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Tawaf Crowd Simulation using Reciprocal Velocity Obstacles

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***Abstract*—Studies on crowd simulation have been around us for nearly 30 years. It remains one of the important and fundamental fields in three-dimensional (3D) computer graphics. Simulating large amount of crowds such as the crowd during Hajj is never an easy task. Therefore, a more refined technique is needed to avoid the entities, agents or characters in Hajj crowd from colliding with each other. In order to simulate such a huge crowd, the reciprocal velocity obstacles concept is used. The simulation is made using the reciprocal velocity obstacles as the collision avoidance technique. An experiment with up to 200 pilgrims is then conducted on four different personal computers (PCs) with different specifications.**

Keywords-component; computer graphics; crowd simulation; collision avoidance; reciprocal velocity obstacle; tawaf

I. Introduction

The Hajj starches back thousands of years to the time of Prophet Ibrahim. Every year, millions of Muslims around the world will gather in Mecca to perform the Hajj. It is performed in the last month of the Islamic calendar. All Muslims that are physically and financially capable, and can support their family during his absence are required to perform Hajj at least once in their lifetime. Hajj which is one of the five pillars of Islam is considered as one of the largest human gathering in the world, attracting two to three million pilgrim annually. It consists of six pillars which are making the intention (*niat*), *wuquf*, circumambulation (*tawaf*), *sa'ie*, shaving or trimming of hair and performing the pillars in their sequence of order (*tertib*) [1]. This study focuses on Hajj's third pillar which is the *tawaf*.

Crowd simulation on the other hand is one of the important fields in three-dimensional (3D) computer graphics. It is the process of imitating the movements of large amount of entities, agents or characters by replicating human behaviours and interactions. Crowd simulation is needed in order to develop an understanding of the complexity and the degree of crowd interactions of people in spaces over time [2]. Furthermore, it is an important research tool in understanding the overall crowd dynamics across a wide space and on so many levels of a complex structure [2]. Other uses of crowd simulation include simulating an emergency evacuation, video game artificial intelligence (AI) behaviour and recreating places in the past to show how people would have behaved [3]. Besides, the use of crowd simulation can also be seen in films such as the AI armies in *The Lord of the Rings* film series [4], [5], [6], the movement of bats in the *Batman Returns* film, and the movements of crowds in *Hugo* and *World War Z* films [4].

The nucleus of this study is the development of the *tawaf* crowd simulation. This study intends to further understand the crowd's behaviour during pilgrimage specifically during the *tawaf* ritual where pilgrims will circumambulate the Ka'aba seven times in an anticlockwise direction. This paper intends to discuss the related works in the crowd simulation field and briefly discuss the reciprocal velocity obstacles technique in crowd simulation. Furthermore, discussions will also be made on the implementation of the *tawaf* crowd simulation based on the reciprocal velocity obstacles technique together with its results.

Crowd simulation consists of three main elements. The elements are environment models, path planning and collision avoidance. Discussions will be made for all the mentioned elements as we progress through this paper.

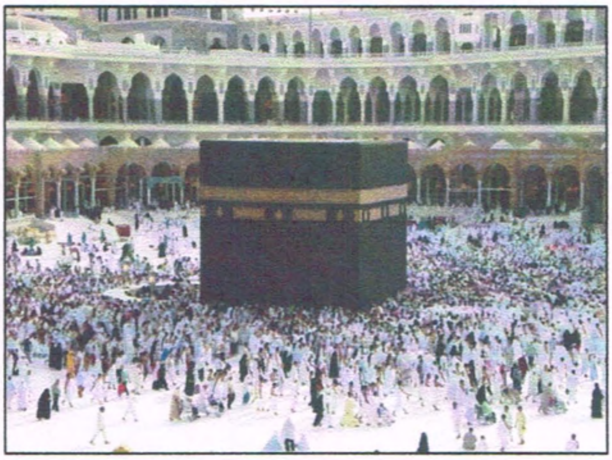

Figure 1. Pilgrims during tawaf

This paper is organized into six sections. The first section, which is the section we are currently at, gives the introduction to this study. Section two discusses related works done by other researchers. The next section discusses the framework of

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the developed system. This is followed by brief discussions on the three main elements of crowd simulation as previously mentioned. The succeeding section discusses the results and the implementation of the *tawaf* crowd simulation. Finally, conclusions and plans for future work are stated at the end of this paper.

II. Related Work

Studies on the crowd simulation field have been around for almost 30 years. Basically, crowd simulation consists of three important areas [5], [6]. The first one which is realism of behavioural [8] is mainly used for simple two-dimensional (2D) visualizations because most of the attentions are concentrated on simulating the behaviours of the group [5]. The second area is high-quality visualization [9] where the production of a more convincing visual is given higher priority than realistic behaviour [5]. This area is regularly used in motion picture productions and computer games [5]. Lastly, the convergence of both mentioned areas are mainly used in applications like training systems [5].

One of the early studies on crowd simulation is the flocking technique. It was introduced by Reynolds in 1987 to simulate animal flocking, herds and schooling [10]. Every single agent in the simulation is referred to as a *boid*. The key idea behind this research is complex crowd behaviour can be achieved through individual boids following simple rules.

In 1995, Helbing and Molnár published a paper [11] on a technique called the social force model to simulate pedestrian dynamics. Their work is considered a breakthrough and has been referred by many other researches because it reproduces many of the common features observed in pedestrian movement. In this technique, pedestrians follow a set of social rules that guide their movement. These rules include respecting the personal space of other pedestrian, follow other pedestrian by keeping a safe distance between them and avoid getting too close to walls and obstacles.

There are numerous studies that have been conducted on crowd simulation in recent years specifically replicating the *tawaf* rite. Mulyana and Gunawan [12] implement the Hajj crowd simulation based on the intelligent agent where it allows different goals and behaviours be added to individual agents. Khan and McLeod [13] on the other hand, developed a *tawaf* simulator called *TawafSIM* using the agent-based modelling and simulation approach. The simulator models the microscopic behaviour of Hajj pilgrims performing *tawaf*. The agent-based model is also used in a technique proposed by Curtis *et al.* [14]. The technique uses that model and combines it with a finite state machine and a geometric collision-avoidance algorithm in order to model the goals of each pilgrim and to control local interactions between the agents respectively.

III. System Framework

Figure 2 shown on this page is the framework of the Hajj crowd simulation system. The scene consists of two categories of objects. The first category, the static objects consists of objects that are motionless. This includes building models and mountains. The next category on the other hand, which is the dynamic objects, consists of moving objects which is mainly the pilgrims. These two categories which form the scene will then be tested for collision avoidance using the reciprocal velocity obstacle technique. In a situation where a dynamic object is in a collision course with another dynamic object or with a static object, it will recalculate its velocity and avoid collisions from happening. The simulation will finally be updated to show the effects of the computations previously made.

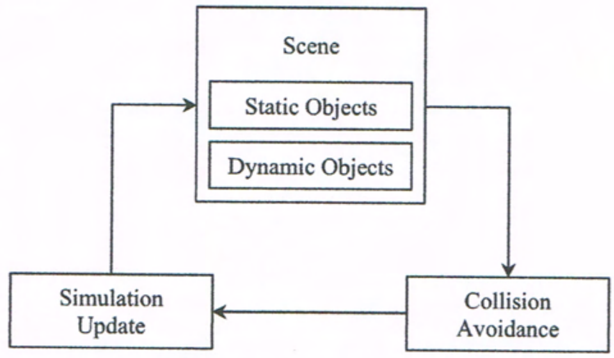

Figure 2. System framework

IV. Environment Models

Environmental modelling is closely related to behavioural animation. It plays an important role in bringing the scene to life. It facilitates the simulation of entities dwelling in their surrounding environments.

V. Path Planning

Path planning or motion planning in crowd simulation is used to help agents find their path in order to achieve their individual goal. It has been subjected to intensive research especially in the robotics field. The techniques developed as the results of these intensive results are then applied in crowd simulation systems.

VI. Collision Avoidance

The ROV concept was introduced by van den Berg *et al.* [15] as an extension to the velocity obstacle concept which was pioneered by Fiorini and Shiller in [16]. It is a concept for local reactive collision avoidance that considers the reactive behaviour of other agents by implicitly assuming them making similar collision avoidance reasoning [3]. Thus, in other words, the responsibility of avoiding collisions is shared by both agents that are on collision course. Each agent knows all the other agent's position, velocity and shape to enable them to avoid collision. When an agent is on collision course, it will compute a new velocity that is the average of its current velocity and a velocity that lies outside the other agent's velocity obstacle, hence enabling the agent to choose a velocity close to its current velocity. This principle which is the basic idea behind reciprocal velocity obstacles is formalized and defined in the definition below.

$$RVO_B^A(v_B, v_A) = \{v'_A \mid 2v'_A - v_A \in VO_B^A(V_B)\} \quad (1)$$

The reciprocal velocity obstacles of agent B to A, $RVO_B^A(v_B, v_A)$ contains all the velocities of agent A that are the average of the current velocity, v_A and a velocity inside the velocity obstacle of agent B, $VO_B^A(V_B)$. It can be interpreted geometrically as the velocity obstacle $VO_B^A(V_B)$ that is translated such that its apex lies at $\frac{v_A+v_B}{2}$ [15] as shown in the following figure.

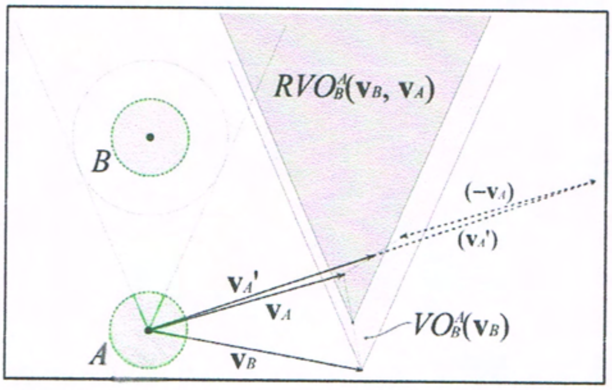

Figure 3. The reciprocal velocity obstacles of Agent B to Agent A [14]

As discussed by van den Berg *et al.* [15], there are several guarantees in the reciprocal velocity obstacles concept. The reciprocal velocity obstacles ensures that both agents in collision course will automatically choose to pass each other on the same side if each of them chooses a velocity outside the other agent's reciprocal velocity obstacles that is closest to its current velocity. Besides, this concept also ensures that both virtual agents select a velocity outside the reciprocal velocity obstacles induced by the other agent. Thus, these two characteristics will always guarantee that this concept will produce a collision-free and oscillation-free navigation respectively [15], [17].

VII. RESULTS AND IMPLEMENTATION

The Hajj crowd simulation is implemented based on the reciprocal velocity obstacles concept as discussed in the previous section. The Unity game engine is used to simulate the *tawaf* ritual. The experiment is repeated on four different personal computers (PCs), both with different hardware specification. Table 1 below shows the hardware specification of all four PCs, which includes the central processing unit (CPU), its processing speed, the capacity of the random access memory (RAM) and the type of graphic card used.

TABLE I. HARDWARE SPECIFICATIONS

PC	CPU	Processing Speed (GHz)	RAM (GB)	Graphic Card
A	Intel Core 2 Duo	2.10	4	NVIDIA G105M
B	Intel Core i7-4770	3.40	8	AMD Radeon HD8570
C	Intel Core i7-2600	3.40	8	NVIDIA GTS450
D	Intel Core i7-3770	3.40	8	NVIDIA GTX555

The simulation consists of models of the Masjidil Haram and Mecca's major landmarks. Besides, the model used as the pilgrim is a human model wearing the *ihram*. The human model is then cloned to simulate different number of pilgrims. Each of the cloned models has basically the same characteristics. The only difference is their velocity which is computed based on the RVO technique, explained earlier in this paper. Figure 4 and Figure 5 below shows the screenshot of the rendered scene of the *tawaf* rites. Both figures consist of the same number of pilgrims with different camera angle.

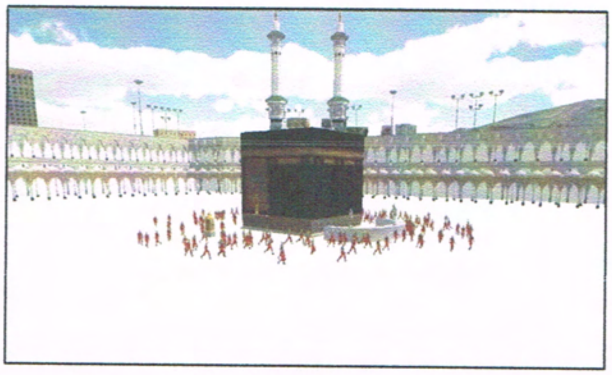

Figure 4. Tawaf simulation side view

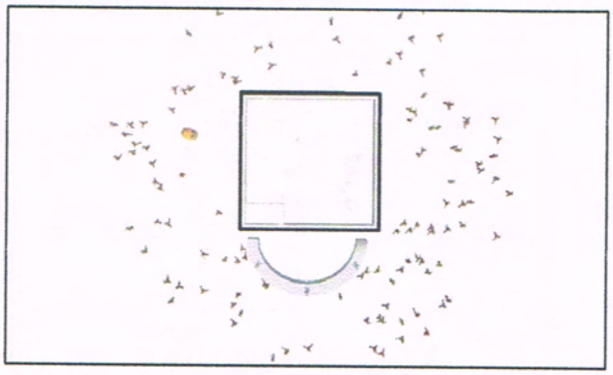

Figure 5. Tawaf simulation top view

As mentioned previously, the experiment is repeated on four different PCs with different specifications. The results of the conducted experiment are shown in Table 2.

TABLE II. FRAME RATE FOR DIFFERENT NUMBER OF PILGRIMS AND PC

Number of Pilgrims	Frame Rate			
	PC A	*PC B*	*PC C*	*PC D*
50	38.4	52.4	65.3	66.3
100	18.4	26.0	57.6	59.4
150	12.4	19.3	35.2	41.5
200	10.4	14.9	26.5	29.9

The table above shows the number of pilgrims against the frame rate. Different number of pilgrims is used during the experiment. In general, the frame rate correlates with the number of pilgrim used. As shown in Table 1 and Graph 1, it can be seen that as the number of pilgrims increases, the frame rate decreases.

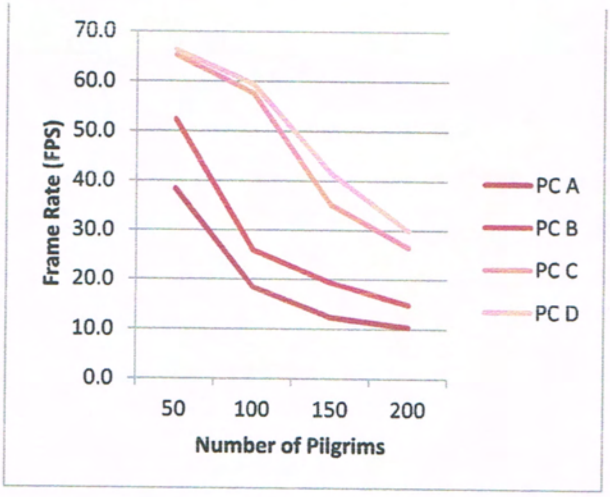

Figure 6. Number of pilgrim per frame rate

VIII. Conclusions and Future Works

This paper discusses the reciprocal velocity obstacles concept, which is a more refined collision avoidance technique than its predecessor. The reciprocal velocity obstacles concept is then implemented to simulate the huge crowd during the *tawaf* ritual in the Hajj. An experiment with up to 200 pilgrims was conducted on two different PCs with different specifications to clearly see the effects of the specifications on the simulation performance. It is clear that a PC with higher specifications will have higher simulation performance, thus less 'jumpy' images.

In future, this study plans to implement the *tawaf* crowd simulation using the reciprocal velocity obstacles with higher number of pilgrims. We plan to implement the simulation with up to 1 000 pilgrims. This simulation is planned to be implemented on a PC that have higher specifications than the one currently in use. That PC is needed in order for us to be able to cater the higher number of computations without excessively affecting the simulation performance.

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