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Real-time Collision Avoidance for Pedestrian and Bicyclist Simulation: a smooth and predictive approach

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Abstract

This article introduces a new collision avoidance model enabling the design of efficient realistic virtual pedestrian and cyclist behaviors. It is a force-based model using collision prediction with dynamic time-windows to predict future potential collisions with obstacles and other individuals. It introduces a new type of force called sliding force to allow a smooth avoidance of potential collisions while enabling the pedestrian to continue to progress towards its goal. Unlike most existing models, our forces are not scaled according to the distance to the obstacle but depending on the estimate of the collision time with this obstacle. This inherently integrates obstacles' velocity. This greatly reduces the computational complexity of the model while ensuring a smooth avoidance. This model is oscillation-free except for concave obstacles. It enables the reproduction of inherent emergent properties of real crowds such as spontaneous organizations of pedestrians into lane lines, etc. This model is computationally efficient and designed for real time simulation of large crowds.

Keywords: collision avoidance, pedestrian behavior, crowd simulation, cyclist behavior

1. Introduction

The modeling of the dynamics of pedestrians and bicycles is of great theoretical and practical interest. In the past two decades, research from a broad range of fields such as computer graphics, physics, robotics, social science, safety science and training systems has created simulations involving collections of individuals.

Two major kinds of crowds and bicycle simulations may usually be distinguished depending on whether they seek to achieve: a high-level of behavior realism (safety simulation, social sciences) or high-quality

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visualization (movie productions, computer games, virtual reality)[1]. Within the first category, simulation results are usually consistent with observations of real population and can therefore serve as a basis for theoretical studies for the evaluation and prediction of actual system behaviors. In the second area, behavior's models are not the priority and do not usually match quantitatively the real world. However, individuals are fully animated 3D characters and application users may have a high degree of interaction with the simulation. Recent research and applications tend to unify these two areas, especially in the domain of training systems where both aspects are necessary for an effective training.

Our approach is part of this effort, aiming at providing realistic virtual city environments populated with a large number of realistic simulated individuals [2, 3]. This article introduces a new collision avoidance model enabling the design of efficient — even realtime — realistic behaviors of pedestrians and bicyclists. Our approach extends the social-force model [4] with a new type of force: the sliding force. In the rest of this paper, we use the same behavior model for the pedestrians and for the bicyclists.

The paper is organised as follows. Section 2 presents some background on existing behavioral simulation models. Section 3 introduces our new force-based behavioral model. Then, Section 4 describes results of the experiments conducted in different typical environmental configurations to validate the proposed model and a short comparison of these results with previous models. Finally, Section 5 summarises the results of the paper and draws some conclusions on the proposed model.

2. Background

The importance of detailed design and pedestrian interaction is best demonstrated using the case studies that have been done by [4, 5]. The case studies used microscopic pedestrian simulation to determine the flow performance. The analytical model for microscopic pedestrian model has been developed by [6] and [7], but the numerical solution of the model is very difficult to obtain, and simulation is more practical and favorable. Reynolds [8] proposes to build pedestrian models from a collection of "steering behaviors". These steering behaviors are largely independent of the character's specific means of locomotion. Combinations of steering behaviors (pursue a target, obstacle avoidance, etc.) can be used to achieve higher-level goals. Teknomo [9] proposes a model based on the microscopic pedestrian traffic characteristics from both the simulation and the real-world data. One of the key points in the motion of pedestrians is to avoid collision with the other pedestrians and with the obstacles. The models inheriting from the force-based model of [8] are able to avoid collisions. Unfortunately, the trajectories of the pedestrians differ from the ones of real humans. This is due to the lack of collision prediction and anticipation of the other pedestrians' motions. Predictive and cooperative models for pedestrians are proposed to avoid collisions [10, 11, 12, 13]. Karamouzas [14] focuses on the agent-agent collision avoidance. However, like most force-based models, they inherit from [8] approach while trying to avoid these common pitfalls like oscillations and deadlocks. Treuille [15] proposes a dynamic potential field that simultaneously integrates global navigation and moving obstacles such as other people, efficiently solving the problem of the motion of large crowds without the need for explicit collision avoidance. A bicycle behavioral model is often a constrained instance of pedestrian's model, or a specialization of a vehicle's model [16, 17, 18, 19, 20].

3. Collision Avoidance Model

In our simulation model, each individual is modeled as a convex volume in a 3-dimensional space. Although, our model assumes the individuals, and the obstacles move in a 2-dimensional space. Even if any kind of convex volume would work in our algorithm, we used bounding capsules with a fixed up axis. In this way, individuals are modeled as a circle with radius r_a in a 2-dimensional space, which preserves the computational time. r_a is the maximal extent of the individual's body. During the simulation, the distance between the individual and any object is always greater to r_a. Any individual a has to navigate toward a specified target position $\mathbf{p_t}$ without colliding with the obstacles around that may be moving or stationary. The pedestrian accelerates at a preferred rate w_a and moves with a preferred velocity v_a^{des}. In the rest of this paper, $\mathbf{p_a}$ refers to the position of the individual's bounding volume center and $\mathbf{v_a}$ is its instant velocity vector. The instant trajectory of the individual, represented as a pale yellow strip is bounded by two lines $T_{left}(t)$ and $T_{right}(t)$, and the orange circle represents the minimum safe distance d_m the individual tries to keep at all time between itself and its surroundings ($d_m \geq r_a$).

The collision avoidance model presented in this paper is based on the hypothesis that any individual will try to avoid an obstacle while minimizing the energy required to solve the conflict (principle of least effort). Minimizing the energy requires changing direction as smoothly as possible thus as early as possible while continuing to make progress towards his goal. Although it is quite simple for static obstacles, it is more challenging for moving obstacles. We propose a predictive approach to detect whether a moving obstacle may become a danger and to estimate the time to collision. This latter will then be used to scale the avoidance force of the corresponding obstacle.

Let M be the set of all obstacles perceived by the individual. An obstacle is an object or an individual in the field of perception. The hypothesis is that all the entities around the individual at a given time may be seen as potential obstacles, and may be avoided. Our model can be broadly described by the following equation:

$$\mathbf{F} = \sum_{i \in M} U(t_c^i) \cdot \hat{S}_i \qquad (1)$$

$$\mathbf{F_a} = \mathbf{F} + w_a.\delta_{\|\mathbf{F}\|} \frac{\mathbf{p_t} - \mathbf{p_a}}{\|\mathbf{p_t} - \mathbf{p_a}\|} \qquad (2)$$

$\mathbf{F_a}$ is the force that should be applied by the individual a to move toward its target and avoiding the obstacles in M at the same time. Basically, $\mathbf{F_a}$ is the sum, named $\mathbf{F}$, of all the collision-avoidance forces computed for each element of M. $\hat{S}_i$ is the direction of the avoiding force, whose computation is detailled in Section 3.2. t_c^i and $U(t)$ are the estimated time to collision to i, and the scaling function of this time, respectively. They are both detailed in Section 3.3. Two special cases may occur when computing $\mathbf{F_a}$: the individual does not perceive any obstacle around; or all the obstacles are too far to contribute to $\mathbf{F}$. To avoid the individual to stay at the same position in these two cases, $\mathbf{F_a}$ includes the attractive force to $\mathbf{p_t}$. This attractive force is applied only if $\mathbf{F}$ has a null length.

3.1. Sliding force

This paper introduces a new type of force, named the sliding force. Unlike repulsive forces that are commonly employed by now classical force-based models [4], the sliding force is not only intended to keep the pedestrian away from an obstacle but also to guide it toward its target position while circling around the obstacles in a most smooth fashion. The classic force-based approaches use two types of forces: one for the collision avoidance and one for the navigation. In our opinion, finding the scaling of one force relatively to the other is a heavy problem. It requires fine and specific tuning dedicated to each environment in which the individual model may be used. Because the sliding force includes these two types of forces, it provides a convenient solution for this scaling problem. To ensure that the collision avoidance trajectory is as smooth as possible, only the forces that are absolutely necessary are used during the computation of the sliding force. In other words, only the forces to avoid the collisions with the obstacles that are intersecting the individual's trajectory are computed. The determination of the sliding direction and the scaling of this sliding force are two distinct steps in our model. Moreover, the collision avoidance of stationary and moving obstacles are distinguished in two separate cases. The classification of the obstacles in one of these two categories is performed by the individual; and it is based on the perceived velocity of the objects. If an object around has an instant velocity closed to zero, then it is considered as a stationary obstacle.

3.2. Force Direction Determination

The direction of the sliding force is collinear to a vector $\mathbf{s_j}$, which is perpendicular to the direction to the obstacle; where $\mathbf{p_j}$ is the position of the collision point on the obstacle j; and $\hat{y}$ is the global Up vector.

$$\mathbf{s_j} = (\mathbf{p_j} - \mathbf{p_a}) \times \hat{y} \qquad (3)$$

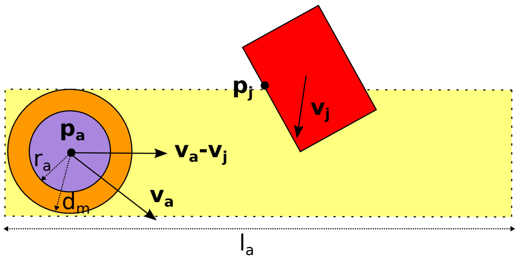

Figure 1. Determination of an obstacle

Since two candidate directions for the sliding force exist, $\hat{s}_j$ and $-\hat{s}_j$, the one that tends to minimize the overall motion to face to and to move towards $\mathbf{p_t}$ is selected.

$$\hat{S}_j = \text{sign}(\mathbf{s_j} \cdot (\mathbf{p_t} - \mathbf{p_a}))\frac{\mathbf{s_j}}{||\mathbf{s_j}||} \tag{4}$$

3.3. Time-based Force Scaling

Most force-based models use monotonic decreasing functions of the distance to an obstacle to scale the corresponding avoiding force. While this approach is certainly the most obvious and is usually quite efficient, it does not take into account the velocity of the pedestrian. Moreover, it underestimates the immediacy of the danger that a dynamic obstacle is representing if it is moving towards the pedestrian with a great velocity. In this paper, a time-based force scaling approach is proposed. The time to collision t_c is estimated and passed as a parameter to a monotonic decreasing function U, which represents the response of the pedestrian to the urgency of the collision. The greater the time to collision is, the lesser the force is. In our opinion, the time scaling is the most accurate way to give a priority to the forces that avoid the immediate collisions. The function U is defined as:

$$U(t_c) = \frac{\sigma}{t_c{}^{\phi}} - \frac{\sigma}{t_{max}{}^{\phi}} \tag{5}$$

with t_c the estimated time to collision, t_{max} the maximum anticipation time. σ and ϕ are parameters that control.

3.4. Avoiding Obstacles

The first step in avoiding obstacles is to determine whether the obstacle is representing an actual danger to the pedestrian or the cyclist, i.e. whether it is intersecting the instant trajectory. The obstacle determination is inspirated by [21]: the bounding volume of the motion of the individual is determined. If this bounding volume has an intersection with the obstacle candidate, then this last is not more considered as a candidate but as a real obstacle. Figure 1 illustrates the obstacle determination by showing the individual, as a circle, and the obstacle candidate, as a box. The motion bounding volume is represented by the dashed box. Its computation is based on the relative velocity Δv between the individual and the obstacle candidate is given by $\Delta v = \mathbf{v_a} - \mathbf{v_j}$, where $\mathbf{v_a}$ and $\mathbf{v_j}$ are the velocity vectors of the individual a and of the obstacle candidate j, respectively. The bounding volume is a 2D oriented bounding box defined by its center c and its two direction vectors d_1 and d_2, as defined by Equation 6. The intersection test between the two volumes is given by [22, 23, 24].

$$\begin{cases} c = p_a + \left(\frac{l_a}{2} - r_a\right).\widehat{\Delta v} \\ d_1 = r_a\,\widehat{\Delta v} \times \hat{y} \\ d_2 = \frac{l_a\,\widehat{\Delta v}}{2} \end{cases} \tag{6}$$

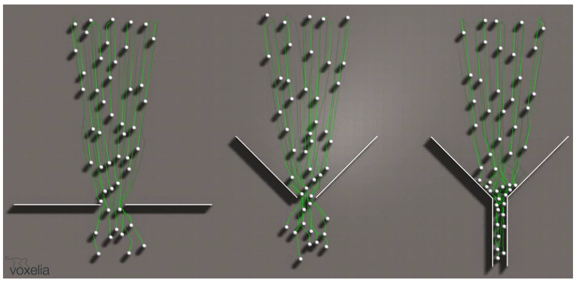

Figure 2. Different cases of environment topology and of pedestrians inside

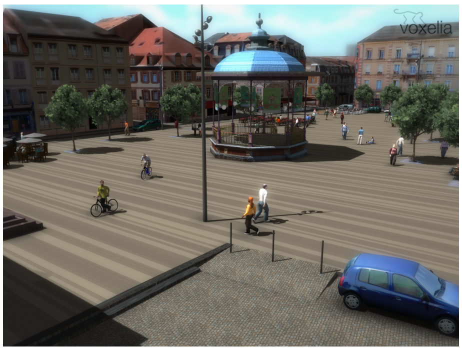

Figure 3. Screenshot of the Simulation of the Parada Area of Belfort

When the motion bounding volume and the bounding volume of the obstacle c are intersecting, two elements for the force computation need to be estimated: the point of impact $\mathbf{p_j}$, and the time to collision t_c. In Equation 7, the numerator represents the distance between the individual's body and the obstacle. This distance may be lower than the safety distance d_m in very constrained environments, but never lower than the size of the body r_a.

$$t_c = \frac{||\mathbf{p_j} - \mathbf{p_a}|| - r_a}{||\Delta v||} \tag{7}$$

Finally, Equations 4 and 5 are used to compute the desired sliding forces.

4. Applications

Our novel force-based approach was implemented on the Unity3D viewer[1], and tested on standard environment topologies [5]. Figure 2 illustrates three examples of bottlenecks in the environment (videos[2]). Figure 3 illustrates the application of the model for the simulation of pedestrians and bicyclists on the Parade of the city of Belfort. As expected, the trajectories of the individuals are smooth and may be used to simulate pedestrians as well as bicyclists. Only physical properties may distinguish these two types of individuals: a pedestrian turns faster than a bicyclist, but this latter runs faster than the pedestrian. Our model implementation permits to execute up to 200 individuals (pedestrians or bicyclists) in real-time (more than 30 frames per second) on a Intel Core i7-3710QM 2.30GHz with Nvidia GTX660M 2GB. As for the other force-based models, the scalability of our model is limited.

According to our experiments, our model has three major drawbacks: (i) oscillations still exist when the individuals are inside a concave obstacle; (ii) when two individuals are facing together, they may block each other, or one of them is turning back for a while; and (iii) when two individuals have been crossing trajectories in the global same direction, and they are not able to adapt their speed, they may pull and walk together.

5. Conclusion

In this paper, we presented a novel force-based collision avoidance model for pedestrian and bicyclist motion behavior simulation. The basic idea behind our model relies on the minimization of the energy required to avoid an obstacle (principle of least effort). It requires changing direction as smoothly and as early as possible while continuing to make progress towards his goal. To support this smooth avoidance,

[1] Unity3D Official website: `http://www.unity3d.com/`
[2] Videos are available on: `http://www.multiagent.fr/Publication:ABMTRANS13`

we introduce a new type of force, named the sliding force. Unlike classical repulsive forces, the sliding force is not only intended to keep the individual away from an obstacle but also to guide it toward its target position while circling around the obstacles in a most smooth fashion. On top of that, we avoid one of the traditional pitfalls of force-based models related to the force scaling, that usually requires fine and specific tuning for each considered environment. In this paper, we propose a time-based force scaling approach based on the estimation of the time to collision. Our novel model was successfully applied to the simulation of pedestrians and bicyclists in standard environment topologies, and on the Parade of the city of Belfort. The main perspective of this work is to study the scalability of the sliding-force model and to compare it to other models such as [10].

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