete scenario needs to be split up into a regular grid. Each cell of the grid has an equal size and contains one or zero persons (Schadschneider et al., 2009). In pedestrian dynamics, unit cells have rectangular (Varas et al., 2007; Ji et al., 2013) or hexagonal (Hartmann, 2010) shapes. Both geometries have advantages and disadvantages (Birch et al., 2007). A finite set of rules routes the pedestrians locally, according to its boundary conditions, through the scenario (Schadschneider, 2001; Ji et al., 2013). Since the spatial resolution is restricted by the size of the unit cell, the pedestrians move cell-wise to their targets. This motion behaviour causes artefacts in comparison to pure euclidean movement (Köster et al., 2011).

Microscopic models simulate pedestrians, similar to cellular automatons, as discrete singular objects. However, the simulation scenario is in continuous space. For this reason, the spatial resolution is only limited by computational accuracy. Many microscopic models, like the social force (Helbing et al., 2002) or the centrifugal model (Yu et al., 2005), are based on physical principles. In these concepts, each object in the scenario has its own potential. The superposition of all forces controls the equations of the motion of crowds. Another microscopic approach is the use of utility maximisation (Hoogendoorn and Bovy, 2004). It is based on the assumption that each pedestrian locally optimises his or her walking behaviour by choosing the route with the least effort. Since an improvement in spatial resolution increases the computational effort, scenarios with large crowds can not be simulated by very detailed models in reasonable time. Usually, good simulation accuracy can be achieved even though only a small part of the total scenario is simulated in detail, while the remaining parts are calculated roughly. Furthermore, some models are more suitable to reproduce special pedestrian dynamic phenomena than others (Duives et al., 2013). In both cases, it is necessary to simulate different parts of the scenario with different pedestrian dynamic models. Since persons can exceed the borders between coupled models, transition rules have to be applied to ensure a coherent transition.

Various hybrid models exist, which carry out these tasks. Anh et al. combine a LWR-model with an agent based Leader-Follower approach to simulate evacuation behaviour on a road network. The straight parts of the streets are calculated by the macroscopic model and the cross-section, in which the pedestrians choose their next target, are simulated in the microscopic scale. Chooramun et al. (2012) designed a concept in which three scales are coupled into one hybrid model to investigate large area evacuations. The models are encapsulated in compartments (e.g., rooms) and connected by small local transition regions (e.g., doors). A coupling of two scales is presented by Xiong et al. (2010). They simulated multiple partitions of a corridor with a microscopic and a macroscopic models. Transition cells are defined on the shared borders of unequal model types.

Current hybrid models have two common weaknesses. The transition of pedestrians between coupled models is limited on elected regions of the boundary (e.g., doors, cross-sections). Therefore, a transition is not possible on the whole border of a model. This approach is sufficient for restricted scenarios (e.g., road networks, buildings) in which the transition can simply happen on local nodes (e.g., cross-sections, doors), but it is inadequate for settings on open areas (e.g., public events). In these scenarios, persons can enter a region from any direction. Therefore, the whole border of a coupled model has to be able to transmit pedestrians to adjacent models. Another weak point of state-of-the-art hybrid modelling is the inflexibility of exchanging the combined models. There is no broad framework which supplies a method to connect arbitrary pedestrian dynamic models. Therefore, we develop TransiTUM, a generic transition framework based on transition zones. In the following we propose a first approach to solve the mentioned problems (see Figure 1a) for the coupling of a cellular automaton and a microscopic model.

2. Composition of the transition framework

The proposed transition framework couples a more detailed model with a more coarse model. The scenario is separated by these models into two independent parts. Each model has knowledge solely about components of the setting which are inside its own layer. The transition framework itself knows about all layers of the scenario. If pedestrians approach the border of their current scale they get transmitted by TransiTUM to the adjacent scale. Therefore, a shared set of parameter has to be assigned to the pedestrians. The minimum set contains the current velocity \( \vec{v}_i \), the next target \( \vec{z}_i \), the diameter \( d_{ped,i} \) and the current position \( \vec{d}_i \) for each pedestrian \( P_i \). The index \( i \) flags pedestrians in the microscopic model, while the index \( j \) flags pedestrians of the mesoscopic model. Additionally, a global peak speed \( v_{max} \) and the duration of time steps for each scale (\( \Delta t_{ds}, \Delta t_{cs} \), respectively) is necessary. These parameters are sufficient for successful transformations. The coupled models export parameters after each simulation time step. TransiTUM reads and modifies this data to enforce the transition of pedestrians. Before the next simulation step, the models import
the modified parameters and execute the simulation based on that information. The transformation of persons from one scale to another is based on the position of the pedestrians $\vec{o}_i$. If a pedestrian entity is put into another model, it is deleted from its current scale and added in the new scale at the nearest possible position (see Section 3). If a pedestrian is placed in one cell of the mesoscopic grid, no further pedestrians can access this cell, since a cell has a maximum capacity of one person. The composition of the transit system is shown in Figure 1b. The microscopic and mesoscopic models plus the $\alpha$-transit area specify the scenario. The mesoscopic model simulates on the $\alpha_{\text{meso}}$-, $\alpha_{\text{out}}$- and $\alpha_{\text{trans}}$-areas, while the microscopic model simulates the $\alpha_{\text{micro}}$, $\alpha_{\text{in}}$- and $\alpha_{\text{trans}}$-areas. So the $\alpha_{\text{trans}}$-area of the scenario is calculated by both coupled models. In this area, the transformation between the different models takes place. Only pedestrians inside $\alpha_{\text{trans}}$ can be transmitted to another scale. Since no pedestrian should reach the borders of his current model during one mesoscopic time step $\Delta t_{cs}$, the width $r_{\text{trans}}$ of the $\alpha_{\text{trans}}$-area has to be large enough:

$$r_{\text{trans}} = v_{\text{max}} \cdot \Delta t_{cs}$$

(1)

This distance is sufficient, since a transition is executed after each time step $\Delta t_{cs}$ and since no pedestrian can be faster than $v_{\text{max}}$. We define the areas $\alpha_{\text{in}}$ and $\alpha_{\text{out}}$ as relaxation zones. If pedestrians are converted to another scale, they mostly have to be shifted to a slightly different position in the scenario. The artefacts caused by the conversion event can decay in the relaxation zones. Therefore, simulation results taken from $\alpha_{\text{in}}$ respectively $\alpha_{\text{out}}$ have to be considered carefully. Due to the relaxation zones, the outcome of $\alpha_{\text{meso}}$ and $\alpha_{\text{micro}}$ should be free of any transition artefacts.

Another problem arises, if the next destination of a person is located outside of his current layer. Then the vector $\vec{z}_i$ has to be truncated to the borders of the actual scale (see Figure 2a) until this person gets transformed.

Different pedestrian dynamic models can have different duration of time steps. Therefore, a generic framework has to support the coupling of models with unequal time steps. Since a finer spatial resolution requires a smaller time resolution, it is assumed that $\Delta t_{ds} \leq \Delta t_{cs}$. For each coarse time step, $\frac{\Delta t_{ds}}{\Delta t_{cs}} \geq 1$ detailed time steps are necessary to reach the same amount of simulation time. This proportion is usually not a natural number, so the detailed steps do not match exactly the duration of the coarse time step. The surplus fractions $\Delta t_{\text{frac}} < \Delta t_{ds}$ get add up in the following $k$ simulation steps till $\sum_k \Delta t_{\text{frac}} \geq \Delta t_{ds}$. At that time, an additional time step $\Delta t_{ds}$ is executed. The necessary number $d_n$ of detailed time steps $\Delta t_{ds}$ to match the $n$th time step $\Delta t_{cs}$ can be calculated by:

$$d_n = \left\lfloor \frac{\Delta t_{cs}}{\Delta t_{ds}} \right\rfloor - \left( n - 1 \right) \left\lfloor \frac{\Delta t_{cs}}{\Delta t_{ds}} \right\rfloor$$

(2)

After the execution of the $n$th mesoscopic time step $\Delta t_{cs}$, an amount of $d_n + 1$ microscopic time steps $\Delta t_{ds}$ are executed (see Figure 2b). Subsequently, the interpolation and transition phase is carried out (see Figure 2c). The interpolation of pedestrian positions is necessary to bring the mesoscopic and microscopic time steps in line for the transformation. We have information about the microscopic positions at the time steps $d_n$ and $d_n + 1$, but the positions at the simulation time step $n$ are required. So we need to interpolate the microscopic positions from $\vec{d}_n$ to $\vec{d}_n^*$:

$$\vec{d}_n^* = \vec{d}_n + \vec{v}_n \cdot \Delta t_{ds}$$

(3)
Parameter $\Delta t_a$ is the time interval from the $d_n$th microscopic to the $n$th mesoscopic step. The velocity $\vec{v}_a$ can be calculated by the weighted average value of the velocities $\vec{v}_{d_n}$ and $\vec{v}_{d_n+1}$:

$$\vec{v}_a = \vec{v}_{d_n} \left(1 - \frac{\Delta t_a}{\Delta t_{ds}}\right) + \vec{v}_{d_{n+1}} \frac{\Delta t_a}{\Delta t_{ds}}$$

(4)

The procedure for the estimation from the $n$th mesoscopic to the $d_n$th microscopic step is similar. However, given the fact that the $(n+1)$th mesoscopic time step is not calculated yet (see Figure 2b), an extrapolation from the $n$th mesoscopic step has to be executed to find $\vec{d}_j$:

$$\vec{d}_j = \vec{d}_j + \vec{v}_n (\Delta t_{ds} - \Delta t_a)$$

(5)

After the positions were inter- and extrapolated, the transformation of the pedestrians can be carried out.

3. Transition of the pedestrians

The propagated movement vector $\vec{d}_i$ is calculated for all microscopic pedestrians $P_i$ in the area of $\alpha_{trans}$.

$$\vec{d}_i = \frac{\vec{v}_i}{v_i} \cdot v_{max} \cdot \Delta t_{cs}$$

(6)

A pedestrian can be transformed if his vector $\vec{d}_i$ approaches the area of $\alpha_{out}$. So only persons, who approach the borders of the microscopic model, can be converted to the mesoscopic scale (see Figure 3a). A microscopic person $P_i$ can intersect multiple unoccupied cells. Next all pedestrians $P_i$ are considered, who intersect at least one ”singular-manned” cells. A cell $c_{m,n}$ is ”singular-manned” if exactly one person intersects this cell $c_{m,n}$. The pedestrians are placed in their ”singular-manned” cell with the lowest $d_{CoM}$ value:

$$d_{CoM} = \left| \vec{d}_i - \vec{S}_{c_{m,n}} \right|$$

(7)

Equation 7 calculates the distance between the center-of-mass of the pedestrian $P_i$ and of the cell $c_{m,n}$ (see Figure 3b). The remaining $P_i$ are staying on cells, which are manned by multiple persons. These cells get occupied by the pedestrian with the lowest $d_{CoM}$ value (see Figure 3c). Individuals, who are still not transformed, intersect solely with cells which are not accessible. So the nearest free cell $c_{m,n}^{\ast}$ inside of $\alpha_{trans}$ has to be found for these persons (see Figure 3d). Therefore, all cells with $d_{CoM} \leq r_{place}$ are examined to find the cell with the lowest $d_{CoM}$ value for each remaining $P_i$. If $d_{CoM} > r_{place}$ the mistake of translating the pedestrian to his nearest cell is larger than refusing the transition of $P_i$ for one time step. The assumption $r_{place} = v_{max} \cdot \Delta t_{cs}$ seems reasonable since a pedestrian can have a maximum speed of $v_{max}$ and the time between two transition phases is $\Delta t_{cs}$ long. After the cells $c_{m,n}^{\ast}$ are determined for all remaining $P_i$, the pedestrian with the lowest $d_{CoM}$ value is transmitted to his preferred cell $c_{m,n}^{\ast}$. If other pedestrians have the same $c_{m,n}^{\ast}$, they have to calculate a new nearest cell. If a person can not find an accessible cell, he does not get transformed during the current transition phase. The process is repeated until all $P_i$ are transmitted to the mesoscopic scale.
By the transition from mesoscopic to the microscopic scale, sufficiently large areas have to be found in the continuous space. Since a pedestrian is assumed as having a circular shape, the minimum needed space is \( \frac{1}{4} \pi d_{\text{ped},i}^2 \) with \( d_{\text{ped},i} \) as the pedestrian’s diameter. At first, the propagation vector \( \vec{\sigma}_j \) is calculated for each mesoscopic pedestrian \( P_j \) in \( \alpha_{\text{trans}} \):

\[
\vec{\sigma}_j = \frac{\vec{v}_j}{v_j} \cdot v_{\text{max}} \cdot \Delta t_{cs}
\]

(8)

If \( \vec{\sigma}_j \) intersects \( \alpha_{\text{in}} \), the person can be transformed to the microscopic scale. Based on the centre-of-mass of the pedestrian’s current cell \( S_{\text{cap}} \), 2D-collision detection tests (Lin, 1993) are executed to find accessible space to place \( P_i \) in the microscopic scale (see Figure 3e). Thereby, only pedestrians with \( d_{\text{CoM}} \leq r_{\text{place}} \) are considered. If multiple solutions are possible, the spot with the lowest \( d_{\text{CoM}} \) value is chosen (see Figure 3f). In the case, that no solution could be found, the pedestrian does not get transformed in the current transition phase.

4. Conclusion

In this paper, the first part of the transition framework TransiTUM was introduced. Doing so, the coupling of microscopic models with cellular automata was presented. TransiTUM overcomes two main issues of current hybrid modelling. Firstly, it is independent of the connected models and can be applied to any pair of microscopic and mesoscopic models. The coupled models export their current position at the end of each time step \( \Delta t_{cs} \) to an external data file. TransiTUM executes the transition by modifying this data file. At the beginning of each time step \( \Delta t_{cs} \), the coupled models import the new positions to start the next simulation steps. Therefore, the simulation is executed independently from the transition of pedestrians. Secondly, pedestrians can enter the transit area from any direction. Furthermore, a coupling of different time scales is possible, since TransiTUM matches unequal time steps by inter-
and extrapolation routines during the transition phase. If pedestrians get transmitted to another model, they are placed in the nearest possible position or into the closest cell to reduce conversion artefacts. Relaxation zones between the coupled models help to minimise left over disruptions. In further research, the coupling of mesoscopic models with the macroscopic scale will be developed. In addition, we plan to develop a zoom-approach which allows to dynamically switch the applied simulation model for a given region of interest.

Acknowledgements

This work is supported by the Federal Ministry for Education and Research (Bundesministerium für Bildung und Forschung, BMBF), project MultikOSi, under grant FKZ 13N12823.

References


