A Hybrid Framework for Crowd Simulation

# Introduction

Crowd movement is an common but complicated and interesting phenomenon in our daily lives. Crowd simulation, user for the study of crowd behavior, has been widely applied to movies, games, and architecture, as well as in sociology and psychology research. Crowd behavior, or pedestrian behavior, is related to the behavior of each individual in the crowd. Thus, an intuitive idea is to make each agent smart, allowing it to make its own decision. This kind of method is called an agent-based method. However, agent-based methods suffer from high-dimensional computation costs, which sharply increases as the number of agents increases, limiting the scope of scenarios to which they can be applied to smaller groups of individuals. Also, some agent-based algorithms have trouble in dense crowd simulations because the high density will lead to a limited solution space, requiring more time to converge. To solve the high density and large population crowd problem, some researchers posited the idea of a continuous method, which considers people as groups, and solves the simulation problem at a macro level. Continuous methods can work well with large dense crowds, but suffer from poorer performance in low-density regions as agents may collide and overlap due to violations of the assumption of density. In order to take advantage of both methods and simulate scenarios with both sparse and dense crowd distribution, \cite{Golas:2013} proposed a hybrid solution which combines and smoothly blends agent-based methods and continuous methods.

However, in the observation of our daily life, pedestrian behavior is more than a combination of individual behavior and dense crowd movement. First, there is also interaction between the dense crowd and individuals outside the crowd. A person can choose to join or avoid a crowd encountered on the way to his target. Second, personal traits are not only individual properties but also crowd properties. As a crowd is a set of individuals with different personal traits, according to convergence theory, the behavior of the crowd is not an independent property, but based on the behavior of each individual in it [TK87]. There is already some research about personal traits in crowd simulation. However, they only focus on individual personality. To address the two problems and integrate them with individual behavior and dense crowd movement, we proposed our hybrid framework. In our framework, we define three types of interaction: agent-agent interaction which represents individual behavior, intra-crowd interaction which represents continuous dense crowd movement, and agent-crowd interaction which represents the decision of individuals when countering crowds. Given these three definitions, we are able to apply an appropriate interaction strategy based on the situation of the dynamic crowd movement. In addition, we integrate personal trait properties into both individuals and crowds. Thus, all three types of interactions are driven by both physical properties like position, velocity and radius, as well as personal traits.

In terms of implementation, we propose a Graph-cut based method to simulate interactions between heterogeneous dense groups within a crowd. Here, the group is a set of agents sharing the same neighborhood, which is a natural concept in continuous crowd methods. The concept of heterogeneous dense groups means that not only does each agent have personal traits, but each group also has traits added to it by its agents. So, our heterogeneous dense crowd simulation is a multi-variable optimization problem, which may have more variables than simply density and velocity. Previous work on continuous crowds are based on the assumption of homogeneous crowds, in which all agents and groups share the same personal traits. Thus, these models, such as potential field \cite{Treuille:2006} or fluid based \cite{Narain:2009}, cannot fit heterogeneous dense crowd simulation situations. To address effective heterogeneous dense crowd simulation, we consider the collisions and cooperation between adjacent groups as a multi-label optimization problem, which is to assign a label for each element in the target set and find the best overall assignment to those labels based on constraints. With this formulation, we introduce the idea of adapting intra-crowd interaction into the multi-label optimization problem, such as Graph-Cut or Belief Propagation, which has been successfully used in stereo matching, image restoration and optical flow \cite{Pedro:2004, Marshall:2003, Qingxiong:2009}, and can be applied to solve the problem of dense crowd simulation. In our work, instead of doing full iteration to achieve min-cut, we only apply a few iterations to smooth the movement of neighbor groups and reduce conflicts between groups.

Our results show that we are able to simulate the behavior of heterogeneous crowds with various agent density distributions. In our experiments, while personal traits of agents changed, we can see significant changes in crowd behavior such as aggressive dense groups \S\ref{section 6.2} and different types of agent-crowd interaction \S\ref{section 6.3}. The key contributions of our work can be summarized as follows:

* We propose a hybrid framework which integrates three different types of crowd behavior and personal traits.
* We develope a graph-cut based method to simulate heterogeneous dense crowd movement.
* We introduce agent-crowd interaction as a new type of crowd behavior and propose a method to simulate it.

# Related Work

In this section, we give a brief overview of prior work on crowd simulation and multi-agent systems. There are two steps, navigation and collision avoidance, in most crowd simulation systems. Navigation, also called global-planning, is the process of finding a path from the current agent position to the goal that avoids collisions with static obstacles in the scene. There has been significant work on this topic \cite{Funge:1999,Bayanzit:2002,Lamarche:2004,Sud:2007,Sud:2008}, but we will not cover it here.

Collision avoidance is another popular area of work where a large amount of research has been done. One of the traditional ways to classify collision avoidance methods is based on the representation of crowds as either discrete or continuous. In discrete representation, also called agent-based representation, the collision avoidance decision is made by each individual agent with respect to other agents and obstacles. A number of different models like social forces \cite{Helbing:1995, Helbing:2005, Gayle:2009, Sud:2007}, sociological factors \cite{Musse:1997}, psychological factors \cite{Pelechano:2008} and synthetic-vision based steering \cite{Ondrej:2010} have been used to formulate the collision avoidance behavior of agents. There are also many methods based on the spatial and geometric relationships between agents \cite{VDBerg:2008, VDBerg:2009 ,Guy:2009, VDBerg:2011}. As geometrically-based methods have shown very good quality and became very popular in recent years, many other models were adapted into these methods for further quality improvement and more complicated agent behavior simulation. \cite{Guy:2010} proposed a least-effort energy model to minimize individual collision avoidance cost from an energy-optimization view. \cite{Guy:2011} introduced a personal traits model and the transformation between simulation parameters and personal-traits model based on a video user study. \cite{Kim:2012} incorporated a stress model into crowd simulation system to simulate crowd behavior during an event. \cite{Best:2014} proposed a density-filter based method to detect neighborhood density for each agent and applied a local planner to achieve better performance in various density scenarios.

For continuous representations, agents are influenced by their dense neighborhood and have less freedom to make independent collision-avoidance decisions. Continuum theory for pedestrians flow was first proposed by \cite{Hughes:2003} and extended by \cite{Treuille:2006}. The approach of \cite{Treuille:2006} combined global planning and local collision avoidance into a single pipeline and provided good performance for medium-sized crowds with a common goal. However, this approach is not suitable for tightly packed crowds and/or varying goals. The state-of-art work of continuous methods is \cite{Narain:2009}, which combined a Lagrangian representation of individuals with a coarser Eulerian crowd model to capture discrete motions of individual agents and macroscopic flow of crowds. The work of \cite{Narain:2009} can simulate large numbers of agents at interactive rates and has good performance on dense crowds.

To make good use of advantages of both methods, and to avoid the drawbacks, a hybridization of those two methods could be a good solution. \cite{Golas:2013} presented a long-range collision avoidance model which smoothly blends agent-based and continuous algorithms to simulate the movement of crowds with various densities.

Besides crowd locomotion, there is also significant research on the influence of properties like personality and stress on the crowd. \cite{Durupinar:2008} proposed a method to map parameters of the HiDAC model to each agent using the OCEAN personality model to personality traits. \cite{Salvit:2011} explored the Myers-Briggs Type Indicator (MBTI) to define agent personality and ran experiments on how agents interact with the environment based on the MBTI model. \cite{Farhangian:2011} modeled recruiters’ personalities and found these can have a significant effect on team formation in organizations with temporary projects. \cite{Prada:2009} presented a FFM personality model which generates diversity interaction in the behavior of social agents in teamwork.

Our approach focuses on more complicated pedestrian behavior in heterogeneous crowds in which both the density and personality vary from position to position, and agent to agent. To achieve this goal, we propose our hybrid framework to integrate three types of interactions between agents and crowds which are driven by both physical simulation parameters (e.g., preferred speed, radius and planning time horizon), personal traits of agents, and small agent groups in crowds {section 3}. In section 4, we introduce our continuous algorithm to address the heterogamous dense crowd simulation problem, defined as intra-crowd interaction in our framework. The details of agent-crowd interaction about agents’ choices of avoiding or joining a crowd in their way are described in section 5. We demonstrate the advantages and efficiency of our hybrid framework in section 6. Finally, we conclude with the contributions and limitations of our work, and discusse the future work in section 7.

# Hybrid Framework

In this section, we introduce the agent model, crowd model. and the overall pipeline of our hybrid framework. There are three types of entities in our framework: agent, group and crowd. An *agent* represents a single person in the system with simulation parameters and personal traits. A *group* is a set of people sharing the same neighborhood. The neighborhood is defined as a 2D grid in the scene. A *crowd* is a set of groups which are adjacent to other groups in the same crowd. If we consider the groups in the scene as vertices, and the adjacent relationship as edges, a crowd is a connected component of the scene. Both groups and crowds have average density, speed, and personal traits. A crowd also has a contour to support agent-crowd interaction.

## Agent Modeling

We follow the definition of personal trait proposed by \cite{Guy:2010}, in which they applied the Eysenck 3-factor model \cite{Eysenck:1985} to agents. Besides personal traits, each agent also has basic simulation attributes derived from RVO \cite{VDBerg:2009}, including, maximum neighbors’ distance, maximum number of neighbors, planning horizon, agent radius, and preferred speed. Based on linear regression in their user study, Guy et. al. provide a mapping matrix for transforming simulation parameters into personal traits. They also applied PCA to simplify the three factors into two, called PC1 and PC2, which are extroversion and carefulness. In our approach, we take simplified PC1 and PC2 traits as personal trait examples to simulate agent-agent interaction. We directly use the linear mapping matrix from \cite{Guy:2010} to transform basic simulation attributes to personal traits. After we get PC1 and PC2, we scale them to a new domain to simplify later computations.

## Crowd Modeling

Based on the method described in \cite{Narain:2009}. we define our crowd model with density, average velocity, and group personal traits to convert discrete agent information to continuous crowd information. Like \cite{Narain:2009}, we first use a Navigation Mesh as our global planning algorithm for each agent. Then the information of discrete agents is transferred to 2D grid-cells with the same size. Agents in a cell will be considered as a group. The density and velocity can be computed as,

where is the position of the agent, is the prefered velocity of the agent, is the mass of each agent which are unity.

While simulation parameters are converted into continuous representations, we can compute the group traits based on each agent’s personal traits at the same time.

In this paper, we use unified weight for all the agents in the group.

Once the cells are converted to a continuous representation, we can apply either continuous crowd or agent-based algorithms to them based on the density of each cell. For the th cell, if, it should be marked as a sparse cell and the agent-based algorithm described in \S\ref{section:5} is applied. Otherwise, it should be marked as a dense cell, and we refine the crowd information by minimizing the inter-group collision energy described in (\S\ref{section:4.1} and \S\ref{section:4.2}). Then, the density and velocity at the agent position can be interpolated from cell density and cell velocity using the bilinear interpolation mentioned in \cite{Treuille:2006}. We can get the final velocity of each agent by interpolating between the continuum velocity and the agent's preferred velocity , depending on the crowd density at its location:

## Overview of the pipeline

The computation pipeline of our hybrid framework can be summarized as follows:

1. Compute a preferred velocity for each agent using the Navigation Mesh
2. Divide our scene into uniform-sized 2D grid-cells from the top view
3. Compute the density , velocity and personal traits for each 2D cell
4. Mark grids as either dense or sparse based on the density of each cell (see \S\ ref{section:3.2})
5. Merge adjacent dense cells as crowds (see \S\ref{section:5.1})
6. Reduce inter-group collisions and refine group velocities using a graph-cut based method (see \S\ref{section:4}) for agents in high density cells
7. Update velocities of agents in dense regions by group velocities (see \S\ref{section:3.2}) and extract contours and average velocities for dense groups (see \S\ref{section:5.1}).
8. Add dense group contours to agent-based algorithm as moving obstacles and simulate agent-agent and agent-crowd interactions (see \S\ref{section:5.2}).

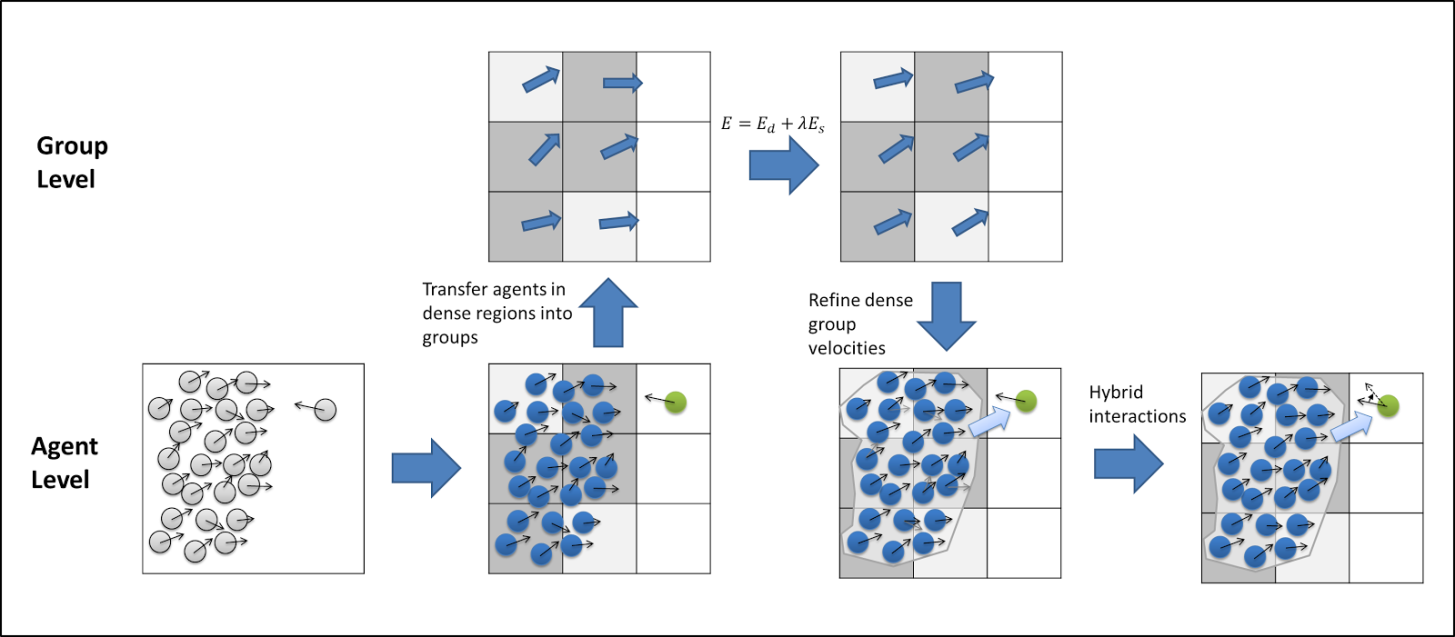


Figure 1

# Intra-Crowd Interaction

According to our observations of dense crowd behavior, collisions, merging, and negotiations constantly happen between groups in dense crowds. However, unlike local collision avoidance strategies for agents which can be considered as rigid bodies, groups are highly influenced by neighbor groups and have the tendency to share the same movement. We also find that groups have traits which are determined by the personal traits of the people inside them. However, previous work like \cite{Treuille:2006} and \cite{Narain:2009} are based on the assumption of homogeneous groups. Inspired by our observations and aiming to simulate interactions between groups with different traits, we propose a minimal energy model to describe and solve intra-crowd interaction for heterogeneous groups.

## Energy Modeling

We define intra-crowd interaction as a labeling problem by assigning to each cell a label . Each cell is a group of agents. As the influences from horizontal and vertical directions are independent (from different neighbor groups) in one simulation step, we call the energy minimization process twice to minimize collision energy of the horizontal and vertical directions separately. Thus, for each optimization pass, we could have *m* labels by dividing horizontal or vertical space into *m* pieces. Each of the labels represents the scale of velocity on the *x* or *y* axis. We assign at least 81 labels for each direction to approximate the discrete velocity we got from Graph-Cut to the optimal value. The energy function , composed of a data energy and a smoothness energy , is defined as:

The data energy is the sum of data cost of each cell with a label . In our energy model, the data cost is defined as the product of a scale value and the absolute distance between the horizontal or vertical projection of the average cell velocity and the value of the selected label . Data cost represents the effort of the group to change its velocity on *x* or *y* axis to certain label.

The scale value is computed by the group traits and . Although there are several potential functions to compute the scaled weight with different personal traits model ,  
in this paper, we choose a simple linear equation of two traits to give an estimated value of . A more precise formulation will be given in future work with measurement data. In our experiment, the and will be set as 0.3 and -0.3, respectively

The smoothness energy represents the velocity difference between neighboring cells. We use a standard 4-neighbor system for dense cells, so that the smoothness energy is the sum of spatially varying horizontal and vertical neighbor smoothness costs , where if and then . Letting denote the set of all such neighboring cell pairs, the smoothness energy is

In equation \ref{eq:6}, , also can be written as , is a non-decreasing function of the label difference, and can be directly computed as the absolute difference between two labels. Here, is the weight of the edge which is determined by the difference between group traits in two neighboring groups. In our model, is adjusted to restrict the maximum density of each group (see \S\ref{section:3.3}).

With the definition of the energy function , we can use Graph Cut or Belief Propagation algorithms to compute labels for each cell to achieve the minimal energy cost. In our implementation, we use the Graph Cut implementation from \cite{Boykov:2001, Boykov:2004, Kolmogorov:2004}. We make a slight change, in that we only run two iterations of the expansion move algorithm to decrease the discontinuity, instead of achieving a totally stable status.

## Constraints

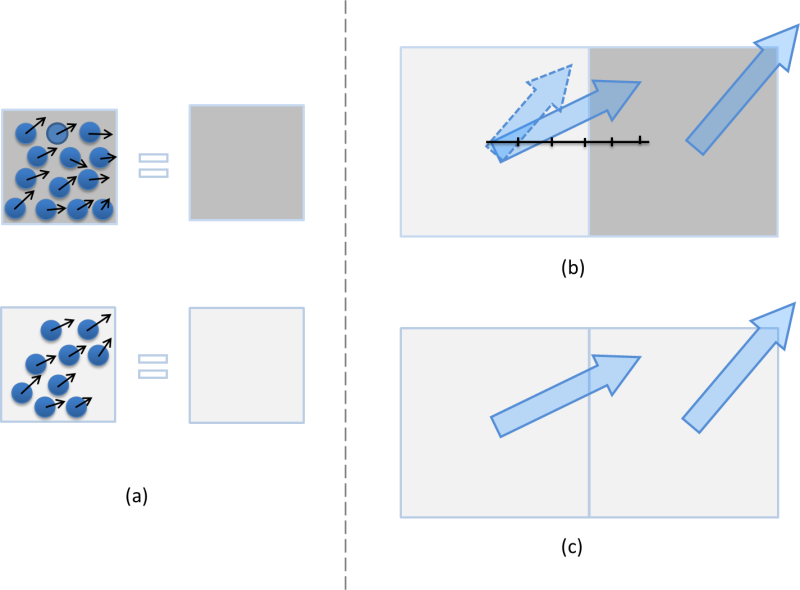
While trying to reach the minimal energy cost for inter-group collisions, we should also keep the density of each group below the maximum density because of the incompressibility of the human body. If the density of cell is below , agents can be pushed into the cell from neighboring cells. Otherwise the cell is incompressible. The smooth term should be,

where is a constant value as a penalty of labels which could lead to potential overcrowding (see in Figure \ref{figure:grid\_constraints}).

## Obstacles and Rearrangement

If there are obstacles in the scene, we use a similar strategy as \cite{Narain:2009}. For each cell, we compute the fraction of area that is inside the navigation mesh, and multiply the by the fraction as the new maximum density for this cell.

After each continuous crowd algorithm step, we rearrange overlapped agents to solve inter-agent collisions which often happen in continuous crowd algorithms. We divide the cell into several bands along the average velocity direction, and give agents a band ID. Then, we traverse each band to check if there are agents the collide with other agents in the next band. If they overlap, we move the agent in the next band slightly in another direction until they are no longer overlapped. We also push overlapped agents from the middle of each band to both sides in case two agents in the same band are overlapped. For each simulation frame, we do 10 iterations of rearrangement to achieve smooth movement for every rearranged agent.



# Agent-Crowd Interaction

After crowd behavior, we introduce individual behavior including agent-agent interaction and agent-crowd interaction. For agent-agent interaction, we simply apply the RVO algorithm to achieve good quality of collision avoidance behavior between agents. In this section, we mainly focus on agent-crowd interaction. Agent-crowd interaction simulation is based on the personal traits of individual agents in low density regions, and spatial information of both those agents and the crowds nearby. Thus, we first extract the contour of crowds as the boundary of a moving obstacle from an agent’s point of view. Then, the decision of whether avoid or join the crowd is determined by the personal traits of the agent. These algorithms are described in detail in sections 5.1 and 5.2.

## Dense Crowd Contour Extraction

After we convert discrete agent information into group representation and mark each group as dense or sparse, we merge adjacent groups into crowds. By considering the groups as vertices, and connections between groups as edges, we can construct a graph structure to represent the relationship between groups. Then we can simply apply a connected-component labeling algorithm to extract each crowd. During the process, we can also record neighbors of each cell, which will also be used to build links for smoothing terms.

Then we extract the contour of each crowd . As we only need rough contours to support agent-crowd interactions, we use the simple contour extraction algorithm described below,

* For each group do

1. Sort group in the crowd by its vertical center position in ascending order, positions of group centers on the top and bottom of the list are marked as and
2. For groups in the same vertical level, sort again by horizontal position in ascending order, and mark the position of group center on the top and bottom of the list as and
3. Connect points in such an order: , , , … , , , , , … , and to create a contour polygon . Here, *N* is the number of different vertical values of all the groups.

## Avoid or Join, Agent Behaviors

To simulate avoid or join behaviors, we convert the PC1 and PC2 traits to the minimum distance to crowds and maximum tolerable density, respectively. We began with some observations about individual pedestrian behavior when encountered with crowds on the path. Based on those observations, we came up with two empirical conclusions. With a higher PC1, which means more extroverted, an agent is more likely to walk directly into a crowd in its way on the way to the target. Thus, the minimum distance to crowds should be smaller. Otherwise, the agent would choose to avoid the crowds earlier. An agent with a higher PC2, which means he has a careful personality, will try to avoid walking into a very dense crowd to protect himself. So an agent with a higher PC2 will have a lower maximum tolerable density. The ranges of each parameter are shown in table \ref{table:1}

|  |  |  |  |
| --- | --- | --- | --- |
| Parameters | Min | Max | Equation |
| PC1 | -1 | 1 | - |
| PC2 | -1 | 1 | - |
| Min. Dist. | 0 |  |  |
| Max. Density | 0 |  |  |

Then, for a crowd with average density and velocity , and an agent with velocity , if , then we set the planning horizon for obstacles as , which is the time for the agent to avoid the crowd. Otherwise, The crowd will not be treated as an obstacle to this agent.

Based on our experience, crowds rarely change their speed and direction for several individuals while agents are not close enough to the crowds. When individuals get close enough, they will be absorbed into the crowd automatically due to the method we described in \S\ref{section:3.2}. Thus, behaviors like an agent walking through a crowd will be part of the continuous crowd algorithm instead of agent-crowd interaction.

# Results

## Performance

Our approach was implemented in C/C++. We provide our run-time performance on an Intel Core i7 at 2.9GHz with four cases in Table \ref{table:2}. We measured the per-frame performance of both the agent-based module and the continuous module, and the entire hybrid pipeline. From Table \ref{table:2}, we can see that the agent-based portion is the performance bottleneck when there are large numbers of agents in the scene. A pure continuous algorithm, in our case the Graph-Cut based method, shows much better performance when the number of agents increases to 10k. When the agent number is around 5k, our method could reach real-time performance for most cases. Although the performance is not very impressive, it was still close to other hybrid solutions (please refer to Table 1 in {Golas:2013}) while we provided more complicated agent and crowd behaviors.

|  |  |  |  |
| --- | --- | --- | --- |
| Scene | # Agent | Modules | Time(ms) |
| Crossing | 500 | Pure Agent-based (RVO)  Pure Continuous  Hybrid | 0.7~3.8  0.2~2.7  1.1~6.9 |
| 4 Crossing | 4,000 | Pure Agent-based (RVO)  Pure Continuous  Hybrid | 6.6~22.1  24.2~42.5  37.4~49 |
| 4 Crossing L | 10,000 | Pure Agent-based (RVO)  Pure Continuous  Hybrid | 60.7~373.4  36.6~61.5  107.3~379.5 |
| 4 Crossing XL | 25,000 | Pure Agent-based (RVO)  Pure Continuous  Hybrid | 243.7~436.1  25.7~170  143.7~480.3 |

Table 2. Performance of our methods in four scenes. We give both minimum time and maximum time here. There are significant differences between min and max time due to the rearrange O(nlogn) and contour extraction steps O(nlogn). As the agent could either apply discrete or continuous algorithms, the time cost is not very stable during frames. In all scenes, the map is divided into cells sized 20 units. One unit is close to the diameter of an agent.

## Heterogeneous dense crowd experiment

We compared different crowd behaviors in heterogeneous and homogeneous crowds. In our experiment, shown in Figure X, we defined two groups: the experiment group and the control group. In the experiment group, there were two groups of agents with different personal traits. Thus the group traits were different. Red agents were set to be more aggressive, meaning higher extroverted and lower carefulness values. Green agents were relatively more shy and assigned lower extroverted and higher carefulness personal traits. So the red group was relatively more aggressive than the green group. In the control group, all the agents in red and green share the same personal traits. In Figure X, the left side is the experiment group while the right side is the control group. From top to bottom, the first row is the original position of the two groups, which is the same for both experiment and control groups. The second row is a later frame. In the experiment group, some of agents from the red group “invade” into green group while few green agents venture into the red group. In the control group, both groups are exchanging agents along the middle line. The third row is even later, and in the experiment group, the red group is obviously in a dominant position. In the control group, there are no noticeable signs showing which group is more dominant.

|  |  |
| --- | --- |
| C:\Users\jason\Pictures\inner_group.PNG  (a) | |
| C:\Users\jason\Pictures\inner_group_1.PNG  (b) | C:\Users\jason\Pictures\inner_group_samepc_1.PNG  (c) |
| C:\Users\jason\Pictures\inner_group_2.PNG  (d) | C:\Users\jason\Pictures\inner_group_samepc_2.PNG  (e) |

Figure X. Heterogeneous Dense Crowd vs. Homogeneous Dense Crowd. (a) is the original position for both crowds. (b) and (d) are later frames of the heterogeneous dense crowd. (c) and (e) are later frames of the homogeneous dense crowd. In the hetereogeneous dense crowd, the red group is relatively more aggressive while all groups are the same in homogeneous dense crowd. The two groups are assigned intersecting paths, which means they must encounter and compete with each other during the simulation. Comparing the left column (heterogeneous) to the right column (homogeneous), we can see siginificant differences in that the aggressive group (red in the left column) shows its dominance in this compitition between the two groups.

## Agent-Crowd Interaction Experiment

In this experiment, we compared the different behaviors when agents with different personal traits encounter a dense crowd. There are three different choices in such situations according to the strategy introduced in Section 5.2. The first choice is to avoid the crowd from a distant place. Agents with lower extroversion and higher carefulness will have the first choice because higher carefulness leads to a behavior of avoiding dense crowds and not getting hurt, and lower extroversion leads to keeping a greater distance from dense crowds. The second choice is based on both high extroversion and carefulness, which leads to avoiding the crowd when the crowd is rather close. The third choice happens when carefulness is high, which means the agent is too careless to pay attention to the potential damage of being in a dense crowd. In this case, the agent will choose to join the crowd. The choice here is also related to the density, distance, and velocity of the crowd. In the experiment, shown in Figure X, the left group is individual agents (red) with lower extroversion and higher carefulness that encounter a dense crowd (green). From the position and trajectories of the agents, we can see that those agents have perfectly bypassed the dense crowd. In the middle group, agents have both high extroversion and carefulness. Thus, one of the agents (the second one from left) is not able to avoid the crowd, while others just turn a little to get avoid the crowd. In the right group, the careless agents just go through the crowd. From this experiment, we can see that different choices are made based on the personality of each agent and the environment (dense crowds).

|  |  |  |
| --- | --- | --- |
| C:\Users\jason\Pictures\agent_crowd_highpc1.PNG  (a) | C:\Users\jason\Pictures\agent_crowd_lowpc1.PNG  (b) | C:\Users\jason\Pictures\agent_crowd_lowpc2.PNG  (c) |

Figure X. Different Choices When Encountering A Crowd. (a) represents the behavior of individual agents with low extroversion and high carefulness. (b) represents the behavior of individual agents with both high extroversion and carefulness. (c) represents the behavior of individual agents with lower carefulness. Compare the three pictures from (a) to (c). In (a), all the agents successfully bypass the dense crowd. In (b) the three agents in the left are trying to avoid the dense crowd, however, the second left agent fails to do so as he is already too close to the crowd, and so becomes part of it. In (c), as agents are careless, they just walk through the crowd. Noticeable differences between each choice could be found by looking at the trajectory and orientation of each red agent, which reveals that the choices are affected by personalities.

# Conclusion and Future Work

In this paper, we present a hybrid framework for heterogeneous crowds with various densities. We define three types of interactions in crowd behaviors, agent-agent interaction, agent-crowd interaction and intra-crowd interaction. Our hybrid framework enables the simulation of more realistic crowd movement with combinations of the three interactions, especially the agent-crowd interaction, which is first introduced in crowd simulation. We formulate and develop our Graph-Cut based model to reduce collision energy between heterogeneous dense groups housing agents with different personal traits inside.

There are some limitations in our approach. First, because the formulation of the energy model is based on a Graph-Cut algorithm, we are using discrete values to represent a continuous interval. We are looking for interpolation methods to provide continuous values for the energy model. Secondly, our pipeline is not implemented in parallel, which limits our performance. A GPU-based implementation is needed, and is planned as future work. We are also looking for accurate pedestrian locomotion measurements to support and modify our agent and group model.

# Reference

@article{Hughes:2003,

author = {Roger L. Hughes},

title = {{THE FLOW OF HUMAN CROWDS}},

journal = {Annual Review of Fluid Mechanics},

volume = {35},

year = {2003},

pages = {169--182},

issue = {1},

doi = {10.1146/annurev.fluid.35.101101.161136},

masid = {3898873}

}

@article{Treuille:2006,

author = {Treuille, Adrien and Cooper, Seth and Popovi\'{c}, Zoran},

title = {Continuum Crowds},

journal = {ACM Trans. Graph.},

issue\_date = {July 2006},

volume = {25},

number = {3},

month = jul,

year = {2006},

issn = {0730-0301},

pages = {1160--1168},

numpages = {9},

url = {http://doi.acm.org/10.1145/1141911.1142008},

doi = {10.1145/1141911.1142008},

acmid = {1142008},

publisher = {ACM},

address = {New York, NY, USA},

keywords = {crowds, human simulation, motion planning}

}

@article{Narain:2009,

author = {Narain, Rahul and Golas, Abhinav and Curtis, Sean and Lin, Ming C.},

title = {Aggregate Dynamics for Dense Crowd Simulation},

journal = {ACM Trans. Graph.},

issue\_date = {December 2009},

volume = {28},

number = {5},

month = dec,

year = {2009},

issn = {0730-0301},

pages = {122:1--122:8},

articleno = {122},

numpages = {8},

url = {http://doi.acm.org/10.1145/1618452.1618468},

doi = {10.1145/1618452.1618468},

acmid = {1618468},

publisher = {ACM},

address = {New York, NY, USA},

keywords = {continuum, crowds, incompressibility, planning}

}

@inproceedings{Golas:2013,

author = {Golas, Abhinav and Narain, Rahul and Lin, Ming},

title = {Hybrid Long-range Collision Avoidance for Crowd Simulation},

booktitle = {Proceedings of the ACM SIGGRAPH Symposium on Interactive 3D Graphics and Games},

series = {I3D '13},

year = {2013},

isbn = {978-1-4503-1956-0},

location = {Orlando, Florida},

pages = {29--36},

numpages = {8},

url = {http://doi.acm.org/10.1145/2448196.2448200},

doi = {10.1145/2448196.2448200},

acmid = {2448200},

publisher = {ACM},

address = {New York, NY, USA},

keywords = {collision avoidance, crowd simulation, hybrid algorithms, lookahead}

}

@article{Boykov:2001,

author={Boykov, Y. and Veksler, O. and Zabih, R.},

journal={Pattern Analysis and Machine Intelligence, IEEE Transactions on},

title={Fast approximate energy minimization via graph cuts},

year={2001},

month={Nov},

volume={23},

number={11},

pages={1222-1239},

keywords={computational complexity;computer vision;image restoration;minimisation;simulated annealing;Markov Random fields;NP-hard;approximation algorithms;arbitrarily large sets;common constraint;computer vision;discontinuity preserving energies;discontinuity-preserving case;early vision;energy minimization;expansion algorithm;expansion moves;fast approximate energy minimization;general energy functions;global minimization;global minimum;graph algorithms;graph cuts;ground truth;image restoration;local minimum;maximum flow;minimum cut;object boundaries;sharp discontinuities;simulated annealing;smoothness constraints;standard algorithms;swap algorithm;swap moves;Approximation algorithms;Computer vision;Energy measurement;Image restoration;Labeling;Markov random fields;Minimization methods;Motion estimation;Simulated annealing;Stereo vision},

doi={10.1109/34.969114},

ISSN={0162-8828}

}

@article{Kolmogorov:2004,

author={Kolmogorov, V. and Zabih, R.},

journal={Pattern Analysis and Machine Intelligence, IEEE Transactions on},

title={What Energy Functions can be Minimized via Graph Cuts},

year={2004},

month={Feb},

volume={26},

number={2},

pages={147-159}

}

@article{Boykov:2004,

author = {Yuri Boykov and Vladimir Kolmogorov},

title = {{An Experimental Comparison of Min-Cut/Max-Flow Algorithms for Energy Minimization in Vision}},

journal = {IEEE Transactions on Pattern Analysis and Machine Intelligence},

volume = {26},

year = {2004},

pages = {1124--1137},

issue = {9},

doi = {10.1109/TPAMI.2004.60},

masid = {1231695}

}

@inproceedings{VDBerg:2008,

author = {van den Berg, J. and Ming Lin and Manocha, D.},

booktitle = {Robotics and Automation, 2008. ICRA 2008. IEEE International Conference on},

title = {Reciprocal Velocity Obstacles for real-time multi-agent navigation},

year = {2008},

month = {May},

pages = {1928-1935},

doi = {10.1109/ROBOT.2008.4543489},

ISSN = {1050-4729}

}

%% referenced in Related Work

%% navigation

@article{Bayanzit:2002,

author = {O. Burchan Bayazit and Jyh-Ming Lien and Nancy M. Amato},

title = {{Better Group Behaviors in Complex Environments using Global Roadmaps}},

journal = {Artificial Life},

year = {2002},

masid = {925884}

}

@inproceedings{Funge:1999,

author = {Funge, John and Tu, Xiaoyuan and Terzopoulos, Demetri},

title = {Cognitive Modeling: Knowledge, Reasoning and Planning for Intelligent Characters},

booktitle = {Proceedings of the 26th Annual Conference on Computer Graphics and Interactive Techniques},

series = {SIGGRAPH '99},

year = {1999},

isbn = {0-201-48560-5},

pages = {29--38},

numpages = {10},

url = {http://dx.doi.org/10.1145/311535.311538},

doi = {10.1145/311535.311538},

acmid = {311538},

publisher = {ACM Press/Addison-Wesley Publishing Co.},

address = {New York, NY, USA},

keywords = {action, behavioral animation, character animation, cognitive modeling, computer animation, intelligent characters, knowledge, planning, reasoning, sensing}

}

@article{Sud:2008,

author = {A. Sud and E. Andersen and S. Curtis and M. Lin and D. Manocha},

title = {{Real-Time Path Planning in Dynamic Virtual Environments Using Multi-Agent Navigation Graphs}},

journal = {IEEE Transactions on Visualization and Computer Graphics},

year = {2008},

masid = {14004603}

}

@inproceedings{Sud:2007,

author = {Sud, Avneesh and Gayle, Russell and Andersen, Erik and Guy, Stephen and Lin, Ming and Manocha, Dinesh},

title = {Real-time Navigation of Independent Agents Using Adaptive Roadmaps},

booktitle = {Proceedings of the 2007 ACM Symposium on Virtual Reality Software and Technology},

series = {VRST '07},

year = {2007},

isbn = {978-1-59593-863-3},

location = {Newport Beach, California},

pages = {99--106},

numpages = {8},

url = {http://doi.acm.org/10.1145/1315184.1315201},

doi = {10.1145/1315184.1315201},

acmid = {1315201},

publisher = {ACM},

address = {New York, NY, USA}

}

@article{Lamarche:2004,

author = {Fabrice Lamarche and StÃ©phane Donikian},

title = {{Crowd of Virtual Humans: a New Approach for Real Time Navigation in Complex and Structured Environments}},

journal = {Computer Graphics Forum},

volume = {23},

year = {2004},

pages = {509--518},

issue = {3},

doi = {10.1111/j.1467-8659.2004.00782.x},

masid = {1696750}

}

%% agent based collision avoidance

@article{Helbing:1995,

author = {Dirk Helbing and PÃ©ter MolnÃ¡r},

title = {{Social force model for pedestrian dynamics}},

journal = {Physical Review E},

volume = {51},

year = {1995},

pages = {4282--4286},

issue = {5},

doi = {10.1103/PhysRevE.51.4282},

masid = {1392727}

}

@article{Helbing:2005,

author = {Dirk Helbing and Lubos Buzna and Anders Johansson and Torsten Werner},

title = {{Self-Organized Pedestrian Crowd Dynamics: Experiments, Simulations, and Design Solutions}},

journal = {Transportation Science},

volume = {39},

year = {2005},

pages = {1--24},

issue = {1},

doi = {10.1287/trsc.1040.0108},

masid = {6094093}

}

@inproceedings{Gayle:2009,

author = {Russell Gayle and Ming C. Lin and Dinesh Manocha},

title = {{Multi-Robot Coordination using Generalized Social Potential Fields}},

booktitle = {International Conference on Robotics and Automation},

year = {2009},

pages = {106--113},

doi = {10.1109/ROBOT.2009.5152765},

masid = {6122420}

}

@article{Musse:1997,

author = {S. R. Musse and D. Thalmann and D. Terzopoulos},

title = {A Model of Human Crowd Behavior: Group InterRelationship and Collision Detection Analysis},

year = {1997},

journal = {Computer Animation and Simulation},

pages = {39--51},

masid = {15746}

}

@book{Pelechano:2008,

author = {Nuria Pelechano and Jan M. Allbeck and Norman I. Badler},

title = {{Virtual Crowds: Methods, Simulation, and Control}},

volume = {3},

year = {2008},

pages = {1--176},

issue = {1},

doi = {10.2200/S00123ED1V01Y200808CGR008},

masid = {13339609}

}

@inproceedings{Guy:2009,

author = {Stephen J. Guy and Jatin Chhugani and Nadathur Satish and Ming C. Lin and Dinesh Manocha},

title = {{ClearPath: Highly Parallel Collision Avoidance for Multi-Agent Simulation}},

booktitle = {Symposium on Computer Animation},

year = {2009},

pages = {177--187},

doi = {10.1145/1599470.1599494},

masid = {13666949}

}

@inproceedings{Guy:2010,

author = {Guy, Stephen J. and Chhugani, Jatin and Curtis, Sean and Dubey, Pradeep and Lin, Ming and Manocha, Dinesh},

title = {PLEdestrians: A Least-effort Approach to Crowd Simulation},

booktitle = {Proceedings of the 2010 ACM SIGGRAPH/Eurographics Symposium on Computer Animation},

series = {SCA '10},

year = {2010},

location = {Madrid, Spain},

pages = {119--128},

numpages = {10},

url = {http://dl.acm.org/citation.cfm?id=1921427.1921446},

acmid = {1921446},

publisher = {Eurographics Association},

address = {Aire-la-Ville, Switzerland, Switzerland}

}

@inproceedings{Guy:2011,

author = {Guy, Stephen J. and Kim, Sujeong and Lin, Ming C. and Manocha, Dinesh},

title = {Simulating Heterogeneous Crowd Behaviors Using Personality Trait Theory},

booktitle = {Proceedings of the 2011 ACM SIGGRAPH/Eurographics Symposium on Computer Animation},

series = {SCA '11},

year = {2011},

isbn = {978-1-4503-0923-3},

location = {Vancouver, British Columbia, Canada},

pages = {43--52},

numpages = {10},

url = {http://doi.acm.org/10.1145/2019406.2019413},

doi = {10.1145/2019406.2019413},

acmid = {2019413},

publisher = {ACM},

address = {New York, NY, USA}

}

@inproceedings{Kim:2012,

author = {Kim, Sujeong and Guy, Stephen J. and Manocha, Dinesh and Lin, Ming C.},

title = {Interactive Simulation of Dynamic Crowd Behaviors Using General Adaptation Syndrome Theory},

booktitle = {Proceedings of the ACM SIGGRAPH Symposium on Interactive 3D Graphics and Games},

series = {I3D '12},

year = {2012},

isbn = {978-1-4503-1194-6},

location = {Costa Mesa, California},

pages = {55--62},

numpages = {8},

url = {http://doi.acm.org/10.1145/2159616.2159626},

doi = {10.1145/2159616.2159626},

acmid = {2159626},

publisher = {ACM},

address = {New York, NY, USA},

keywords = {crowd simulation, dynamic behaviors, psychological models}

}

@book{VDBerg:2009,

author = {Jur P. van den Berg and Stephen J. Guy and Ming C. Lin and Dinesh Manocha},

title = {{Reciprocal N-body Collision Avoidance}},

booktitle = {International Symposium of Robotics Research},

year = {2009},

doi = {10.1007/978-3-642-19457-3\_1},

masid = {5180902}

}

@inproceedings{VDBerg:2011,

author = {Jur P. van den Berg and Jamie Snape and Stephen J. Guy and Dinesh Manocha},

title = {{Reciprocal collision avoidance with acceleration-velocity obstacles}},

booktitle = {International Conference on Robotics and Automation},

year = {2011},

pages = {3475--3482},

doi = {10.1109/ICRA.2011.5980408},

masid = {39363812}

}

@article{Ondrej:2010,

author = {Jan Ondrej and Julien PettrÃ© and Anne-HÃ©lÃ¨ne Olivier and StÃ©phane Donikian},

title = {{A synthetic-vision based steering approach for crowd simulation}},

journal = {ACM Transactions on Graphics},

volume = {29},

year = {2010},

issue = {4},

doi = {10.1145/1833351.1778860},

masid = {13334362}

}

%% personality and emotion factors

@inproceedings{Durupinar:2008,

author = {Durupinar, Funda and Allbeck, Jan and Pelechano, Nuria and Badler, Norman},

title = {Creating Crowd Variation with the OCEAN Personality Model},

booktitle = {Proceedings of the 7th International Joint Conference on Autonomous Agents and Multiagent Systems - Volume 3},

series = {AAMAS '08},

year = {2008},

isbn = {978-0-9817381-2-3},

location = {Estoril, Portugal},

pages = {1217--1220},

numpages = {4},

url = {http://dl.acm.org/citation.cfm?id=1402821.1402835},

acmid = {1402835},

publisher = {International Foundation for Autonomous Agents and Multiagent Systems},

address = {Richland, SC},

keywords = {OCEAN personality model, autonomous agents, crowd simulation},

}

@article{Farhangian:2011,

title={Modelling the Effects of Personality and Temperament in the Team Formation Process},

author={Farhangian, Mehdi and Purvis, Martin and Purvis, Maryam and Savarimuthu, Bastin Tony Roy},

year={2011}

}

@inproceedings{Prada:2009,

title={Personality in Social Group Dynamics},

author={Prada, Rui and Ma, Samuel and Nunes, Maria Augusta},

booktitle={Computational Science and Engineering, 2009. CSE'09. International Conference on},

volume={4},

pages={607--612},

year={2009},

organization={IEEE}

}

@incollection{Salvit:2011,

title={Toward a Myers-Briggs type indicator model of agent behavior in multiagent teams},

author={Salvit, Jordan and Sklar, Elizabeth},

booktitle={Multi-Agent-Based Simulation XI},

pages={28--43},

year={2011},

publisher={Springer}

}

@inproceedings{Best:2014,

title={DenseSense: Interactive Crowd Simulation using Density-Dependent Filters},

author={Best, Andrew and Narang, Sahil and Curtis, Sean and Manocha, Dinesh and Koltun, Vladlen and Sifakis, Eftychios},

booktitle={Eurographics/ACM SIGGRAPH Symposium on Computer Animation},

pages={97--102},

year={2014},

organization={The Eurographics Association}

}

@article{Turner:1957,

title={Collective behavior.},

author={Turner, Ralph H and Killian, Lewis M},

year={1957},

publisher={Prentice-Hall}

}

%% Graph Cut and BP

@inproceedings{Pedro:2004,

author = {Pedro F. Felzenszwalb and Daniel P. Huttenlocher},

title = {{Efficient Belief Propagation for Early Vision}},

booktitle = {Computer Vision and Pattern Recognition},

volume = {1},

year = {2004},

pages = {261--268},

doi = {10.1109/CVPR.2004.1315041},

masid = {1788499}

}

@inproceedings{Marshall:2003,

author = {Marshall F. Tappen and William T. Freeman},

title = {{Comparison of Graph Cuts with Belief Propagation for Stereo, using Identical MRF Parameters}},

booktitle = {International Conference on Computer Vision},

year = {2003},

pages = {900--907},

doi = {10.1109/ICCV.2003.1238444},

masid = {1796448}

}

@article{Qingxiong:2009,

author = {Qingxiong Yang and Liang Wang and Ruigang Yang and Henrik StewÃ©nius and David NistÃ©r},

title = {{Stereo Matching with Color-Weighted Correlation, Hierarchical Belief Propagation, and Occlusion Handling}},

journal = {IEEE Transactions on Pattern Analysis and Machine Intelligence},

volume = {31},

year = {2009},

pages = {492--504},

issue = {3},

doi = {10.1109/TPAMI.2008.99},

masid = {4596061}

}