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Simulation of Crowd Movement in Spiral Pattern during Tawaf

Aliyu Nuhu Shuaibu[1], Ibrahima Faye[1], Aamir Saeed Malik[1] & Mohammed Talal Simsim[2]

[1] Center for Intelligent Signal and Imaging Research, Universiti Teknologi PETRONAS, Malaysia

[2] Umm al-Qura University, College of Engineering and Islamic Architecture, Saudi Arabia

Correspondence: Ibrahima Faye, Center for Intelligent Signal and Imaging Research, Universiti Teknologi PETRONAS, Malaysia. Tel: 60-5368-7693. E-mail: ibrahima_faye@petronas.com.my

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Abstract

Simulation of large crowd is of great interest in different areas of applications such as path planning, entertainment, psychology, sociology, civil engineering, computer vision, etc. In recent years, crowd simulation models faces computationally intense problems such as poor crowd management, control, global navigation, they affect the performance of real-time simulation of thousands of pedestrians. The objectives of this study were to improve the performance of the pedestrians during the ritual of Tawaf. The proposed model involves spiral patterns with inward and outward pedestrian movements during Tawaf. We plotted the pedestrians' distribution in terms of the following parameters: density, duration and walking speed; then used statistical test (t-test) to determine if there was a statistical significant among the parameters. The simulation outcome of the spiral pattern implies lower density compared to the circular pattern. We obtained maximum density of 8 persons/m^2 for the circular movement pattern which falls within Level of Service (LoS-E) and 4 persons/m^2 for the spiral path within LoS-C. This result lends support to the idea that flow rate determines how quickly the system reaches its dynamic state. Thus, high flow rate makes the system unstable, because of the effect of increases in density.

Keywords: crowd movement, pedestrian, simulation, Tawaf, congestion, real-time

1. Introduction

Crowd is considered as a phenomenon that often comprises large individuals, audience, mass, aggregation etc. sharing a common goal in a given environment. Crowd movement is of significant value in various fields of research such as psychology, sociology, civil engineering, computer vision, etc. In some scenarios, a crowd of individuals presents a well-organized sequence and shows constructive action. However, individuals in the crowd may behave differently at certain instance because of mental factors, sociological factors, and physiological factors. For instances, pedestrians may realize an imminent collision, and decide to change their movement paths, or alter their walking speeds in order to navigate to the nearest social cluster. The interesting research areas like sociology, psychology, and computer science are usually applicable in describing the behavior of complex, and heterogeneous crowd scene.

The phenomenon of crowd movement can be exemplified by pedestrian pilgrims performing Tawaf at Masjid Al-Haram as shown in Figure1. Tawaf is an Arabic word that refers to the Islamic rituals performed by Muslims during Hajj or Umrah at Masjid Al-Haram. Masjid Al-Haram (Qibla) is called the "Grand Mosque", and is located in the city of Makkah, Saudi Arabia. It is one of the Islamic holiest places, and the world's largest mosque around, where all Muslims turn towards when performing daily prayers. Among the five pillars of Islam is the Hajj, which is required by every Muslim to perform if able to do so at least once in his/her life time. During Hajj and Umrah, Muslims are to perform circumambulatory movements around the Ka'aba seven times, in counter-clockwise direction. 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 was also called house of worship which was built thousands of years ago.

Figure 1. Pedestrians performing Tawaf under the newly constructed handicapped bridge

Annually, approximately six million Muslim pilgrims perform both Hajj and Umrah. Tawaf is one of the worship activities performed during Hajj pilgrimage. It comprises several stages that are performed on specific days. This results in high pilgrim densities during peak periods. During Hajj, about 50,000 pilgrims perform Tawaf per hour, within the Mataf area. The Mataf area is the place where the Tawaf ritual is being performed. Earlier studies (Koshak and Fouda 2008) 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 as described in (Curtis, et al., 2011). Expert finding shows that as pilgrims approach the line they do stop while searching for it. This was considered among the dominant causes of the slow movement of pedestrians along the section.

In General, several pilgrims arrive at Mataf area in order to perform Tawaf at a random flow. Pedestrians are permitted to perform Tawaf any time. Nevertheless, there is no control on the influx of individuals to the Tawaf area and the actual density of pilgrims near the Ka'aba grows to an optimum limit sometimes. For that reason, the movements of people in the vicinity of the Ka'aba at times approach total stand still. Presently, there are yet additional issues which increase the over-crowding problems:

1) Pilgrims who finished their own circling near Ka'aba are always in close proximity to it. Soon after completion, such pilgrims proceed outward in a pattern that clash with other pedestrians.

2) Extended time delay as a result of congestion and blockage is usually due to the queuing at the attraction areas. The time taken to perform Tawaf at optimum period increases exponentially compared to the time when pilgrims' density is low.

3) The entrance directly to the Tawaf area is not restricted to particular gates. As a result of the unrestrained entrances, pilgrims easily flow into the area through different directions. This triggered traffic jam within the Tawaf area.

In a public domain such as stadium, airports, shopping malls, railway stations, religious gathering area etc., it is difficult to monitor every individual action or detect suspicious behavior. The problems pose in the crowded area arise from crowd's collective patterns in congestion, confined exit, mass panic, protest, concert, etc. Generally, the nature of human emotions can lead to collective behaviors that result in significant threats to public safety management team. Literature reveals that one way to minimize the occurrence of disaster incidence in crowded setup is via crowd management, control and remodeling of the anticipated disaster regions especially in the Tawaf area. The need to develop a better and well-coordinated movement pattern which aims at reducing the congestion level is paramount. Filling this gap in the literature is one of the motivations for conducting this study. It is hoped that, by satisfying this research work the outcome would have been able to push back the frontier of knowledge for the humanity.

Pedestrian crowd simulation has been widely studied by various techniques. The existing crowd models are categorized as macroscopic and microscopic (Teknomo 2002), and also mesoscopic depending on the amount and type of details they cover. Macroscopic models only deal with the general properties of the crowd e.g., values of speed and density in different paths in the system, crowd flux statistics, etc. Both microscopic and macroscopic models do not model the movements or specification of individual pedestrians. Macroscopic also relate density to walking speed and flow of pedestrians.

Microscopic models deals with the movement details of individual pedestrian e.g., individual speed, individual position, etc. They allow modelers to investigate the interactions among the pedestrians. Mesoscopic models are somewhere in between. They consider individuals but do not simulate the movements (e.g., queuing models). In a crowd simulation model we may have layers. In one layer, macroscopic behavior (e.g., navigation) are modeled while the small scale movements are simulated in microscopic layer (i.e., path selection, avoid collision etc.). Moreover, in some models both macroscopic and microscopic layers are integrated and done in a single layer for better realistic simulation (S. Sarmady, et al., 2011).

The most commonly used models in crowd modeling and simulation include the following: force based (Helbing, et al., 2000; Helbing, et al., 2002; Helbing, et al., 2001), matrix-based (Kirchner and Schadschneider 2003; Lárraga and Alvarez-Icaza 2010; Lárraga, et al., 2005; Maerivoet and De Moor 2005; S. Sarmady, et al., 2011; Varas, et al., 2007), rule-based (Shiwakoti, et al., 2011), physic-based models e.g., lattice gas (Fukamachi and Nagatani 2007; Marconi and Chopard 2002; Wolf-Gladrow 2000), continuum model (Hughes 2002; Jiang, et al., 2010; Laval and Leclercq 2010; Sewall, et al., 2010; Zhang, et al., 2012). Gas, particle, fluid dynamics and force-based methods used physical models to simulate movement of pedestrians. Matrix-based models divide its environment into grid cells structure and apply Cellular Automata (CA) to simulate the movement of agent between cells. In Rule-based model, creatures such as birds and fishes are simulated in the form of flock and interaction is determined based on their perception to the environment.

A study based on the general cognitive model for multi-agent behavior understanding using the social comparison theory was presented in (Fridman and Kaminka 2011). Typical behaviors in agent-based are herding, decision-based method, queuing, collaborative, escape, etc. Models of this type are applicable to evacuation (emergency) as well as normal situations. A new approach to simulate virtual agents in crowd scene during emergency was presented in (Braun, et al., 2006). A way finding computational approach for agent-based system with trained leader personnel during panic situations by applying some basic rules of communication was proposed in (Pelechano and Badler 2006). A novel pedestrians' representation was presented in (Curtis and Manocha 2014) based on pedestrian motion combined with geometric optimization.

In force base model, pedestrians are subjected to forces which are measured by different motivations (Helbing, et al., 2002). A critical analysis was presented based on seven methodological approaches for crowd evacuation models including the cellular automata models, lattice gas models, agent based models, social force models, game theoretical models and animal based experimental models (Zheng, et al., 2009). Modeling of independent factor, decision making capability and their impact on a desired social group of pedestrians, for a normal situation, was presented in (Zainuddin and Shuaib 2011) and (Zainuddin and Shuaib 2010).

A model was suggested on potential spiral movement pathway to improve basic safety and throughput involving pilgrims during the Tawaf (Al-Haboubi and Selim 1997); however this model was considered unrealistic because of the effects of a tunnel construction would have on the master plan of masjid Al-Haram. The relationship between pedestrians and the congestion level was presented for different observation and translate the outcomes to simulation scenario associated with Tawaf rituals (Siddiqui and Gwynne 2012). A system that simulates the flow of pedestrian agents during dense situation of Tawaf and the associated parameters such as the heterogeneity, age, behavior and gender via a finite state machine was presented by (Curtis, et al., 2011). Comparisons of pedestrian movements on spiral path and circular path using the waiting point concept based on social force model and shortest path algorithms are presented in (Z. Zainuddin, et al., 2009). The design effectiveness was carried out in terms of duration to complete the Tawaf and average velocity of the Pilgrim agents.

Microscopic pedestrian models considered significant detailed analysis of pedestrians' navigation and traffic flows. It has been successfully applied for better understanding of pedestrian movements. Practical and theoretical design policy can be used to predict the flow performance of pedestrians. Force-based model uses simple differential equations to describe pedestrian movement in a continuous pattern with defined physical variables. Cellular automata model uses discrete cells transition and Moore neighborhood assignment to describe pedestrian movements. CA model is considered more suitable for evacuation situations because of its faster computational time. However, arbitrary cells scoring need more justifications. Similarly, rule-based model fails to provide realistic result in high density situations.

2. Method

The implementation is carried out on commercial simulator (SIMWALK) that was built based on social force model. The simulator can generate a population capacity up to 6,000 pedestrians. A sample size of 1,000 pedestrians is taken into consideration with 50% males, and 50% females and 5% handicapped agents. The Level of Service (LoS) which is the density that determines the tendency of free flow, or the break flow of different agents was assigned consistent with the observed crowd at Tawaf as presented in Table 1.

Table 1. User defined level of service

Level of service (LoS)	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

This research is meant to simulate the movement of pedestrians during the Tawaf ritual. We proposed movement model for the Tawaf path planning and later implement it on SIMWALK software platform. The parameters of interest are the durations, density, walking speed, and the design dimensions of the simulation area. Because of the difficulties in simulating a large number of pedestrian agents on small scale simulator, we scale down the Mataf surface area from 8500 sq. meters to 1826 sq. meters which is compatible with the maximum range of our simulator engine (6000 agents).

Other parameters such as interaction range were assigned 170cm with Log interval of 10 steps for each pedestrian agent. Individual pedestrian agents classified as kids assigned 7% of the population within the age range <1-15 years old, and the remaining group 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. Figure 2 shows the flow chart of the study. Geometric layout information is presented at the data acquisition stage. Next, is simulator calibration follow by setting the initial conditions: handicapped agents, normal agents, age category, and walking speed. All pedestrians are expected to perform seven lapses of Tawaf rituals as follows: Tawaf count is given by the condition; $0 \leqslant$ count $\leqslant 7$ with an increment of count++. The displacement of pedestrian from the center is given by; $0 \leqslant \theta i \leqslant 2\pi n$.

All waiting points are set by initializing coordinates parameters for every pedestrian agent. Pedestrians are assumed to start from one end of the spiral, and proceed to the assigned waiting points with zero delay until the seven lapses are completed, and exit. The simulation platform tested all possible combination of the spiral counts for the duration, density, and velocity of pilgrims' agents.

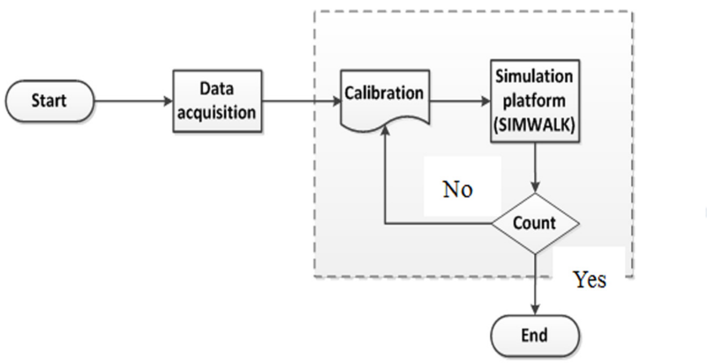

Figure 2. Study flow chart

2.1 Social Force Model

Let the pedestrian agents be subjected to social forces (e.g. attraction force, a repulsion force, pushing force, and frictional force) as proposed by (Helbing, et al., 2000). The first category; attraction, and repulsion forces are referred to as the social forces. The second category; pushing, and frictional forces are called the physical forces. The summation of forces that act on pedestrian i resulted in the acceleration as shown in Eq. (2). The generalized social force model is defined in Eq. (3). The temporal change in location xi(t) of pedestrian i at time t is given by:

$$\frac{dx_i(t)}{dt} = \vec{v}_i(t) \qquad (1)$$

$$m_i \frac{d\vec{v}_i(t)}{dt} = m_i \frac{\vec{v}_o \ell_\circ - \vec{v}_i(t) + \xi_i(t)}{\tau} + \sum \vec{f}_{ij} + \sum \vec{f}_{ib} + \sum \vec{f}_{ik} \qquad (2)$$

$$\vec{f}_{ij}(t) = \vec{f}_{ij}^{\,att}(t) + \vec{f}_{ij}^{\,rep}(t) + \vec{f}_{ij}^{\,push} + \vec{f}_{ij}^{\,friction}(t) \qquad (3)$$

Where:

$\vec{f_i}$(t) = Sum of forces influencing pedestrian *i*

τ = Relaxation time

ξ_i = Individual fluctuation

m_i = Mass of pedestrian i

$\vec{v}_\circ$ = Initial desired velocity

$\vec{v}_i(t)$ = Velocity of pedestrian i at time t

$\ell_\circ$ = Direction in which pedestrian i is moving

$\vec{f}_{ij}$ = Interaction force between pedestrian i, and j

$\vec{f}_{ib}$ = Interaction force between pedestrian i, and boundary b

$\vec{f}_{ik}$ = Interaction force between pedestrian i, and group of pedestrians k

$\overrightarrow{f_{ij}^{att}}(t)$ = Attraction forces between pedestrian *i*, and *j*

$\overrightarrow{f_{ij}^{rep}}(t)$ = Repulsion force between pedestrian *i*, and *j*

$\overrightarrow{f_{ij}^{push}}(t)$ = Pushing force between pedestrian *i*, and *j*

$\overrightarrow{f_{ij}^{friction}}(t)$ = Frictional force between pedestrian *i*, and *j*

The social force model has been successfully applied to different situations and simulates quite great scenarios such as normal organized phenomena (Helbing, et al., 2001). The model is considered among the best developed models in crowd simulation. However, there are few challenges related to this model. Firstly, the interaction aspect of the model does not guarantee non-collisions among pedestrians. Secondly, most of the researchers focused more attention to the physical behavior and interaction rather than the real agents flow.

2.2 Parameterization of Logarithmic Spiral

Recently, a new multipoint search method for n-dimensional spiral optimization using logarithmic spirals was proposed in (Tamura and Yasuda 2011).The parameterization of spiral is presented in (Aliyu N. 2013) which is formulated as follows: suppose the pedestrian moves on the spiral trajectory, the spiral path relations is described in equations (4) and (5) with angular displacement Θ, and radius r as follows:

$$x_i = r_i \cos(\theta_i) \tag{4}$$

$$y_i = r_i \sin(\theta_i) \tag{5}$$

The possible patterns of movement include the following:

6in_1out: spiral movement which is inward for the first 6 laps and outward for the last lap.

5in_2out: spiral movement which is inward for the first 5 laps and outward for the last 2 laps

4in_3out: spiral movement which is inward for the first 4 laps and outward for the last 3 laps

3in_4out: spiral movement which is inward for the first 3 laps and outward for the last 4 laps

2in_5out: spiral movement which is inward for the first 2 laps and outward for the last 5 laps

1in_6out: spiral movement which is inward for the first lap and outward for the last 6 laps

Ar_in_7out: spiral movement which is outward for the 7 laps from arbitrary entrance

7in_Ar_out: spiral movement which is inward for the seven laps and arbitrary exit

Pedestrian behavior during Tawaf is simulated based on design modality presented in Figure 3: Create a new project, and import into the simulator which is achieved via Computer-Aided Design (CAD) toolbox, and import to 2-D simulator, place waypoints in the architecture; the process is followed by plan building, grouping of agents based on priority (attraction and non-attraction trajectories) and scheduling agent walking path. Multiple simulations are run to optimize project settings and simulation results are analyzed in order to verify the proposed concept, and critical areas.

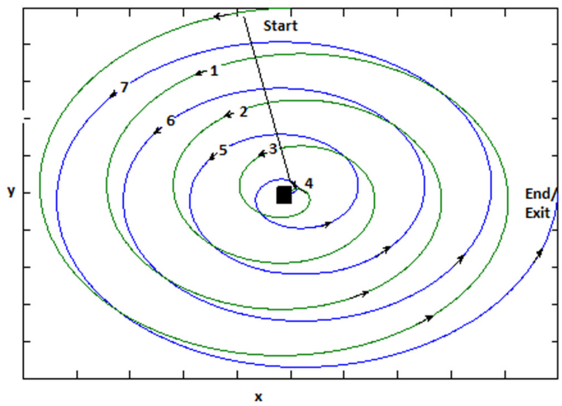

Figure 3. Spiral Tawaf movement pattern

3. Results

In this section, the simulation results for all the possible combinations of spiral patterns are presented. Table 2 shows the Tawaf durations of spiral patterns with average duration of each pattern equal to 10 iterations. The fastest average durations is achieved with 4in_3out pattern in 37 minutes. After successful iterations, a hypothesis test is performed to evaluate the significance of the difference between the performances of 4in_3out compared to other patterns.

Table 2. Tawaf durations for 1000 pedestrians

Pattern	Mean duration (min)
P1: 4in_3out	37.43
P2: 3in_4out	47.56
P3: 6in_1out	59.44
P4: 1in_6out	52.18
P5: 5in_2out	45.19
P6: 2in_5out	46.28
P7: 7in_Art_out	52.14
P8: Art_in_7out	61.12

3.1 Statistical Paired T-test

The analysis suggests whether the pattern duration is significant or not. A statistical paired t-test is performed on each pattern. Let μa and μb be respectively the mean durations of spiral movement pattern 4in_3out and one of the other patterns: 6in_1out, 5in_2out, 3in_4out, 7in_out, 1in_6out, 2in_5out and Ar_in_7out. The null and alternative hypotheses are as follows:

Ho: There is no difference in mean duration between the two patterns (i.e. $\mu a = \mu b$)

Ha: The patterns differ in mean duration (i.e. $\mu a \neq \mu b$)

The probability value is obtained from a t-test distribution table at degree of freedom (n-1) and is compared at level of significance (α=0.05). For any P-value greater than the critical value, the null hypothesis is correct whereas for any P-value less than the critical value the null hypothesis is rejected at the level of significance. The results at level of significance α=0.05 are presented in Table 3. The null hypothesis is rejected at significance value for all pairs.

Table 3. Result of t-test at significance level (α=0.05)

Method	t-value	p-value	Null hypothesis (H_0)
4in_3out vs. 3in_4out	34.745	5.954×10^{-18}	Rejected
4in_3out vs. 6in_1out	78.229	2.979×10^{-24}	Rejected
4in_3out vs. 1in_6out	65.491	7.225×10^{-23}	Rejected
4in_3out vs. 5in_2out	32.403	2.051×10^{-17}	Rejected
4in_3out vs. 2in_5out	30.835	4.934×10^{-17}	Rejected
4in_3out vs. 7in_Art_out	34.637	6.289×10^{-18}	Rejected

3.2 Incorporating Complexity for Pedestrians Movement

The simulation is performed by incorporating more complexity parameters for a group of pedestrians X, and Y. The simulation is set up by varying population capacity, and handicapped percentage. Simulation result is presented in Table 4, in each case egress duration of each group is recorded. It is seen that, in the simulation run, group X pedestrians exit the simulation area faster than group Y. This result is due to the interaction/blockage along the pedestrians' path.

Table 4. Simulation result on complexity incorporation

Group X (min)	Group Y (min)	Population X	Population Y
55.11	66.06	900	100
65.05	72.02	800	200
46.18	59.42	700	300
54.22	62.00	600	400
57.18	62.50	500	500

Figure 4 shows the average density against duration for a single lapse of Tawaf on spiral movement patterns. The average walking speed against duration is presented in Figure 5. The average completion time for a single lapse of Tawaf is 37.43 minutes based on 4in_3out pattern. For simplicity, we used 1000 pedestrians for the simulation run. The average velocity of pedestrian is approximately 0.87m/s.

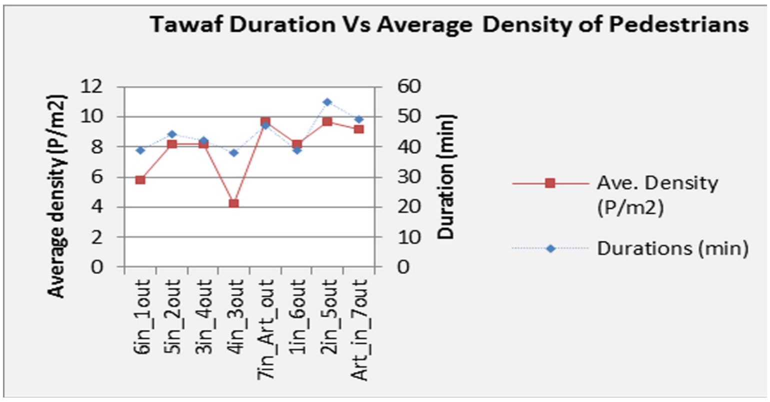

Figure 4. Tawaf duration against the average density of pedestrian agents

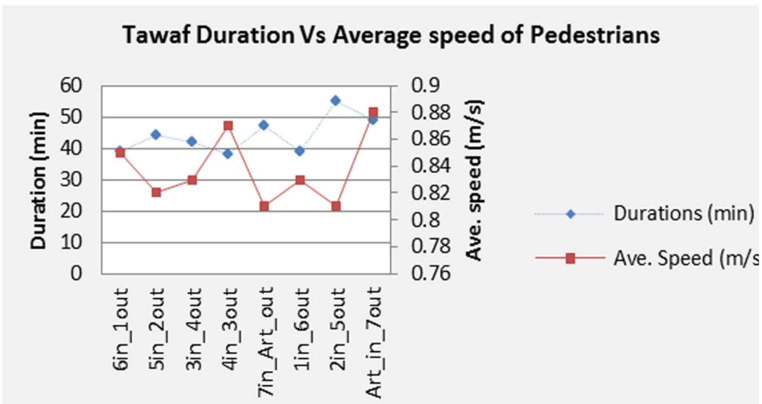

Figure 5. Tawaf duration against the average speed of pedestrian agents

In 2008, the authors (Koshak and Fouda 2008) used GPS/GIS devices to track pilgrims during Tawaf. They divided the Tawaf area into sections and calculated the average velocity of pilgrims in those areas. The average velocity computed in this work matches the mean speed obtained in (Z. Zainuddin, et al., 2009). The authors findings also show that the walking speed range tracked at less than 1.00 m/s which implied higher density during the Tawaf movements.

3.3 Spiral Model Comparison with Circular Method of Performing Tawaf

The simulation outcome of the spiral pattern implies lower density compared to the circular pattern. Since flow rate determines how quickly the system reaches its dynamic state; thus, high flow rate makes the system unstable, because the density builds up easily. For the circular movement pattern above we obtained maximum density of 8.8 persons/m^2 which falls within LoS-E (restricted movement); this means pedestrian agents cannot easily leave the Mataf area.

Figure 5 shows the average time taken for the pilgrims to complete the Tawaf ritual. It can be seen that the average time taken for undirected circular Tawaf varies for the 10 iterations while the spiral pattern remains almost constant. This remains undesirable because of the density created in the circular pattern of movement due to uncoordinated design. From Figure 6, we can see that the spiral pattern of movement gives faster duration for Tawaf completion. This is because the pedestrians were directed to the specified path with a reduced amount of conflict during the ritual. Table 5 shows the average completion time for single laps of Tawaf spiraling in pattern 4in_3out, and circular pattern. A t-test is performed, as presented in Table 6, to determine the significance between the spiral, and the circular pattern. The P-value obtained is less than the level of significance (α=0.05). The null hypothesis is rejected.

Table 5. Comparison between spiral and circular movement

Method	Average duration (min)	Average density (P/m^2)	LoS
Spiral pattern (4in_3out)	37.43	4.2	C
Circular pattern	66.24	8.8	E

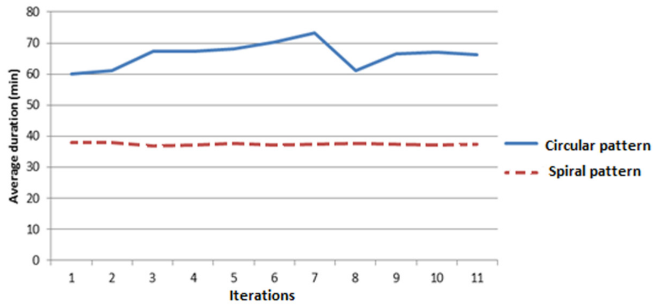

Figure 5. Tawaf duration for 10 iterations

Table 6. t-test at significant level

Method	t-value	p-value	Null hypothesis (H_0)
Spiral 4in_3out **vs.** Circular pattern	21.544	2.657×10^{-14}	Rejected

4. Discussion

This research work presents the background on pedestrian study specifically used in crowd modelling and simulation related to Tawaf ritual. The work focused on microscopic pedestrian simulation model. A detailed comparison is provided for three microscopic based crowd models: social force model, cellular automata model and rule-based model. The advantages and major drawbacks of each model were highlighted. Spiral pattern approach to Tawaf movement was implemented on a social force model based simulator, which is aimed at reducing the congestion level at Mataf area and pedestrian throughput. Outcomes such as average velocity, average completion time and average density were computed for different spiral movement scenarios. The simulation showed that the pattern 4in_3out (4 laps inward and 3 laps outward) outperforms the other patterns and the differences in average duration are statistically significant.

There are some limitations and constraints in this study. Firstly, the software computational capabilities may not be sufficient to simulate greater number of pedestrians. Secondly, the study proposed spiral movement pattern that is only applicable to the Tawaf ritual. In general, some pedestrian may not follow the spiral pattern as suggested but if majority of the pedestrians follow, it is anticipated that this will facilitate the agent's traffic flow.

5. Conclusion

The study presents the importance of the spiral model for optimizing pedestrian flow during Tawaf. The implementation was performed on commercial simulator SimWalk that was built based on social force model. In spite of the efforts by researchers in the field of modeling, and simulation of crowd applicable to Tawaf, anomaly is still observed during the ritual. However, the recent implementation of handicapped multi-level bridge in Mataf area has significantly eased the movements of the handicapped, and old age pilgrims with no report of anomaly. Further studies can be done on the following:

-Modeling the behavior of pedestrians during Tawaf movement in real-time using a simulator that is capable of simulating larger crowd.

-Density and flow rates of pedestrians could give relevant information on crowd dynamics if there are sufficient data.

-An additional overhead bridge may still be considered for single spiral fold, so as to overcome the effect of the collision among pedestrians.

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