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Technical Section

Continuum crowd simulation in complex environments

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ABSTRACT

This paper presents a novel approach for crowd simulation in complex environments. Our method is based on the continuum model proposed by Treuille et al. [13]. Compared to the original method, our solution is well-suited for complex environments. First, we present an environmental structure and a corresponding discretization scheme that helps us to organize and simulate crowds in large-scale scenarios. Second, additional discomfort zones around obstacles are auto-generated to keep a certain, psychologically plausible distance between pedestrians and obstacles, making it easier to obtain smoother trajectories when people move around these obstacles. Third, we propose a technique for density conversion; the density field is dynamically affected by each individual so that it can be adapted to different grid resolutions. The experiment results demonstrate that our hybrid solution can perform plausible crowd flow simulations in complex dynamic environments.

1. Introduction

Crowd simulation has become an important research field in computer graphics, virtual reality, the social sciences and civil engineering. Over the last few decades, numerous advances have made modeling virtual crowds feasible for various purposes and applications. In this paper, we address the problem of simulating plausible crowd movement for large-scale crowds in complex environments. The environments used in our project are very complex and usually have multi-floor structure, such as a large pedestrian overpass, a subway station and an office building. We are also interested in simulating more plausible behaviors for large crowds in these environments.

An ideal way to capture the nature of a crowd is through agent-based models, which drive the individual agents to create realistic group motion, but considerable efforts are still required to design the proper model for each individual. Recently, a novel approach inspired by fluid dynamics was presented by Hughes [11,12] and then extended by Treuille et al. [13]. The continuum model implemented by Treuille et al. only needs to calculate the potential function for a group once, and it then derives optimal paths for all group members simultaneously. The individuals in their system are able to exhibit smoother motion than had been previously reported. Therefore, we chose the continuum model as the basis of our simulation system.

Although the original model could exhibit smooth motion, there are still some problems that need to be solved when we simulate crowds in complex environments. Firstly, we need to solve how to represent and organize a large-scale, complex environment. The continuum crowd method has never been implemented in this kind of environment before, so we must consider a corresponding discretization scheme to adapt to the environmental representation. Secondly, pedestrians always keep a certain, psychologically plausible distance from obstacles, so we need to design a technique to reflect this characteristic within the continuum framework. Thirdly, a small cell size is usually used in complex environments to represent narrow passages or small obstacles exactly, but the density conversion technique in the original continuum method is insufficient to simulate crowds accurately in this situation.

In this paper, we focus on addressing the three specific and unavoidable problems mentioned above. The results demonstrate that our approach is capable of performing plausible crowd flow in complex dynamic environments and that it is a useful complement to the original continuum crowd model proposed by Treuille et al. [13].

The rest of the paper is organized as follows: Section 2 introduces related work on crowd simulation. We briefly describe the continuum crowd model in Section 3, and then we present our environmental structure, additional discomfort fields and density conversion technique in Sections 4–6. A test case and its experimental results are shown in Section 7. We draw some conclusions and suggest further discussions in Section 8.

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2. Related work

In this section, we briefly review some relevant methods for path planning and crowd simulation.

The cognitive model was introduced to obtain highly autonomous animated characters in dynamic virtual worlds [4,9]. It is the most accurate way to create ultra-realistic crowds, but the computation cost is huge.

Agent-based behavior methods can be traced back to the seminal work of Craig Reynolds in 1987 [1]. In his model, simple local rules could help to generate complex flock behaviors. Reynolds later expanded his work to include additional behaviors such as seeking, pursuit and evasion [2]. Brogan and Hodgins [6] proposed an animation algorithm for controlling the movements of creatures with significant dynamics. Sociological aspects were taken into account to simulate crowd behavior by Musse and Thalmann [28]. Additionally, psychological effects were considered for obtaining agents' actions by Pelechano et al. [26]. Musse and Thalmann [10] presented a hierarchical behavior model for real-time simulation of virtual human crowds. Many crowd simulation methods have been derived from the social force model presented by Helbing [7,8]. This model assumed a mixture of socio-psychological and physical forces that influence crowd behaviors in panic situations. Chenney [5] described a technique for representing and designing velocity fields using flow tiles. Shao and Terzopoulos [3] integrated cognitive components with a rule-based model to attain fully autonomous pedestrians in a large urban environment. Sung et al. [23] used a probabilistic method to steer characters to their goal. Pelechano et al. [21] applied a combination of psychological and geometrical rules to a social and physical force model to simulate large, dense crowds of autonomous agents. Hengchin Yeh et al. [19] introduced the concept of composite agents to model emergent behaviors among individual agents. Jin et al. [32] presented a hybrid method combining a user-specified vector field with an autonomous movement component for controlling individual behavior. Guy et al. [35] present a new local collision avoidance algorithm that can handle large heterogeneous crowds and is easy to parallelize. Many locally controlled crowd models needed tailored techniques to solve the problem of navigation.

Navigation is probably the most crucial behavior in computer crowd simulation [22]. Pettré et al. [17] proposed a novel approach that could extract topological information automatically and recognize walkable regions from the geometry model of an uneven and multilayered virtual environment; however, it is hard to gain full-scale knowledge of objects and regions only through a 3D geometric model. In two papers, Shao and Terzopoulos modeled the virtual environment as a hierarchical collection of maps, with each of these maps designed for different purpose; their combination can support accurate and efficient environmental information storage and retrieval [8,27]. Bayazit et al. [14] presented a graph-based roadmap containing topological information and adaptive edge weights for global planning. Sung et al. [15] employed a fast path planner based on probabilistic roadmaps for navigating characters through environments. Lamarche and Donikian [16] presented a hierarchical path planning algorithm based on topological pre-computations. A three-layer method for agent steering was introduced by Goldenstein et al. [20]. Kamphuis and Overmars [25] extended path planning to exhibit realistic coherence. Sud et al. [24] used Voronoi graphs to compute and update navigational graphs. Yersin et al. [30] presented a hybrid architecture in which different regions exploited different planning algorithms according to their level of interest. A two-level navigation algorithm combining a global roadmap with a local planning method based on RVOs was introduced by van den Berg [31].

Recently, a novel approach to simulate crowds was inspired by fluid dynamics. Hughes introduced a model that describes crowds as a continuous density field and presents a dynamic potential function to guide the density field optimally toward its goal [11,12]. Inspired by Hughes's work, Treuille et al. [13] proposed the continuum crowd model by transforming Hughes's continuous crowd field into a particle representation, and the method used in this paper to simulate crowds is based on this work. Compared to agent-based methods, the continuum approach allows simulating thousands of pedestrians in real-time and could demonstrate several observed phenomena, such as lane formation and vortex forms. It is also a global navigation method that unifies local collision avoidance and global planning in one simulation framework, thereby solving inherent conflicts naturally and exhibiting smoother individual motion that has been previously reported [13]. In Yersin's architecture [30], the continuum model was only employed in the regions of high interest instead of the whole scenario. Compared with their solution, we made some practical improvement on the original continuum model but they mainly focused on the efficiency of architecture. More recently, Narain et al. [33] presented a hybrid continuum-based method for capturing both the discrete motion of each agent and the macroscopic flow of the crowd and suggests a way to improve agent–agent interaction.

3. The original continuum crowd model

In the original Ref. [13], the continuum crowd model assumes that people choose paths so as to minimize a linear combination of the following three terms: the length of the path, the amount of time to the destination and the discomfort felt, per unit time, along the path. Therefore, if we let Π be the set of all paths from x to some point in the goal and assume that the speed field f, discomfort g, and goal G are fixed, a person at location x will pick the path $P \in \Pi$ minimizing:

$$\min_{P \in \prod} \left(\underbrace{\alpha \int_P 1 ds}_{\text{Path Length}} + \underbrace{\beta \int_P 1 dt}_{\text{Time}} + \underbrace{\gamma \int_P g dt}_{\text{Discomfort}} \right) \tag{1}$$

Here, α, β, and γ are weights for individual terms; ds and dt means that the integral is taken with respect to path length and time. These two variables are also related by $ds = f\,dt$, where f is the speed. Using this equality and letting $C = \alpha f + \beta + \gamma g / f$ be a unit cost field, we may rewrite Eq. (1) as

$$\min_{P \in \prod} \left(\int_P C ds \right) \tag{2}$$

The authors defined a potential function ϕ to find optimal paths given the path cost described in Eq. (2). In the goal $\phi = 0$ and everywhere else, ϕ satisfies the eikonal equation: $\|\nabla\phi(x)\| = C$.

The speed field f measures the maximum permissible speed of movement for every point and every direction in the domain. To obtain this field, the authors designed a density-dependent mechanism. Every person could influence the nearby speed field. Each person can be converted into an individual density field, denoted ρ_i for the ith person. The crowd density ρ is simply the sum of each individual density field:

$$\rho = \sum_i \rho_i \tag{3}$$

Then, three different equations are defined to describe how density affects speed in different density intervals.