Hybrid Equation-based and Agent-based Modeling of Crowd Evacuation on Road Network

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The major methodologies of crowd simulation in dynamic environment are either based on micro and macro models. Each of the two types of model represent choices in the trade-off between level of details and efficiency. The domain of pedestrian flow simulation in road networks is no exception and theories rely either on equation based model (LWR) or agent based models. There is a growing interest for hybrid modeling that combines both models together. This paper addresses the problem of combining both micro and macro models of pedestrians to speedup identification of optimal evacuation plan. The goal is therefor to use efficient macro modeling in part of the road networks that do not require fine grained model and less efficient but more detailed micro modeling elsewhere. The key issue raised by such an approach is to demonstrate the consistency of the resulting hybrid model. Preliminary results presented in this article are a proof of concept of how important speed up may be obtained using hybrid model to simulate evacuation plan in road networks.
1 Introduction

Nowadays, panic situations (fire, bomb attack, tsunami, earthquake, etc) in urban areas threaten more and more human lives. Evacuation plan in panic situation is becoming an important application of simulation in many projects [10],[2]. Real environments for such simulation often include road networks. The movement of pedestrians in road networks is a complex system to study. Evacuation simulation can be used to predict the performance of evacuations and thus become an importance method for evacuation analysis. Evacuation in Geographic Information Systems (GIS) representing road networks in reality needs to carry out.

Optimizing evacuation plan in Nhatrang city is the issue that we desire to address in the long term. Nhatrang is a famous beach for tourism but it is near earthquake sources from Philippine that may cause tsunami disasters. The problem studied in this paper is building the model of the evacuation in road networks with the assumptions of $J$ junctions, $B$ different safe places that pedestrians ought to reach, one direction to escape from endangered places.

Macro model of the evacuation problem is often described using fluid dynamic model. Environment of this model is often considered as homogeneous and the the fluid system dynamics is represented by density of evacuees. The road networks of macro environment is considered a finite directed graph. The macro model can calculate the parameters of the model is fast and simple. Nevertheless, to find a solution for the macro model usually requires many assumptions that do not match at all human behaviors. On the contrary, agent bases models consider each pedestrian supporting very realistic models. Each agent has a specific set of behaviors, actions and relationship with other agents. This model shows us the interaction of the agent with other agents and the internal changes of the agent. In addition, heterogeneous environment GIS is considered in this model. The evacuation issue can also be looked at as macro point of view if we estimate the parameter of all agents. The weak point of such models is its data and huge computation time. The problem using simulations to optimize rescue plan becomes intractable. The focus of the paper is therefore to explore hybrid modeling to benefit from the efficiency of macro model and the advantage of agent based model.

2 The approaches applied in pedestrian flow

When we consider the environment being very large, all areas of the environment are not equally important in the evacuation issue. There are importance areas that should be observed in detail under the micro model but the others areas could be reviewed under the macro model.

Hybrid model integrate micro macro models of pedestrians to speed up identification of optimal evacuation plan.

The road networks that use in maco model is represented as a finite directed graph $G = (E, V)$ that edges and vertices are roads and junctions of the road
networks respectively where $E$ is the set of roads and $V$ is the set of junctions. At the junction $V_\alpha \in V$, let $\delta^-_\alpha$ (resp. $\delta^+_\alpha$) the set of indices of all the incoming roads to $V_\alpha$ (resp. outgoing roads from $V_\alpha$). The safe places are called destinations. The dangerous places that pedestrians want to escape are sources. Every edge $(u,v) \in E$ has a non-negative, real-valued capacity $c(u,v)$. If $(u,v) \notin E$, we assume that $c(u,v) = 0$. We distinguish two special set of vertices: set of a sources $S = \{S_1, S_2, \ldots, S_n\}$ and a set of destinations $D = \{D_1, D_2, \ldots, D_m\}$.

2.1 Macro model

This subsection deals with a macro model of pedestrian flow on a road network. The pedestrians are homogeneous with the spatial and the time is continuous. More precisely, we consider the conservation law formulation proposed by Lighthill, Whitham and Richards (LWR) [8] represented the fluid dynamic by partial difference equations. This nonlinear framework is based simply on the conservation of density pedestrians in one road and is described by the equation:

$$\frac{\partial p}{\partial t} + \frac{\partial}{\partial x} f(p) = 0,$$

where

$$f(p) = pv(p), \quad v(p) = v_{max} \left(1 - \frac{p}{p_{max}}\right).$$

and $(t,x) \in \mathbb{R} \times \mathbb{R}_+$ are time variable and spatial variable. $p = p(x,t) \in [0, p_{max}]$ is density of pedestrians, $v = v(t,x)$ is the average velocity pedestrians and $f(p) = pv(p)$ is the pedestrian flow. if there is an initial value, the equation (1) is called Riemann. The initial values is chosen as following

$$p(x,0) = \begin{cases} p_l \text{ if } x \leq 0, \\ p_r \text{ if } x > 0. \end{cases}$$
where \( p_l, p_r \) are two parameters being constant values.

Because the function \( f(p) \) is concave, the weak solution of the Riemann problem that published in [5], [8] is.

(i) if \( p_l < p_r \) the solution including a shock wave is given by

\[
p(x,t) = \begin{cases} 
  p_l & \text{if } x \leq v_{\text{max}} \left(1 - \frac{p_r + p_l}{p_{\text{max}}} \right) t, \\
  p_r & \text{if } x > v_{\text{max}} \left(1 - \frac{p_r + p_l}{p_{\text{max}}} \right) t. 
\end{cases}
\]  

(ii) if \( p_l < p_r \) the solution of the equation is

\[
p(x,t) = \begin{cases} 
  p_l & \text{if } x \leq v_{\text{max}} \left(1 - \frac{2p_l}{p_{\text{max}}} \right) t, \\
  p_{\text{max}} v_{\text{max}} & \text{if } v_{\text{max}} \left(1 - \frac{2p_l}{p_{\text{max}}} \right) t \leq x \leq v_{\text{max}} \left(1 - \frac{2p_r}{p_{\text{max}}} \right) t, \\
  p_r & \text{if } x > v_{\text{max}} \left(1 - \frac{2p_r}{p_{\text{max}}} \right) t. 
\end{cases}
\]  

(iii) if \( p_l = p_r \) the solution is constant and given by: \( p(x,t) = p_l \).

We investigate with a network of roads, as in [8]. This means that we have a finite number of roads (with one of the two endpoints possibly infinite) that meet at some junctions. Each road \( i \) is modeled by an interval \( I_i = [a_i, b_i] \), possibly with either \( a_i = -\infty, b_i = +\infty \).

In the case of the LWR model the conserved quantity is the variable \( p_i = p_i(x,t) : I_i \times \mathbb{R}_+ \rightarrow \mathbb{R} \), so that on each edge \( i \) of the network, the pedestrian is governed by the following scalar conservation law:

\[
\frac{\partial p_i}{\partial t} + \frac{\partial}{\partial x} f(p_i) = 0, \forall i \in I 
\]  

where

\[ f(p_i) = pv(p_i), v(p_i) = v_{i,\text{max}} \left(1 - \frac{p_i}{p_{i,\text{max}}} \right), \forall i \in V. \]  

In addition, the initial values of road \( i \) are two constant values, i.e

\[
p_i(x,0) = \begin{cases} 
  p_{i,l} & \text{if } x \leq 0, \\
  p_{i,r} & \text{if } x > 0. 
\end{cases}
\]  

The solution in each road has the same formulas with the case of one road that we has just represented above. This model is appropriate to reveal shock formation as it is natural for conservation laws, whose solutions may develop discontinuities in finite time even for smooth initial data. However, the behaviors of pedestrians are distinguish but they can not represent in the LWR model. The importance behaviors in evacuation are investigated by agent based model. In addition, at an junction of road networks dynamic of flow changes complex so micro model will be used and be investigated in the next subsection.
2.2 Micro model

In micro model, we use agent based model for the issue. We choose method to build the model by the Overview Design concepts Detail (ODD) protocol. The ODD protocol is famous and use widely in represent agent-based model that we can read detail in [3].

Overview

• Purpose

This model represents the issue in detail that pedestrians are agents and we find the emergence when pedestrians moving in the road networks environment to the safe places. Moreover, pedestrians behaviors decides time spending in evacuation.

• Entities, state variables and scales

In our model, we introduce two kinds of entities. First, the pedestrians are entities. The pedestrian who knows to help other pedestrians and was trained evacuation in the past or knows all information about environment to get the safe place effectively is called fox agent. The pedestrian evacuating randomly or following one fox agent is called sheep agent. Second, each road in the road networks is component of GIS environment as entity. The heterogeneity GIS environment plays an important role in decision-making of agents. We choose GIS 2D plane to present the environment in this model.

The pedestrians has state variables that are the positions (in road or safe place, perception in moving of the pedestrians). The agent pedestrian is an agent with his own behavior, his own purpose and his own environment knowledge. The knowledge environment of the agent depend on the spatial that the agent can see. The decisions of the agent are generated based on its perception environment and the information shared by the other agents. Before the agent moves, he needs to know the other agents surround, road infrastructure. The constraints in the dynamic traffic, the agent interact other agents. The agent collects all information that he observes his neighbors about the positions, velocities. During agent moves, he adapts his speed to reach his desired speed. Indeed, if his speed is less than the desired speed, and if there is enough space, he may decide accelerate.

Spatial scale in this model is meter and the unit time is minute. We consider the time that all the pedestrians move to the safe places and the specific area.

• Process overview and scheduling

First, agent pedestrian moves one direction to escape the dangerous place. In this model, we assume that from the left hand side to the right hand side.

If he is sheep agent, at junction he choose randomly road. If he is fox agent, he moves to the shortest path. During he moves, he helps the others neighbors.
In the panic situation, the pedestrians want to escape the dangerous place as quickly as possible. If they have not any information to evacuate, they often move randomly or follow the crowd pedestrians. Because of complexity of the road networks, sheep agent is difficult in finding the safe place or reaches the safe place is too late.

The finding roads of the agents follow diagram (Fig. 2)

![Flowchart of sheep and fox agent](image)

**Figure 2**: Process of sheep agent and fox agent in moving

**Design concepts**

- **Basic principles**

  The agents follow one direction moves on the road to safe place. Fox agent chooses the shortest path and sheep agent moves randomly path or follows one fox agent.

- **Emergence**

  The result shows that more the number of foxes in population lesser time spending of the population.

- **Adaptation**

  Fox agent choose the effective information that helps him goes to the safe place as quick as possible. We consider an agent $i$ arbitrary. His velocity depends on the neighbors forward his position and the capacity of the road. If a number of neighbors are greater than a critical then he can not move forward so the
velocity is equal 0. if the neighbors are crowd then it moves slowly, contrary if
the neighbors are few then he moves fast follow himself velocity. His velocity is
represented:

\[ v(i) = v_{\text{average}} \left( 1 - \frac{\text{neighbors}(i)}{\text{critical}} \right) \]  

(9)

where critical depends on the capacity of the road and the local density of the
agent \( i \). Each agent will have an argument about the position, velocity, different
goals, the circle observation, his decision choose direction when he stands at the
junctions.

- Objectives
  Fox agent’s objectives are finding the shortest path from current position to one
  of safe places and helping the sheep agents. The objectives of sheep agent are
  finding an fox agent and exploring a safe place when he can not find any fox
  agent.

- Prediction
  Fox agent can predict the block of the traffic when he senses the crowd. The
  prediction of the fox agent helps himself and the followers evacuate more effec-
tively.

- Sensing
  A fox agent has two level in sensing environment. The high level of sensing that
  fox agent finds the sequence of roads that is shortest path form his position to
  one of destinations. The low level of sensing is local environment that help him
  to avoid the obstacles, the crowd and moves on the road.
  A sheep agents has only low level in sensing and try to find an fox agent.

- Interaction
  The sheep agent tries to find a fox agent and he always follows him. The fox
  agent considers information form the panels that help he get information from
  environment and temporary situation.

- Collectives
  The sheep agents follow on fox is called group. The fox agent of each group is
  the leader that help all members of the group to escape dangerous to the safe
  place.

Detail

- Initialization
  The initial data are the number of agents evacuating, the number of safe places,
  the road networks is represented GIS environment.

- Input data
  Data are the densities and velocities of sources. The proportion of fox agent in
  the pedestrians.
3 Hybrid evacuation flow model on road networks

3.1 Environment of the hybrid models

The environment in hybrid is Gis road networks. Each road in the simulation is huge so we separate by three small patches. The role of each part of each road in the simulation is not equal. There are some areas are very importance in evacuation but some areas can be ignored. Unimportance areas are represented macro model and the importance areas are represented micro model. Simplify the representation model in this paper, each road is divided in three patches. The patch 1 and 3 are micro model, the patch 2 is macro model.

![Figure 3: a, The Gis environment in the micro model; b, the abstract environment representing direct graph in macro model; c, hybrid environment in hybrid model.](image)

- Micro patch 1

  Pedestrians are simulated by agent based model that each agent is fox or sheep. The simulation in this patch is represented in the micro model. The environment is represented by GIS.

- Macro patch 2

  This patch is stretch of the road, hybrid simulation of this patch has two triggers that aggregation trigger changes pedestrians from micro patch to density of pedestrians in macro patch and disaggregation trigger does vice versa. The length $L_i$ and capacity $c_i$ of the road $i$ are parameter of patch 2. The patch 2 is two special positon, the position changing from patch 1 to patch 2 is called source and the end position changing from patch 2 to patch 3 is called destination.

- Micro patch 3

  This patch is simulated the same patch 1.

  The environment is represented in direct graph in marco model, GIS road networks in micro model and combined graph and GIS in hybrid model. The figure a) shows the micro environment, the figure b) represents the macro environment and the hybrid environment is showed in the figure c) that width roads dedicate for the micro environment and others represent macro environment.
3.2 Interfacing the two models

Transition from micro to macro models

Micro pedestrians moving towards the macro patch. The micro pedestrians transfer to the parameter in macro. Each road has three patches. We choose one arbitrary road \( i \) and consider detail:

- The number of pedestrians at source the from the time \( t \) to \( t + 1 \). The aggregation trigger changes number of pedestrians of micro model to the flow of pedestrian as the parameters \( p_i(t, \text{source}) \) of macro that is investigated in patch 2.

- The average velocity of the number pedestrians at source gives the velocity of flow pedestrian in the macro patch 2 \( v_i(t, \text{source}) \).

Transition from macro to micro models

![Figure 4: The macro transform to micro.](image)

The figure (Fig. 4) illustrates the transition from the macro patch that is called tube to the micro patch.

The length of the macro patch of road \( i \) is denoted \( L_i \).

- The macro values \( p_i(t), v_i(t) \) of source is used for the the initial of macro model. The average time flow of pedestrian to pass the tube of the road \( i \) is

\[
T(t) = \frac{L_i}{v_i(t, \text{source})}.
\]

Applied formula solution of the macro model, at the time \( t + T(t) \) we have results about density and velocity of pedestrians flow at the destination \( p_i(t + T(t), \text{destination}), v_i(t + T(t), \text{destination}) \). The flow of pedestrian at \( t + T(t) \) is

\[
q_i(t + T(t), \text{destination}) = p_i(t + T(t), \text{destination}).v_i(t + T(t), \text{destination}).
\]

These results are the parameters of micro model for the patch 3. Firstly, we assume the flow of pedestrians is Poisson process that was used in [9], [7]. Using the Poisson distribution with parameter \( \lambda = \text{mean} = \).
\(q_i(t+T(t),destination)\) at destination generates the number of pedestrian agents.

- Velocity of each pedestrian is generated by the normal truncated distribution with the \(\mu = \text{mean} = v_i(t+T(t),destination)\), at destination.
- The time for one agent order \(k\) at the time \(t\) comes into the tube is released out of the tube to the patch 3:

\[
t + T(t) + g[k, q_i(t+T(t),destination)].
\]

(11)

where \(g[k, q_i(t+T(t),destination)]\) is value of Gamma distribution

This formula is based on the theory of Poisson process that we can read in [12][13]. The arrival time of agent order \(k\) follows Gamma distribution with parameter \(q_i(t+T(t),destination)\).

4 Implementing the model

4.1 Simulation of the micro model

Nhatrang data are used to simulate the evacuation of the pedestrians. The Nhatrang data are GIS including the road networks, buildings, beach, rivers, sea and safe places calling targets. These data are real data of Nhatrang city of Vietnam. Parameters of the model are the numbers of foxes, sheep, average and variance velocity of pedestrians. The simulation of the model is showed in the figures (Fig. 5)

Figure 5: The shape of the fox agent is circle, the shape of sheep agent is square. The fox agent chooses one of the safe place to reach and. Each safe place has one color that difference with the other safe places. A fox agent has one color respecting to his safe place. The follow result uses constant mean velocity 10 m/7.5 seconds and variance velocity 1 m/7.5 seconds (the unit of the time in simulation is 7.5 seconds). These three figures are described the simulation respecting to the time step a. \(T = 1\), b. \(T = 150\), c. \(T = 350\).

The simulation gives us the average time of an agent from his init position to the one of the targets. In addition, the importance result is the number of the agents who reached the targets showed in the (Fig. 6).
The results of simulation help us to analysis the relationship between the number of foxes, sheep agent with the agents reaching the targets and the time one agent needs spending. The figure a (Fig. 7) is the simulation result with difference the numbers of foxes and sheep. The figure b (Fig. 7) shows the function the numbers of agent that reach to the targets with the numbers of foxes and sheep variables by linear regression.

Figure 7: The follow result uses constant mean velocity 10 m/7.5 seconds and variance velocity 1 m/7.5 seconds. a. Figure a shows simulation result of the number of agents reaching the targets. b. Analysis result of the agents reaching the target by using the linear regression.

4.2 Simulation of the hybrid model

This section present a hybrid macro-micro evacuation of pedestrians in road networks. Each road is divided three patches, patch 1 and patch 3 are micro patch and the patch 2 is the macro patch. To simplify the program, we consider a road networks having 9 roads as figure (Fig. 8)

Hybrid model in road networks is represent GIS of road network in the figure (Fig. 8). Each road has three patches, the micro model is simulated in GIS and
Figure 8: Micro model of the road networks and Hybrid model of road networks are implementation. The number of people hibernating (not simulated in the ABM) are proportional to the speedup provided by the hybrid modeling. Indeed, only the fraction of the total pedestrians are effectively consuming simulation CPU.

The stretch as a tube like a edge of directed graph is considered macro model. Therefore, all junctions respectively the begin and the end of the roads are investigated detail in micro model.

5 Discussion and conclusion

The problem of speeding up very large ABM such as the ones used in crowd simulation is key to support the definition of Decision Support Systems. In this paper we have given an approach to Hybrid modeling for evacuation simulation. The key idea is to exploit advantages from both macro and micro modeling. The problem we have solved in this paper is the central question of having entities that are shared by both models. In other words, the two models of interactions are defined so as to exchange agents at their boundary. A case study of the hybrid modeling shows that it not only offers more efficient execution than micro, but also improves the simulation quality in comparison with macro model. The results presented are yet to be extended to very large simulations including hundred of thousands of pedestrians. Nevertheless, the preliminary results are a proof of concept in the sense that they demonstrate where the source of speed-up of such simulation may be found. Future work includes large scale simulation and exploring various emergent behavior resulting from various types of behaviors.

Bibliography

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