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Spiral Path Simulation of Pedestrian Flow during Tawaf

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Abstract— **Pedestrian agent performing Tawaf is modelled using the concept of parameterization of spiral. The agents are set at defined velocities on spiral trajectory, moving counter clockwise mode inward and outward for decreasing and increasing radii. We present a new trajectory path planning that simulates the movement of individual agents performing Tawaf. Our aim is to simulate complex scenarios involving multiple agents interacting with each other and avoiding collision within a defined path. The simulation was carried out for two proposed approaches; Spiral movement of agents for seven lapses in order of four inward and three outward (4in_3out) and undirected movement in circular pattern. An agent flow optimization comparison was carried out between the proposed methods for agents flow rate, average velocity, Tawaf duration and maximum densities of pedestrians. We found that the spiral movement 4in_3out presents better Tawaf ritual performance with durations of 38 minutes and average density of 4.2 agents per square meter.**

I. INTRODUCTION

Crowd behaviour is considered as a natural phenomenon that often comprises large group of populous, individuals, audience, mass, aggregation and so on, sharing a common goal in a given environment. Crowd movement has a great concern and attention from different field of research such as psychology, sociology, civil engineering and computer vision. In some scenarios, a crowd of individual presents a well-organized sequence and shows a constructive behaviour while in another scenario an individual may behave in a panic manner.

Fig. 1 shows the distribution of thousands pedestrian agents performing Tawaf at Mataf area (Tawaf area) in Masjid Al-Haram. The black structure represents Ka'aba. The Ka'aba is a rectangular cuboid structure which is of vital historical importance to all Muslims around the world. It is also called house of worship which was built thousands of year ago. The Masjid Al-Haram (Qibla) also called the "Grand Mosque" located in the city of Makkah, Saudi Arabia. It is one of the Islamic holiest places and the largest mosque around the universe, where all Muslim around the world turn towards when performing daily prayers. Among the five pillars of Islam is the Hajj, which is required by every Muslims to perform if able to do so at least once in his/her life time. Tawaf is an Arabic word which refers to the Islamic rituals performed by Muslims during Hajj or Umrah at Masjid Al-Haram. During Hajj and Umrah, Muslims are to perform circumambulatory movement around the Ka'aba seven times, in counter-clockwise. The circling is believed to demonstrate unity of believers in the worshipping of Allah, as they move in harmony together around the Ka'aba, while supplicating to Allah. The Ka'aba is a rectangular cuboid structure which is of vital historical importance to all Muslims around the world. It is also called house of worship which was built thousands of years ago.

Fig. 1. Pedestrian agents performing Tawaf at Mataf area

Annually, approximately around six million Muslim pilgrims perform both Hajj and Umrah [1]. It comprises several stages that are performed on specific days. This results in high pilgrim densities during the peak periods. During Hajj, about 50,000 pilgrims perform Tawaf per hour within the Mataf area a place where the Tawaf ritual is being performed [1]. Earlier studies showed that the starting and stoppage points were designated by a line drawn on the ground. The line was then replaced by a light indicator in order to reduce the congestion level around the Ka'aba.

Collision avoidance is a basic problem in crowd movement especially for pedestrian during Tawaf. It can be extended to the context of mobile robots with obstacles or moving object or agents. One of the main challenges in these applications is to develop realistic models for collision avoidance among real crowd in a defined environment. In this paper, we address the spiral path planning for optimum flow and less collision among pilgrim agents performing Tawaf. In practice it is difficult to simulate the behavior of pilgrim agents during Tawaf due to some factors like complex motion flow, random

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flow of pilgrim, heterogeneous population, pilgrim clustering, orthogonal movement, touching of black stone, high density, varying velocities, bilateral and unilateral exit at entrances to the Mataf area [2]

Velocity Obstacles (VO) proposed by [3], has been a successful approach to collision avoidance with moving obstacles. The authors provided a necessary and sufficient condition for a robot to select a velocity that avoids collisions with an obstacle moving at a known velocity. This approach was extended for robot-robot collision avoidance with the definition of reciprocal velocity obstacles [3, 4]. Analysis was performed for every robot for some assumption to select a velocity outside the VO induced by the other robot. However, this formulation only guarantees collision-avoidance under specific conditions, and does not provide a sufficient condition for collision avoidance in general.

Several researchers in crowd modelling and simulation have written a comprehensive analysis regarding group dynamic and agents in a given setup of environment and path planning [5-7]. They computed the simulations of dynamic groups of agents-based pedestrians and the effect of density threshold on group behavior. Collision detection based on sensory systems is also used to predict the future path of the obstacle. However, most of the analyses above are applicable to collision avoidance movement of virtual agents in linear dynamic environment.

Cellular Automata are some of the approaches applied for dynamic crowd simulation. Cellular Automata comprises a workspace of agents divided into discrete grid cells that can be occupied by zero or unit agent. A cellular automaton was applied to different scenario involving individuals on scale of interactions and space utilization based on discrete and continuity of the crowd distribution. The concept of two-dimensional CA Moore neighbourhood was presented in [8] Agents then follow simple rules to move towards their goals through adjacent grid cells.

Computer vision methods can also be used with above models in cases like collision avoidance etc. There are 2D and 3D computer vision techniques [9-11] that can help in various scenarios for crowd behaviour analysis. However, there are carious challenges that are yet to be resoved like illumination, real-time processing, occlusion etc [12].

A couple of researches have been carried out about crowd movement within the Mataf area in the Masjid Al-Haram. AlHaboubi and Selim [9], proposed the spiral design concept which aimed at minimizing the congestion around the Mataf area of Masjid Al-Haram. The spiral was designed around Ka'aba for seven complete rounds with entrance at the outmost end and exit at innermost end leading to a ramp through an underground tunnel. This study is associated with some drawbacks; Tawaf is historical and building an underground tunnel will affect the master plan of Mataf area, thus the model is not realistic in practice.

Zainuddin et al. [10] simulate pedestrian movement around the Ka'aba using SimWalk commercial software. The approach used the social force model and shortest path algorithms. The design effectiveness of the spiral and circular path was carried out in terms of duration to complete the Tawaf and average velocity of the Pilgrim agents. Sarmady et al. [11] applied discrete cellular automata model to simulate the Tawaf circular movement of pedestrian. The movement process of each agent used some decision method to select a cell out of the Moore neighbours for the next update.

This paper addresses the concept of trajectory planning for individual agents on spiral path while performing Tawaf. Our contribution comprises the parameterization of spiral and comparison between two different proposed models for Tawaf ritual that will reduce the congestion level involving individual pedestrians. The concept can be applied to the following: multi-robot navigation in dynamic environment, crowd management, facilitating of safety measures, anomaly detection in crowd scene, traffic analysis, congestion analysis, access control in special areas, personal identification and crowd flux statistics.

II. PROBLEM FORMULATION

A. Problem Definition

Large crowd moving around the Mataf section of Masjid Al-Haram experience the so called "faster is slow effect". Complex motions as a result of pilgrims over-flowing in clusters towards the attraction points Hajarul Aswad (Black stone), Maqam Ibrahim, sometimes result in blockage and jams. This slows down the Tawaf performance of other pilgrims and affects the exit flow, especially at peak period of Hajj. Generally, several pilgrims arrive in order to perform Tawaf at a random flow. Virtually all arrivals are permitted to perform Tawaf any time. Nevertheless, there is no control on the influx associated with any significant number of individuals to the fairly compact Tawaf area, the actual density of pilgrims near to the Ka'aba grows to an optimum limit sometimes. For that reason, the actual movements of people in the vicinity of the Ka'aba results in being extremely slow and also at times approaches a total stand still.

B. Parameterization of Logarithmic Spiral

We propose a new method of performing Tawaf based on analogy of logarithmic spiral phenomena that occurs in nature. The Logarithmic spiral trajectory for seven lapses of Tawaf is represented by the Fig. 2 plotted using a suitable scale

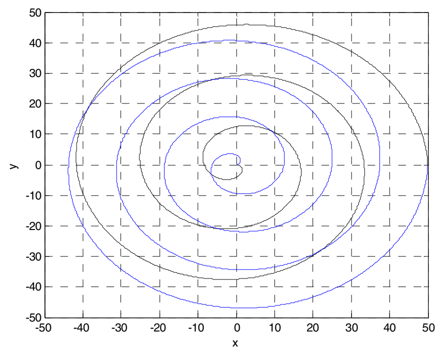

Fig. 2. Spiral trajectory for varying path radius

Recently, a new multipoint search method in metahuristic method for n-dimensional spiral optimization using logarithmic spirals was proposed by Tamura and Yasuda [12]. This approach extends the earlier method of 2-demensional spiral optimization.

Our parameterization approach will focus on logarithmic spiral of smooth turning for seven complete lapses of Tawaf for decreasing radius inward and increasing radius outward. The parameterization of spiral is formulated as follows:

Suppose the pedestrian agent that moves on the spiral trajectory shown in Fig. 2 possess the following parameters: n revolutions, angular velocity θ_i and varying radius r_i. The spiral path relations are as follows:

$$x_i = r_i \cos(\theta_i) \tag{1}$$

$$y_i = r_i \sin(\theta_i) \tag{2}$$

The subscripts $i=1,2,3,...m$ indicates the number of iteration for the update of the animation either moving inward or moving outward of the spiral for a common center 0, where m indicates the maximum number of iterations. Equation (1) and (2) show the agent's position in 2-D plane. For our algorithms, the common center is a square representing the Ka'aba which serves as the exchange point from linearly decreasing radius of the spiral to linearly increasing radius of the spiral.

C. Parameterization for circular movement

The circular model describes the circumambulation of the pilgrim agent around the Ka'aba seven times in counter clockwise direction. The parameterization is modelled using animated point looping in counter clockwise mode for seven consecutive lapses. For simplicity, our model assumed that the actual Tawaf is performed on circular undirected pattern. However, we noted that there may be anomaly during the movement due to some factors earlier mentioned above especially queuing and stopping at the black stone. The parameterization of circular movement is formulated as described in the next paragraph.

Suppose the animated agent moving on the circular trajectory possess the following parameters: n revolutions, angular velocity θ_i and radius r_i of the circle of different iterations, varying radius and speed of the moving agent, the polar equations (3) and (4) describing the motion of an agent is given by:

$$x_i = r_i \cos(\theta_i) \tag{3}$$

$$y_i = r_i \sin(\theta_i) \tag{4}$$

These equations together with comet function for 2-D animation resulted to a moving data on a smooth path.

III. METHODOLOGY

A spiral is a curve in the plane or in the space which runs round a center in a special way. The model of spiral path planning uses the Logarithmic spiral which runs both clockwise and counter-clockwise depending on the nature of the movement. The Tawaf simulation was carried out for two methods using the concept of waiting points. Method 1: Pedestrian performing Tawaf on spiral turn for seven lapses in order of 4in_3out. Method 2: Pedestrian performing Tawaf in circular trajectory. Some agents parameters corresponding to real Tawaf Scenario is taken into consideration such as surrounding temperature, agents gender, height, body breadth, age range, percentage of handicaps, agents speed range, population capacity, level of service, surface area of Mataf, approximate diameter, start area, waiting area with zero delay, exit area, agents profile settings and agents configurations.

[Spiral movement algorithm]:

Step 1: [Initialization]

Set the initial conditions for all the spiral parameters such that $0 \le n \le n_m$ and $0 \le \theta_i \le 2\pi n$ of □(r,θ), note that maximum iteration $i=1,2,3,...m$ for Tawaf is $n_m=7$.

Step 2: [Generating pedestrian agents]

The agents are assigned with initial time steps and move around the spiral path via the waiting points as implemented using the function $comet(x_i, y_i)$ in 2-dimensional space.

Step 3: [Updating $x-y$ coordinate]

$$x_i(n+1) = r_i(n+1)\cos(\theta_i) \tag{5}$$

$$y_i(n+1) = r_i(n+1)\sin(\theta_i) \tag{6}$$

Step 4: [Lapses counts and termination]

For $n=7$ end simulation for single laps of Tawaf otherwise return to initialize stage and continue for $n=n+1$.

The simulation was carried out using the concept of waiting points for zero delay forming spiral of seven turns counter-clockwise and spiral for decreasing and increasing radius as shown in Fig. 3. The waiting points represent the path used by every pedestrian agent in a unified direction while performing the Tawaf.

We generate a population of 1000 pedestrian agents with 50% male and 50% female and 5% handicap agents. The Level of Service (LoS) which is the density that determines the tendency of free flow or break flow of individual agents was assigned consistent with the observed crowd at Tawaf as presented in Table 1.

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TABLE 1
USER DEFINED LEVEL OF SERVICE

Level of Service Categories	Interpretation	Density (P/m^2)
LoS-A	Free flow of pedestrian	1.0
LoS-B	Minor interaction among pedestrian	1.2
LoS-C	Some restriction to agent speed	2.0
LoS-D	Movement restriction for agents majority	5.0
LoS-E	Movement restriction for all agents	8.0
LoS-F	Shuffling movement for all agents	10.0

Other parameters such as interaction range was assigned 170cm with Log interval of 10 steps for each pedestrian agents, average surrounding temperature was also considered as 30°C during Tawaf, individual pedestrian agents classified as kids assigned 7% of the population within the agents age range [1-15] years old and the remaining population assigned within (16-84) years old. All timing results are taken on an Intel Core™ i7-2600 CPU vPro at 3.40Gz, 8.00GB and 64-bit OS.

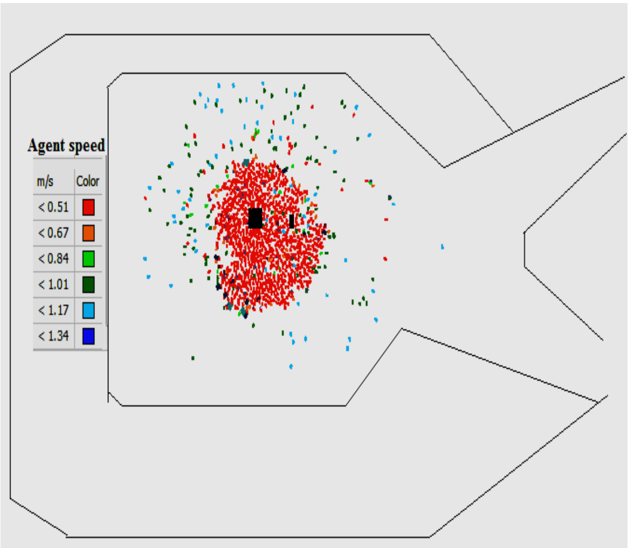

Fig. 3. The layout of Mataf area showing speed of pedestrian agents performing Tawaf on spiral path.

Fig. 3 shows the simulation outcomes of our algorithms. The pedestrian are distributed into different speed region as indicated on the legend. Agents navigating closer to Ka'aba possess lower speed within the range of 0.51-0.67 m/s because of the congestion due to attraction points. We also observed that the pedestrian walking speed in other spatial regions ranges from 0.5-1.34 m/s. The agents are configured with necessary parameters corresponding to real pedestrian. They follow the defined path for decreasing radius four times inwards until they reach closer to the center and continue outward three times for increasing radius until they return to the outer loop and exit. For the complete Tawaf the spiral trajectory for both inward and outward movement resulted in an overlapping spiral at some interval. For simplicity, we assume both entrance and exit at the outermost end of the spiral indicated as start and exit points.

IV. RESULT ANALYSIS AND DISCUSSION

In this section the simulations outcome of our proposed spiral model for Tawaf movement are presented. The aim is to achieve results that are close to reality for smooth flow of crowd during Tawaf. Several simulations were run for the proposed spiral path model. The following were computed; average density of the crowd, average velocity of individual agents and duration to complete the Tawaf.

TABLE 2
SUMMARY OF THE SIMULATION OUTCOMES

Methods	Duration (min)	Average Density (P/m^2)	Level of Service (LoS)
Spiral movement (4_inward, 3_outward)	38.0	4.2	C
Circular pattern (Undirected situation)	60.1	8.8	E

Table 2 shows the average completion time for single lapse of Tawaf spiralling 4_inward, 3_outward obtained as 38.0 minutes and 60.1 minutes for circular pattern (Undirected situation). Our simulation outcome implies lower density compare to undirected situation. Since flow rate determines how quickly the system reaches its dynamic state. Thus, high flow rate makes a system unstable because density builds up easily. For the circular movement pattern above we obtained maximum density of 8.8 persons/m^2 which falls within the restricted to movement category. This means pedestrian agents cannot easily leave the Mataf area. Based on the density and duration we conclude that the seven lapses spiral movement gives an optimum flow of individual agents during Tawaf.

Fig. 4 shows the average time taken by individual pedestrian agents to complete the single lapse of Tawaf for 1000 pedestrian agents. Fig. 5 shows the average velocity distributions for each of the pedestrian agents during Tawaf. During the simulations it was observed that the agents walking speed ranges within 0.32-1.34 m/s. In each case, the black trajectory represents the spiral pattern and the blue trajectory represents the circular pattern.

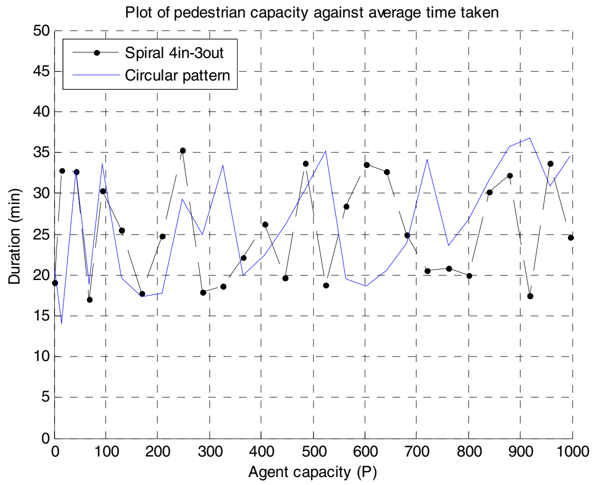

Fig. 4. Comparison between average time taken to complete the seven lapses of Tawaf and pilgrim capacity for the proposed methods

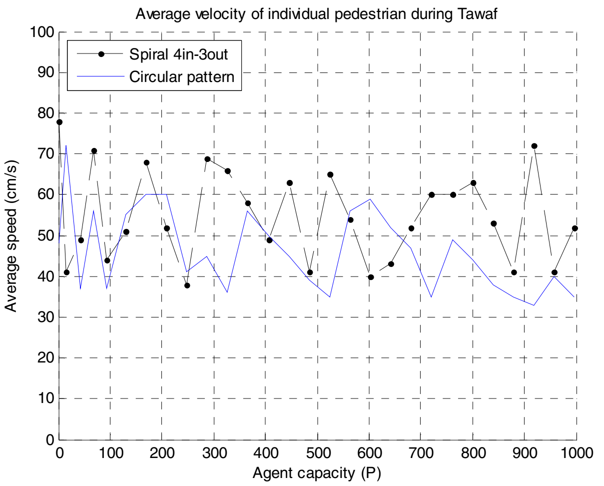

Fig. 5. Comparison between average velocity and capacity of individual agent during Tawaf for the proposed methods

V. CONCLUSIONS

This study has succeeded in coming out with mathematical model describing the spiral movement of agents during Tawaf based on a spirals for decreasing and increasing radius of the path. The result outcomes such as average velocity, average completion time for single lapse of Tawaf, maximum density were compared for the two methods. All computations were carried out in 2-dimensional space. The simulation outcomes of the seven lapses movement spiraling in the order of 4_inward, 3_outward give an optimum Tawaf flow of individual agents. The *LoS-C* obtained indicates free movement of agents, less clogging possibilities and smooth flow of individual pedestrian.

In future work we intend to make quantitative assessment on the flow rate by increasing the population capacity to correspond with the dense scenario of Tawaf and consider the factors such as queuing at black stone (Hajarul Asward), waiting at Hateem and their resultant effect on service time. Also, we shall investigate the effect of crowd turbulence during egress observed in real crowd especially for the agents that stop for other purposes during Tawaf.

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