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Simulating the Circumambulation of the Ka'aba using SimWalk

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Abstract

The study of pedestrian flow is important to simulate pedestrian path which would help in the design of proper walking facilities to avoid disasters during panic and evacuation situations. To date, many models have been introduced which includes the Benefit Cost Cellular Model, Cellular Automata Model, Magnetic Force Model and the Social Force Model(SFM). The SFM is the most recent form of pedestrian model and is widely used in computer simulation software as the model is more realistic which is characterised by repulsion and attractive forces. The equations of pedestrian models are based on second order differential equations which can be solved using standard numerical techniques. This work uses the pedestrian simulation computer software, SimWalk, to study the simulation of pedestrian flow. This software can design pedestrian walking areas and simulate the movement of pedestrians in a crowd. SimWalk uses the SFM as its basic equation to find the pedestrian's path. The basic algorithm to design the pedestrian walking path in this software is the shortest-path algorithm where the pedestrian finds the shortest route to reach his/her destination after avoiding all the obstacles. The study of circumambulation of the Ka'aba is taken as an illustrative example, where performing Tawaf is one of the rituals when performing Hajj. The process of Tawaf involves circumambulating the Ka'aba seven times in a counter clockwise direction. The pilgrims face two main problems in this situation. The first is the overflowing of the pilgrims during the Hajj season. The large number of pedestrians will cause crowd congestion and may cause disasters as pedestrians push into each other. Elderly pilgrims and women face difficulties in completing the seven rounds. Secondly, entry into the Tawaf area is unlimited which causes pilgrims to flow in from various directions at the same time. This study suggests various mitigation measures to alleviate the problems associated to circumambulation of the Ka'aba. The entries into the Tawaf area are directed and limited and simulations are done using SimWalk to compare the differences of the time taken to complete the seven rounds.

Keywords: pedestrian flow, SFM, circumambulation, tawaf, Ka’aba

1. Background of the Microscopic Pedestrian Simulation Model

The growing number of pedestrians in the world nowadays has urged the need to design safer pedestrian walking facilities. Microscopic Pedestrian Simulation Model (MPSM) [1] is a computer simulation model used to determine the pedestrian’s movement. In MPSM, pedestrians are treated individually. There are a few types of MPSM namely the Benefit Cost Cellular Model, the Magnetic Force Model, Queuing Network Model, and the SFM.

The Benefit Cost Cellular Model was developed by Gipps and Marksjo [1]. In this model, an area is divided into 0.5 by 0.5 m^2 cells. Pedestrians will occupy one cell. Calculation will be done to find the net benefit in each cell. A pedestrian will move to the cell that has the maximum net benefit.

The net benefit,

$$B = S - P(\sigma_i) \tag{1}$$

where, S is the repulsive effect of the score and $P(\sigma_i)$ is the gain score or motivation force for a pedestrian to move to his destination.

The Cellular Automata Model is similar to the Benefit Cost Cellular Model. This model is widely used in the simulation of traffic. However, this model is also used in simulating pedestrians.

The Magnetic Force Model was developed by Okazaki, Mathushita and Yamamoto. This model is based on the magnetic field where the pedestrian is assumed to have a positive pole while the destination is the negative pole. Obstacles such as walls have positive pole too. Thus, a pedestrian is attracted to his destination while repelling other obstacles. Calculation for this model is based on the Coulomb’s Law to calculate the force from a pole and acceleration force to avoid collision with other pedestrians or obstacles.

The SFM was developed by Helbing and Molnar [2]. The equations of the model are based on second order differential equations which can be solved using standard numerical methods. In SFM, the pedestrians act as individuals and are affected by external and internal forces. Internal force is the force within pedestrian that motivates him to walk towards his direction. External forces are forces from other pedestrians and obstacles that affect the pedestrian’s walking path.

The Social Force is defined as:

$$\begin{aligned} \mathrm{f}_i(t) &= m_i \frac{\mathrm{dv}_i(t)}{\mathrm{d}t} = m_i \,\mathrm{a}_i(t) \\ &= \mathrm{f}_i^0(t) + \sum_{j \neq 1} \mathrm{f}_{ij}(t) + \sum_{w} \mathrm{f}_{iw}(t) + \sum_{a} \mathrm{f}_{ia}(t) + \sum_{g} \mathrm{f}_{ig}(t) + \xi_i(t) \end{aligned} \tag{2}$$

where: $\mathrm{f}_i(t)$ is the sum of all the forces acting on the pedestrians

$\mathrm{f}_i^0(t)$ is the force of the pedestrians’ next immediate target

$\mathrm{f}_{ij}(t)$ is the repulsive force between two pedestrians

$\mathrm{f}_{iw}(t)$ is the repulsive force between a pedestrian and other obstacles

$\mathrm{f}_{ia}(t)$ and $\mathrm{f}_{ig}(t)$ represent the attraction force; the force that attracts pedestrians to form a crowd in a particular area.

Without loss of generality, attraction forces can be omitted from the equation.

This results in the reduced SFM as follows:

$$\mathrm{f}_i(t) = \mathrm{f}_i^0(t) + \sum_{j\neq 1} \mathrm{f}_{ij}(t) + \sum_{w} \mathrm{f}_{iw}(t) + \xi_i(t)$$

$$= m_i \frac{v_i^0}{\tau_i}\left(\frac{\mathrm{r}_i^k - \mathrm{r}_i(t)}{\left\|\mathrm{r}_i^k - \mathrm{r}_i(t)\right\|}\right) - \frac{v_i(t)}{\tau_i} + \sum_{j\neq 1}\left(\frac{A_i}{B_i}\exp\left[-\frac{\left\|\mathrm{r}_i(t) - \mathrm{r}_j(t)\right\|}{B_i}\right]\frac{\mathrm{r}_{ij}(t)}{\left\|\mathrm{r}_{ij}(t)\right\|}\right)$$

$$+\sum_{w}\left(\frac{A_w}{B_w}\exp\left[-\frac{\left\|\tilde{\mathrm{r}}_{iw}(t)\right\|}{B_w}\right]\frac{\mathrm{r}_{iw}(t)}{\left\|\tilde{\mathrm{r}}_{iw}(t)\right\|}\right) + \xi_i(t) \tag{3}$$

where,

v_i^0 is the desired speed of pedestrian i

$\left(\frac{\mathrm{r}_i^k - \mathrm{r}_i(t)}{\left\|\mathrm{r}_i^k - \mathrm{r}_i(t)\right\|}\right)$ is the unit vector directing to next intermediate target at time t.

τ_i is the relaxation time (time needed to accelerate from current speed to desired speed.)

$v_i(t)$ is the velocity of pedestrian at time, t

A_i is the interaction intensity which is the impact of external forces on the pedestrian. In Simwalk, A_i is denoted as the Object Pressure factor

B_i is interaction distance, which is the impact of distance between pedestrians on potential exerted by pedestrian *i* to pedestrian *j* and is denoted as Pedestrian Pressure Factor

The velocity at time $t + \Delta T$ for the reduced SFM is defined as

$$\mathrm{v}_i(t + \Delta T) = v_i^0 \frac{\mathrm{f}_i(t)}{\left\|\mathrm{f}_i(t)\right\|} \tag{4}$$

and the final position of pedestrian *i* is

$$\mathrm{r}_i(t + \Delta T) = \mathrm{r}_i(t) + \mathrm{v}_i(t)\Delta T \tag{5}$$

Table 1.1: Advantages and disadvantages of MPSM
The table shows the comparison between various kinds of microscopic pedestrian simulation models.

Model	Advantages	Disadvantages
Benefit Cost Cellular Model	Simple and fast	Arbitrary scoring of the cells and pedestrian makes the model difficult to be calibrated in the real world
Cellular Automata Model	Simple	Heuristic approach of updating rules is undesirable
Magnetic Force Model	Has force to avoid collision	The validation can only be done by visual inspection
Queuing Network Model	Evacuation concept	Behavior not clearly shown, collisions are possible

Table 1.1 shows the comparison between various kinds of microscopic pedestrian simulation models. The greatest advantage of the SFM which distinguishes it from the other MPSMs is its ability in representing the interactions among the pedestrians in a more realistic way. The SFM has introduced all aspects of pedestrian flow perfectly [6]. For this distinction, the SFM has been considered by a majority of researchers [1, 7, 8, 9] as the representative model for the environmental phenomena which are caused by the interactions between pedestrians such as congestion.

In this study, we will apply the SFM to investigate crowd behavior during one of the rituals of the Muslim pilgrimage to Makkah, namely the Tawaf. Around three million people perform Hajj every year where thousands of these pilgrims are present in each section of the Masjidilharam at any point of time. Modelling and simulating of this huge crowd will help in managing this event in terms of reducing congestion, smooth flow of crowd and management of evacuation (should any emergency exists). The recently built Jamrat, which has solved a major problem and is very much appreciated by the majority of the pilgrims, is in actual fact, the product of the crowd analysis carried out on the simulation model/system developed by researchers in Crowd Dynamics [7,8].

The solutions that are particularly applicable to the Jamrat situation are not necessarily suitable to the Masjidlharam scenario due to the fact that the crowd dynamics and characteristics at these two locations are different. Hence, we are in a dire need to study suitable simulation models, which could best represent the myriad of activities within and also in the surrounding area of the Masjidilharam. A study has been done by [10], during the USM Hajj Research 2006 visit where some important aspects of the Al-Tawaf crowd have been considered. The authors have observed some important factors that have major contributions to the crowd of the Al-Tawaf area. Unlike the crowd at Jamrat, there are several identified factors that influence the dynamics and behavior of the crowd at the Masjidilharam. These factors are:

(i) the effect of the geometry (the physical structure) on the crowd
(ii) attraction points including Hajar Aswad, Multazam, Maqam Ibrahim, Hijir Ismail and the area surrounding Kaaba as well as relevant activities such as crossing to these attraction points
(iii) the ritual activities such as queuing for Hajar Aswad, making "du'a" at Multazam, praying behind Maqam Ibrahim, carrying of "jenazah", joining and leaving the area, causing excessive crossing
(iv) herding behavior of some people such as clustering and the chain-like behaviour

Due to the complexity of the crowd dynamics and the wide range of characteristics of the crowd at the Masjidilharam, an in-depth study of the various available models is mandatory in order to develop and design a new and robust model that is able to represent and capture the real situation. Taking into consideration the capabilities of the SFM we have mentioned above and the major aspects of Al Hajj crowd, the simulator which is based on the SFM will be the typical simulator to represent the reality of Al-Tawaf ritual. The implementation of the well-developed simulator will be transferable to other areas of crowd especially the crowd during Ramadhan and Hajj seasons.

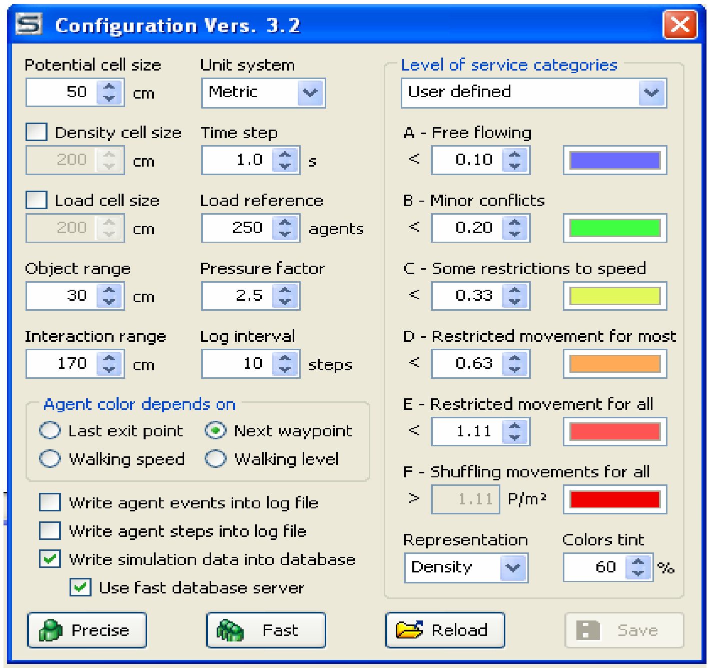
2. Background of SimWalk

Microscopic pedestrian simulation models can be generated into computer simulation software so that we can solve many cases of pedestrian problems. Many simulation models have been designed and available in the market. Each simulation package has its characteristics and advantages. Examples of computer simulation models are AnyLogic, Arena, PanicSim, Exudox, Legion, ProModel, PedGo, Simul8 and Kanbara Sim [4]. All these models are built based on various microscopic pedestrian models.

Particularly, SimWalk is computer simulation software which simulates pedestrians' movement [3]. SimWalk allows the user to design the walkway and space needed and validate the path using the simulation. SimWalk has its own SimDraw, a programme that allows users to draw the architecture plan of their walkway. However, users can also work on their design in AutoCad and import the drawing into SimWalk. This software is built based on the SFM model and the shortest-path algorithm. This software is a flexible model which allows users to define the density, destination, the range of speed for pedestrians, the level of service (LOS), time step, radius of pedestrian, A_i, which is the interaction intensity and B_i which is the interaction distance.

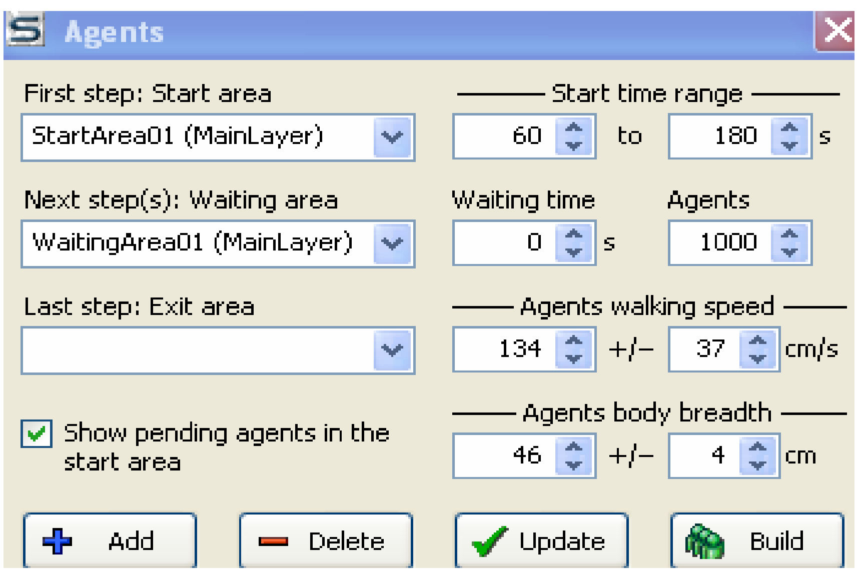
SimWalk can produce many outcomes and results namely density, walking speed of pedestrians, count and flow rates, duration taken by each pedestrian to complete the simulation, the distance traveled, the start time as well as the exit time of the pedestrians. In SimWalk, the pedestrian's route is affected by his destination, speed, interaction with other pedestrians and existence of other pedestrians and obstacles.

Figure 1: Configuration in SimWalk



This figure shows the configuration table of SimWalk
This table allows the user to change the parameters according to the user's choice

Figure 2: Building Agents



This figure shows the configuration table of SimWalk. This page allows the user to create pedestrians according to their speed and body breadth.

3. Application of SimWalk

In this study, Simwalk is used to simulate the pedestrians' movement during circumambulation of the Ka'aba. Performing Tawaf [4] is considered to be a holy ritual among Muslims when performing Haj. The process of Tawaf includes circumambulating the Kaaba seven times in a counterclockwise direction.

The problems involved in circumambulating Ka'aba are:

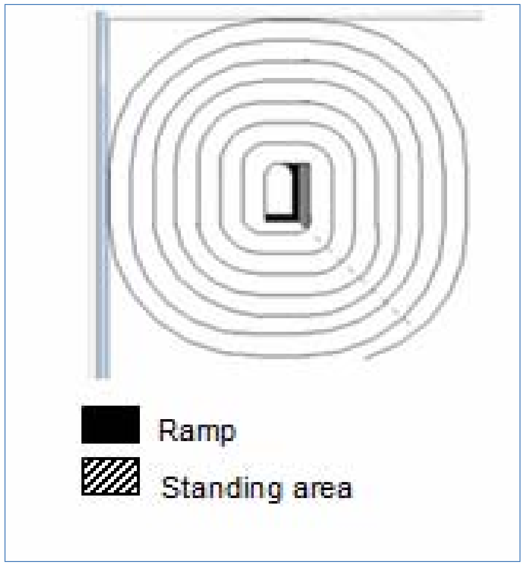
1) Overflowing of Pilgrims during Hajj seasons. The entry into the Tawaf area is not restricted to a limited number of pilgrims only. Hence, during Hajj season, when pilgrims converge into Makkah from all over the world, they can perform Tawaf at any time at their own convenience. After completing the seven rounds, most of the pilgrims wish to reach Ka’aba as close as possible. Pilgrims are not directed into a specified walking path causing them to walk freely. After completing their rounds, pilgrims do not have a proper path to walk out of the area. They would jostle each other through the crowd to move out of the Tawaf area conflicting with the main direction of flow. The large number of pedestrians will cause crowd disasters as pedestrians push into each other. Elderly pilgrims and women will have a tougher time in performing the Tawaf.
2) The entrance into the Tawaf area is not limited to certain entrances only. Due to the unrestrained entrances, pilgrims can flock into the area from various directions. This would cause congestion in the Tawaf area as pilgrims enter from different directions. During the peak period, severe bottlenecks occur at the entrances of the Tawaf area which are compounded by the moving crowd inside the Tawaf area.

3.1. Simulating the circumambulation of the Ka’aba using Simwalk

Method 1. Spiral Path Design

A design was proposed by Haboubi [5] which suggested building a spiral path (Figure 3) around Ka’aba which encircles it seven folds where the entrance of the path is at the outermost fold and the completion of the Tawaf is at the innermost fold leading down a ramp to an underground tunnel. One of advantages of the spiral path design is that the pilgrims need not count the number of times they have circumambulated the Ka’aba. However, the construction of the underground tunnel is considered to be unrealistic as the area of Tawaf is historical and building an underground tunnel may disrupt the area. In order to investigate the effectiveness of the spiral design, a simulation was created using SimWalk to study its impact on crowd flow in terms of the time taken to complete the Tawaf and the pedestrian speed.

Figure 3: The design of the spiral structure in the Tawaf area as proposed by Haboubi [5]



Test run:

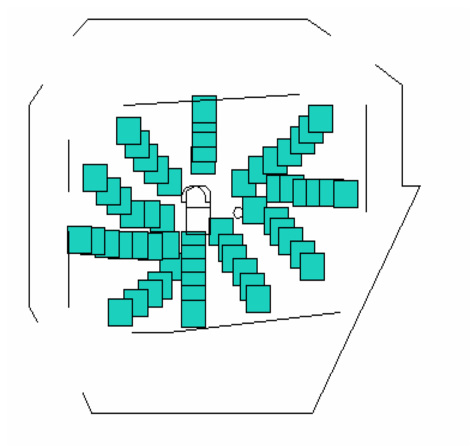
a) Test run: 090729134416
Number of agents: 1000
Average speed (1000 pilgrims): 115 cm/s
Fastest Time to complete 7 rounds: 10.35 minutes
Slowest Time to complete 7 rounds: 50 minutes
Average Time (1000 pilgrims): 21 minutes

This test run shows that a pilgrim takes an average of 21 minutes to complete circumambulating the Ka'aba.

Method 2. Undirected situation

Another simulation was designed to study the circumambulation of the Ka'aba without the spiral design. The drawing of the basic structure of Ka'aba (Figure 4) is taken from Pedestrian Movement at Tawaf [4]. In this simulation, waiting areas were placed in certain areas to guide the pedestrian to walk 7 rounds around the Ka'aba. This method requires plotting of many waiting points. Thus the waiting points are needed to be plotted carefully so that the pedestrians would move in the correct direction and in a circular motion. The closer the waiting points are set; the circular motion of pedestrians is more accurate. The waiting time is set to be 0 seconds as the waiting areas are placed as a guide for the pedestrian to walk around Ka'aba. For simplicity, the entrance into the Tawaf area is limited to one only.

Figure 4: Plotting of Waiting Points



Test run:

a) Test run: 090108123215
Number of agents: 1000
Average speed: 137 ± 37 cm/s
Fastest Time to complete 7 rounds: 21.9 minutes
Slowest Time to complete 7 rounds: 88 minutes
Average Time (1000 pilgrims): 35 minutes

This test run shows that the average time to circumambulate the Ka'aba is 35 minutes. This shows that pedestrians take longer to complete the ritual compared to the Method 1.

3.2. Results and Discussion

Figure 5: The time taken by pilgrims to circumambulate the Ka'aba

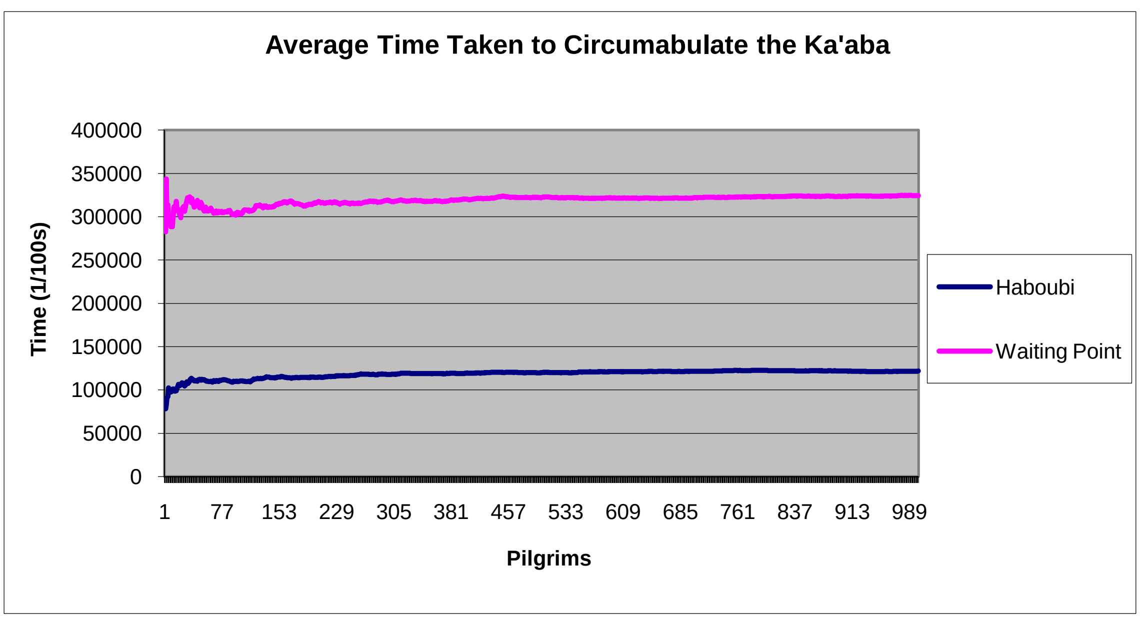


Figure 5 shows the time taken for the pilgrims to complete the Tawaf. For both methods, it can be seen that at the beginning, the average time taken is oscillatory, then stays almost constant as the number of pilgrims increases up to 1000. This is understandable if we take into account that the density in the system remains almost constant over the course of time since there is a balance between the number of pilgrims entering and leaving the system. From this figure, we can see that the spiral path allows pilgrims to complete the circumambulation faster. This is due to the fact that the path taken by the pilgrims was restricted by a predetermined lane which is the spiral path, disallowing them to change lanes. This crucial feature of the spiral path has contributed to the following advantages:

1) The interactions amongst the pilgrims have been in the lowest degree.
2) The uncontrolled operation of the Tawaf activity is replaced by a one-way operation which eliminates cross paths and problems by counter flows.
3) Bottlenecks are reduced as pilgrims who have completed the Tawaf are separated from those who have just arrived.

In contrast, in Method 2, the open area encouraged pilgrims to move freely. On one hand, due to the different characteristics of the pilgrims and the available unrestricted area, some of them prefer to perform the Tawaf in the already congested areas of attraction points, while others prefer to perform it in the middle area or the outer edge to avoid the high density caused by the pilgrims. For this reason, a high percentage of collisions would occur amongst the pilgrims, which in turn, would cause a huge amount of hindrances and delays. On the other hand, the pilgrims who have completed the Tawaf and were in the centre of the Tawaf area or near Ka'aba would move out to perform another ritual such as Alsa'y. Without a proper exit in the open area, pilgrims would tend to jostle their way out through the crowd causing a massive amount of cross paths and counter flows. Similarly, the same hindrances and delays would be caused. Bearing in mind that the simulator is based on the SFM which has the capability of representing interactions between individuals, the above discussions justifies the increase in the time taken to circumambulate the Ka'aba.

Figure 6: Average Pilgrim's Speed

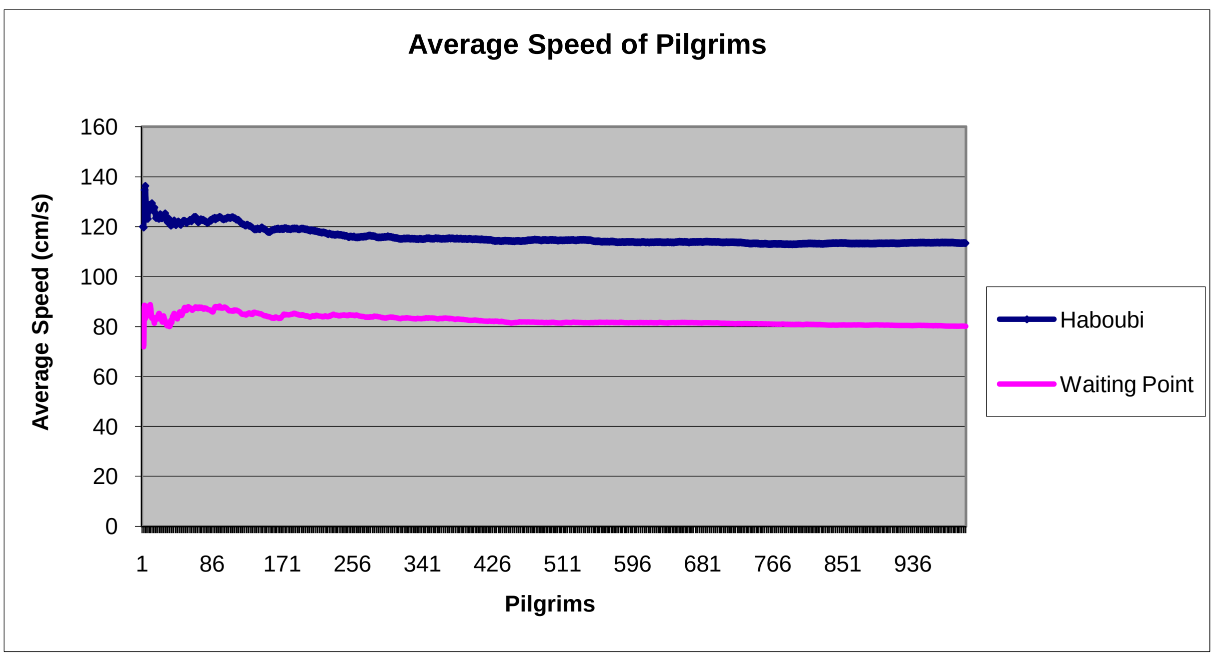


Figure 6 shows the pilgrims' average speed as a function of the number of pilgrims. Similarly, for both methods, in the beginning, the average speed of the pedestrians is oscillatory, then, it remains almost constant as the number of pilgrims increases up to 1000. Again, this is due to the fact that the density stays almost constant as the number of pilgrims entering is balanced by the number of pilgrims leaving the Tawaf area. It can be observed that the average speed of pilgrims in the Haboubi method is greater than the average speed of pedestrians in the Waiting Point method since the directed movement and controlled flow of the crowd in the spiral path allows the pilgrims to move faster. In contrast, the free movement of pilgrims in the open area allows unlimited collisions, cross paths and problems by counter flows occurring, hence, slowing down the average speed of pilgrims.

4. Conclusions

We have presented the governing equations for the Social Force Model. We have made a comparison between various kinds of microscopic pedestrian simulation models, highlighting the advantages as well as the disadvantages of each model. We have briefly discussed the computer simulation software SimWalk and also looked into one of the applications of SimWalk which is simulating the circumambulation of Ka’aba. We have implemented two possible studies in circumambulating the Ka’aba: the first is the method from the study of Haboubi [5] which suggests building a spiral path with panels to circumambulate the Ka’aba while the second method is by plotting waiting points around Ka’aba which directs pilgrims to walk around Ka’aba without building any panels.

Results from the simulations show that building the spiral path is effective in ensuring the smooth flow, a comfortable and safe condition during the circumambulation of the Ka’aba. However, many adjustments have to be done if we would want to implement this spiral path within Ka’aba. The first would be designing a proper exit for the pilgrims after they completed the 7 rounds. A suggestion by Haboubi [5] was to build an underground tunnel for the pilgrims to move out of the Tawaf area. However this method may not be realistic to implement as the underground tunnel entails additional costs and there may be some historical items hidden below the Tawaf area as this is a holy place for the Muslims. Thus, other alternative methods, such as building an overhead bridge that links the centre of the Tawaf area to the exit of the mosques can be considered.

Further work is to be done to gain better insights into the crowd dynamics of pilgrims during Tawaf. Crowd phenomena like lane formation, ‘faster is slower’ effect, herding, just to name a few, still needs to be studied in the context of the crowd in the Tawaf area. Furthermore, extensions would include the study of the effect of incorporation of realistic situations like bottlenecks at entrances and uneven utilization of doors to the crowd dynamics during Tawaf. It is hoped that a better understanding of the crowd dynamics of pilgrims at the Tawaf area can shed some light on the proposal of practical and effective mitigation measures in order to improve the flow of the crowd at the Tawaf area.

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References

[1] K. Teknomo, Microscopic Pedestrian Flow Characteristics: Development of an Image Processing Data Collection and Simulation Model, *Ph.D. Dissertation, Tohoku University*, Japan (2002)

[2] D. Helbing, I.J. Farkas, P. Molnar, T. Vicsek. Simulation of Pedestrian Crowds in Normal and Evacuation Situations *Pedestrian and evacuation dynamics, edited by M. Schreckenberg and S. Deo Sarma*, 21-58. Berlin: Springer-Verlag. (2002)

[3] Stucki, Pascal, Christian Gloor, and Prof. Kai Nagel. Obstacles in Pedestrian Simulations. *Department of Computer Sciences, ETH Zurich*, [September 2003]

[4] Y.T. Matbouli, M.A. Alzahrani, Pedestrian Movement Analysis at Tawaf, *King AbdulAziz University*.

[5] M.H. AlHaboubi, S.Z. Selim, A Design To Minimize Congestion Around The Ka'aba, *Pergamom-Elsevier Science LTD, Computers Industrial Engineering*; pp: 419-428; Vol: 32 (1997)

[6] D.Helbing, L. Bunza, A. Johansson, T. Werner, Self-Organized Pedestrian Crowd Dynamics: Experiments, Simulations, and Design Solutions, *Transport Science*, pp. 1-24; Vol 39(1) (2005)

[7] D. Helbing, A. Johansson, J. Mathiesen, M.H. Jensen and A. Hansen Analytical approach to continuous and intermittent bottleneck flows. *Physical Review Letters* 97, 168001 (2006)

[8] [Wenjian Yu, A. Johansson Modeling crowd turbulence by many-particle simulations. *Physical Review E*, Vol. 76, No. 4. (2007)

[9] Taras I. Lakoba, D. J. Kaup and Neal M. Finkelstein Modifications of the Helbing-Molnar-Farkas-Vicsek SFM for Pedestrian Evolution, *Simulation*, 81, 339-352 (2005)

[10] Fazilah Haron and Zarita Zainuddin A Preliminary Study of the Crowd at the Tawaf Area, *National Seminar on Hajj Best Practices*, (28-30 Mei 2007)