Towards a Digital Makkah – Using Immersive 3D Environments to Train and Prepare Pilgrims

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1 Abstract

Due to its unique position in Islam, Makkah arguably draws more interest and attention from more people than any other city of the world. In this paper, we describe our ongoing effort to design a digital model of the core area of Makkah. We describe a crowd simulation engine that simulates tens to hundreds of thousands of pilgrims at interactive update rates. This engine also provides tools to guide crowd motion to analyze the effects of architectural changes and evacuation plans. Our framework can be used both to provide engaging tutorials on the Hajj or the Umrah, e.g. in immersive environments or videos, and to assist decision makers in solving logistic and organizatorial challenges.

By using digital media to systematically gather, process, and display all information relevant to the pilgrimages to Makkah, we furthermore foster the understanding of non-muslims for the Islamic faith. The last point is important, since the seclusion of the Holy area of Makkah for sacred purposes is often misinterpreted by non-adepts as being occult or exclusionary.

Keywords: Interactive virtual environments, Digital reconstruction and 3D modeling, Virtual cultural heritage.

1 Introduction

To over a billion people worldwide Makkah is the holiest city on earth. One of the five pillars of Islam is performing the pilgrimage (Hajj [حج]) to Makkah, if able, and it is thus every Muslim's aspiration to visit Makkah at least once in his or her life. Furthermore, it is desirable to perform Umrah [عمرة], the lesser pilgrimage. While Hajj can only be performed in the time from the 8th to the 13th day of the month Dhu'l-Hijja, the Umrah can be performed any time, but it is desirable to do so during the month of Ramadan. Annually, more than two million Muslims attend the Hajj, while the Umrah is performed by even more pilgrims.

This huge influx of pilgrims has the potential to cause great logistical and organizational difficulties, and with Islam being one of the fastest growing religions, these problems will surely become more acute in the future.

In this paper, we describe our ongoing effort to design a digital model of the core area of Makkah not only to train and prepare pilgrims, but also to assist decision makers in their task to solve the logistic and organizational challenges during Hajj. Digital media offers an ideal means to systematically gather, process, and display all information necessary to achieve the aforementioned goals.

In the following section, we will describe the background and purpose of our project, in which we focus on the Tawaf [طواف] and the Sa'i [سعى], two central rituals in both the Hajj and the Umrah. In Section 3, we will describe how our 3D model of the Holy Mosque was generated (also see Fig. 1 left). Section 4 describes our crowd simulation and guidance engine that is used to understand the complex and dense crowd flow during Hajj (also see Fig. 1 right). It furthermore allows decision makers to see how planned restructuring such as the planned architectural changes will affect the crowd patterns. In Section 5, we describe how our Visualization Lab can be used to aid planning commissions or how guided training sessions can be given to guests. We finally conclude with directions for future research.

Figure 1. Right: Screenshots of our model of Al-Masjed al-Haram [المسجد الحر ام] and Al-Ka`bah [الكعبة]. Left: Screenshot of the crowd simulation and guidance engine showing 100,000 pilgrims at a campsite.

2 Background and Purpose

In this section we give an overview of the significance and history of the Hajj and we will motivate why tools that simulate the experience of a real Hajj are beneficiary to *augment*—not replace—the pilgrimage.

2.1 The Hajj according to Islamic Tradition

"Hajj (pilgrimage to Makkah) to the House (the Ka'bah) is a duty that mankind owes to Allâh, those who can afford the expenses (for one's conveyance, provision and residence); and whoever disbelieves [i.e. denies Hajj (pilgrimage to Makkah), then he is a disbeliever of Allâh], then Allâh stands not in need of any of the 'Âlamîn (mankind, jinn and all that exists)." (Al-Hilali & Khan, 1996, Surah 3,97) The Qur'an clearly states that the Hajj is a mandatory obligation to Allâh as long as sufficient material means are available. It is therefore that the Hajj is performed by millions of muslims each year, all visiting Makkah within a 6 day period (8th Dhu'l-Hijjah to 13th Dhu'l-Hijjah).

The Hajj commemorates the story of Allâh's messenger Ibrahim (Abraham), peace be upon him (pbuh), as it is described in both the Holy Qur'an (Al-Hilali & Khan, 1996) and the book Genesis of the bible (King James Version). A second aspect is added by rituals that reenact the messenger Mohammad's (pbuh) Hajj in 631 AD (10 AH). According to Islamic tradition, Ibrahim (pbuh) is a Hanîf [حـ ن يف], a practitioner of monotheism (Surah 2,135), and he proclaims his new faith against the will of his father and his people (Surah 21,52—70). He is also revered for building the Ka'bah (Surah 2,127) to be the first house of worship for Allâh in the spot in which he camped with Isma'il (Ishmael, pbuh) and Hajar (Hagar) in Makkah as per Allâh's command.

Ibrahim (pbuh) was married to Sarah, and because of their advanced ages they were unable to conceive (King James Bible, Gen 11:29—30). Allâh granted Ibrahim (pbuh) a vision in which He commanded him to take Hajar, an Egyptian servant, to be his wife. Hajar gave birth to Isma'il (pbuh), the direct ancestor of Allâh's messenger Muhammad (pbuh). Allâh then granted Ibrahim (pbuh) another vision commanding him to take Hajar and her infant child to today's Makkah, which at that time was a barren desert (Surah 14,37). Ibrahim (pbuh) did as commanded and left Hajar and child in the desert. When mother and child ran out of water, Hajar frantically searched for water or help, running back and forth. She climbed the two nearby hills of As-Safa and Al-Marwah repeatedly, but still could not find water. After she climbed the hills seven times, the Archangel Jibril (Gabriel, pbuh) appeared and touched the ground with his heel. In that spot a well, known today as Zamzam, miraculously appeared to save mother and child.

The spot where Hajar and Isma'il (pbuh) camped in Makkah is known as Al-Hijr, and part of it has been rebuilt throughout history, forming a small arc in front of the Ka'bah. Immediately next to this spot, Ibrahim (pbuh) and Isma'il (pbuh) rebuilt the Ka’bah after the first two—one built by the angels and one by Adam—had been lost. The stone on which he stood is called Maqam Ibrahim [مقام إبراهيم] (the station of Ibrahim), and shows Ibrahim’s (pbuh) footprints. Pilgrims to Makkah are to pray two rak’ahat here after the Tawaf [طواف], the circumambulation of the Ka’bah. The search for water and the miraculous saving of Hajar and Isma’il (pbuh) is the basis for an important ritual of the Hajj and the Umrah called the Sa’i [سعى], during which pilgrims walk between As-Safa and Al-Marwah (today part of Al-Masjed Al-Haram) seven times. Also, the Sa’i marks the end of the Umrah at which it is desirable to drink Zamzam water.

2.2 The Hajj Today

Prior to Mohammad’s (pbuh) Hajj, the Hajj had been performed by believers of a multitude of religions, to commemorate the story of Ibrahim and his covenants to Allâh. The first Muslim-only Hajj took place in 631 AD (10 AH), when the messenger Muhammad (pbuh) and his followers performed the pilgrimage. Muhammad (pbuh) cleansed the Ka’bah and removed the many idols that were contained inside. Since that time, it has been officially impossible for non-Muslims to perform the Hajj.

It is commonly believed that the Hajj dates back to the times of Ibrahim, which is sometimes estimated to be 2000 BC. While this date is disputed, it is clear that the Hajj is a very old ceremony that fosters unity and humility in the pilgrim community and has highly beneficial social effects beyond the Muslim community world-wide, as pilgrims return with an increased “belief in peace, harmony and equality among adherents of different religions” (Clingingsmith, Khawaja & Kremer, 2008).

This unity is not only expressed by the uniform clothing of the pilgrims, but also in the pre-Hajj gathering at the traditional gathering points (Miqat) and the Tawaf, the circumambulation of the Ka’bah. In this paper we focus on the Tawaf and the Sa’i for their importance during the Hajj. Also, these two rituals involve extremely dense moving crowds (more than 6 people per square meter), a challenge for both crowd simulation and visualization.

The number of Hajj attendees has generally increased (see also Fig. 2) during the last decade, resulting in about 2.5 million pilgrims in 2009 (Royal Embassy of Saudi Arabia, 1996—2010), of which 154,000 were Saudi pilgrims, 1,613,000 where foreign, and an estimated 753,000 pilgrims were without valid permits. In 2010, this number has further increased to 2.8 million pilgrims. Reasons for this increase in Hajj pilgrims may be that the number of Muslims in the world is increasing, or an overall increase in wealth combined with a “shrinking” of the world due to novel traveling options that allow more and more Muslims to fulfill this pillar of Islam. The hypothesis of growing wealth and Saudi Arabia’s accessibility is further supported by Fig. 3 which shows the number of foreign pilgrims between 1345 AH (1927 AD) and 1430 AH (2009 AD). The strongest

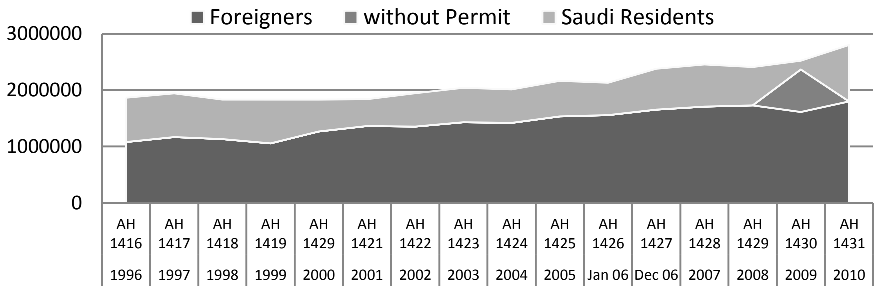

Figure 2. Number of Hajj attendants from AH 1416 to AH 1431 according to the Royal Embassy of Saudi Arabia (1996—2010) and the Islamic Society of East Bay (2010). Numbers for pilgrims without permit are only available for 2009.

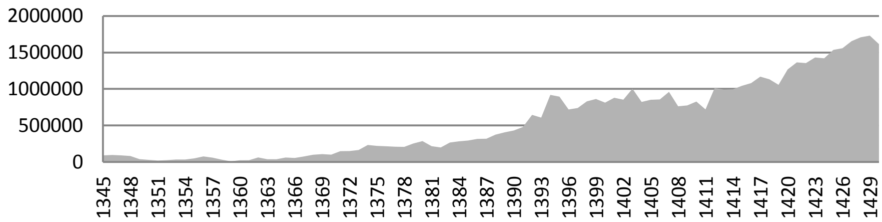

Figure 3. Number of foreign pilgrims from 1345 AH (1927 AD) to 1430 AH (2009 AD) according to the Islamic Society of East Bay (2010).

increase of foreign pilgrims occurs during the reign of King Faisal bin Abdul Aziz Al Saud from 1383 AH to 1395 AH who stabilized Saudi Arabia's financial situation and modernized the country. Since the Hajj can only be performed between the 8^{th} and the 13^{th} of Dhu'l-Hijjah, these 2.5 million pilgrims will perform most of the rituals synchronously, occupying the currently 356,800 square meters of Al-Masjed Al-Haram.

It is clear that such a huge crowd requires a high sophistication in crowd control and security measurements. Although the Government of the Kingdom of Saudi Arabia is constantly increasing the security and also regulates the number of admitted pilgrims, incidents cannot be completely prevented. Most of the incidents occurred during the stoning of the devil ritual (Feb. 11, 2004: 251 pilgrims killed and another 244 injured; Jan 12, 2006: at least 346 pilgrims killed and at least 289 more injured). Other incidents are related to pilgrims not being prepared for the physical demand of the pilgrimage, such as in December 2006, when 243 pilgrims died because of heart-related problems and exhaustion (iol, 2006). While the first type of incidents (stampedes) can be prevented using crowd control, the second type can be prevented by careful preparation. Clearly, crowd control can only be successful if the crowd flow during Tawaf and Sa'i is understood.

The methods outlined in this paper are still under active research, but once fully developed can be used to educate and train pilgrims. While such a virtual experience cannot—and never should—replace the physical experience, it can augment the Hajj, e.g. by preparing pilgrims for the extremely high crowd densities, or by granting an unobstructed view to important sites of the Hajj. Similar to training videos shown in airplanes to guide people through the next airport, instructional videos on the Hajj can be offered on airplanes or beforehand. Such training will gain even more importance in the future, due to the steadily increasing number of foreign pilgrims. These pilgrims may need additional guidance about precise locations, especially since the Government of the Kingdom of Saudi Arabia is actively investigating the possibility of restructuring and extending the Holy Site around the Masjed Al-Haram in order to allow significantly more pilgrims per year. This is motivated by the fact that there are 1.3 billion people of the Islamic faith world-wide. Were they all to perform the Hajj once in a 60 year timespan, the average number of pilgrims in Makkah during the Hajj would be more than 20 million per year. With the recent advent of ubiquitous internet connection, such instructional tutorials and videos could also be taken abroad, thereby further augmenting the benefit of the current TV live-broadcast of the Hajj.

3 Digital Modeling

In this section we detail our efforts to model a precise digital 3D representation of Al-Masjed Al-Haram and its surroundings to be used in educational sessions and crowd simulations. Precision is of utmost importance since only with precise models crowd simulation has any connections to reality.

3.1 Initial Model of Al-Masjed Al-Haram

There is a wide variety of 3D models of the Holy Mosque available on the internet, but none of these models meet our precision requirements. The reason is that standard approaches to automatically obtain high precision models, i.e. exhaustive laser scanning and photogrammetry, cannot be used due to religious reasons. We therefore started with a model from http://www.3dkabah.com, we converted it to the obj format using Polytrans and imported the model into Autodesk Maya for further clean up and improvement.

The model had most of the flaws a human-modeled 3D object can exhibit, such as double-sided faces, coinciding planes, objects placed in wrong locations, missing textures, etc. While some of these flaws will be immediately obvious, such as misplaced objects and missing textures, others such as the coinciding planes will cause severe artifacts during real-time exploration on contemporary graphics adapters (Z-fighting due to the limited precision of the Z buffer). The original model is shown in Fig. 4.

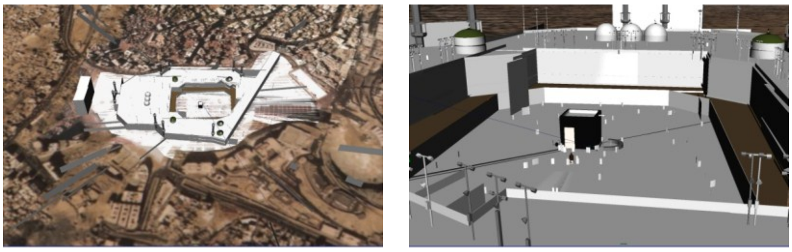

Figure 4. Screenshots of the model from http://www.3dkabah.com

3.2 Improvements of the 3D model

We first cleaned the model thoroughly and fixed the aforementioned problems. Then, we modeled more of the colonnades of the mosque using the initially available colonnades of the 3dkabah.com model as a starting point. We furthermore adjusted the size and position of columns according to 2D close up photographs. Then, we added textures obtained from photographs and we placed the model on a digital elevation map with a spatial resolution of 90m from NASA SRTM data. This elevation map was triangulated and textured using satellite pictures from Google Earth. Note that this is an ad-hoc solution for academic purposes only; aerial pictures are less common in the public domain than elevation data and we are currently negotiating the use of higher resolution, pre-registered images. Figure 5 shows the improved 3D model.

Our current model fulfills basic precision requirements in so far as it ensures functionality and performance of the described crowd simulation system. It can be loaded into our interactive visualization environment in order to be displayed using stereoscopic views.

Figure 5. Screenshots of our improved 3D model. Right: Overview of the empty Masjed al-Haram. Right: Close up of the Ka’abah with Al-Hijr to the right (small stone arc) and Maqam Ibrahim in the front. The black line on the ground to the left marks the start of the Tawaf.

In the future we would like to further increase its detail to the scale of a couple of centimeters to provide virtual walk-throughs. To do so, we are currently negotiating the use of official blue prints and architectural design templates. Furthermore, we would like to annotate the model for use in non-guided tours such as home-studies or pre-recorded movies.

4 Crowd Simulation

In this section we describe our crowd simulation and guidance framework. The purpose of this framework is twofold. Firstly, by comparing simulation results to real video footage, the rules according to which humans move can be analysed and understood. Secondly, once the results of the simulation have been validated, they can be generalized to other situations where direct measurement of the crowd flow is expensive (e.g. due to the number of humans involved) or impossible (e.g. crowd behaviour for architecture that is still in the planning phase). We present a crowd simulation framework that can simulate very large numbers of autonomous agents at high speed. By utilizing latest multi-core processor technology, the response time during crowd planning and guidance is considerably reduced, thereby enabling real-time interaction for about 25,000 agents in complex environments.

Since a full review of existing crowd simulations is beyond the scope of this paper, we refer the reader to Pelechano, Allbeck & Badler (2008).

4.1 Multi-Agent Systems and Collision Avoidance

Our framework implements a multi-agent system (Reynolds, 1987), as most contemporary crowd simulation frameworks do. Such systems represent each individual in a crowd by an abstract entity, called an *agent*. This agent then pursues the goals of the associated individual.

Since all agents pursue their potentially contradicting goals at the same time, they compete in the simulation for the best result for their respective client. Although goals may be very different, all agents are bound by a fixed set of rules. For a crowd simulation engine, the most important of these rules is that of collision avoidance. Any two agents are not only forbidden to collide, but they must actively seek to prevent such collision. This collision avoidance problem can be shown to have exponential complexity in the number of agents or their degrees of freedom (LaValle, 2006), making a precise solution infeasible due to the implied computational cost. We therefore use a fast approximation that generally yields excellent results and is extremely fast. This approximation is called *P-Clearpath* (Guy, Chhugani, et al., 2009), a parallelized extension of velocity obstacles (Fiorini & Shiller, 1998).

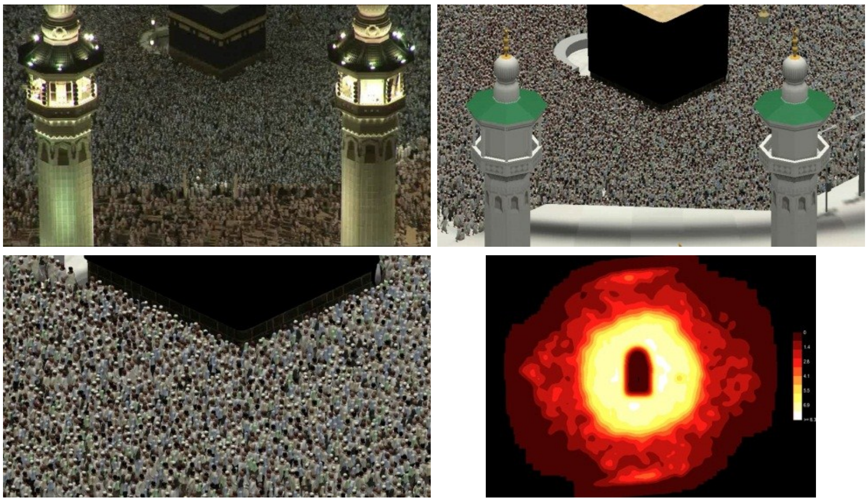

Figure 6. Top: A comparison between footage of the Hajj (left) and our crowd simulation during Tawaf using a simplified model of Al-Masjed Al-Haram. Bottom: Close-up of the simulation (left) and crowd density plot. Images and movies are available thru (Guy, Curtis, et al., 2010).

P-Clearpath computes regions of potential obstructions between an agent and its nearest neighbors. These regions are then avoided by changing the velocity of the involved agent. The result is a visually smooth collision avoidance behaviour between the agents that requires only linear time in the number of agents to compute. Furthermore, it parallelizes exceptionally well since all agents essentially perform the same set of operations (data-parallelism). As a result, P-Clearpath can run the simulation depicted in Fig. 6 with 25,000 pilgrims at about 5-10 updates per second on a single off-the-shelf PC with a quad-core CPU. Due to its data-parallelism, P-Clearpath scales well to higher numbers of cores. Therefore, more complex simulations are possible in real-time as well, albeit at a potentially higher hardware cost.

4.2 Least Effort Goals

Once such a collision avoidance is available, the agents' goals still need to be defined. Clearly, the goal of each agent during Tawaf is to circumambulate the Ka'bah at a certain speed, then move to Maqam Ibrahim to pray two rak'ahat. It is recommended for men to start the circumambulation with four slower rounds at a greater distance to the Ka'bah before spiralling closer and to perform the remaining three rounds at a heightened pace. During the closer rounds it is desirable to touch the black stone in each round (Navdi, 1995). Therefore, the goal of each agent changes with time and although many agents share the same goal, the resultant crowd has very heterogeneous goals. A significant amount of agents even strives for zero velocity while their clients offer prayers at Maqam Ibrahim.

In contrast, the goals of the pilgrims during Sa'i change less continuously each time they reach either As-Safa or Al-Marwah. This makes agents' goals during the Sa'i a lot more homogeneous than during the Tawaf.

As recognized first by Zipf (1949), people try to minimize their effort along their trajectory. The basic essence of this principle of least effort (PLE) is that humans choose to move through the environment to their goals using the least amount of efforts, i.e. by minimizing the time, cost, congestion, or the change of velocity of their trajectory. The least effort formulation has already influenced the design of some recent crowd modeling systems (Still, 2000; Karamiuzas, Heil, et al. 2009; Sarmady, Haron & Hj, 2009). However, it is hard to extend these methods to simulate large crowds with thousands of agents. We use the algorithm of Guy, Chuggani, et al. (2010) for our framework, which is an optimization-based algorithm to generate energy-efficient trajectories based on a bio-mechanical metric. This algorithm follows two principles in terms of computing the trajectories. Firstly, it takes the shortest available route to the destination; and, secondly, it attempts to move agents at their preferred speed.

The performance of the overall algorithm has been tested in different scenarios and also compared by many of the prior crowd simulation methods. Furthermore, the resulting trajectories have been compared with prior data collected on real humans and a close match was observed.

However, we currently only consider paths with no altitude changes, since PLE rules for such changes are not yet available. In the future, the travel of the pilgrims to Mount Arafat poses therefore an interesting challenge that we would like to analyse.

4.3 Crowd Steering and Navigation Fields

In our system, crowd steering can be performed in two ways. The user either places an obstacle into the scene and agents have to find new ways around this obstacle. This can be done in real-time and interactively and is an indispensable tool in the planning of architectural changes. Alternatively, the user can specify a guidance field (vector field) from which a globally smooth *navigation field* is computed (Patil, van den Berg, et al., 2009). This navigation field then changes the goals of agents to follow this field. This method of steering crowds is extremely useful to study the effect of stampedes by assigning strongly different goals to a group of pilgrims.

An analysis of the 2006 incident at the Jamarat bridge suggests that *crowd turbulence* (Helbing, Johansson, & Al-Abideen, 2007) may be suited well to model and understand stampedes. Crowd turbulence basically consists of an initial, steady crowd flow. As the crowd becomes denser, the rate of flow decreases and may undergo an abrupt transition into a stop-and-go motion propagating like waves along the direction of travel. The third and very dangerous stage that may follow is then characterized by clusters of peoples moving randomly into all possible directions. This phenomenon is a very interesting challenge to research in the future, as it is not yet clear how to integrate it properly into a crowd simulation.

4.4 Crowd Visualization

It is clear that the interactive visualization of extremely large crowds requires specialized algorithms that avoid rendering millions of entities at their full resolution. Harnessing recent advances in GPU (graphics processing unit) technology allows to display animated pilgrims using *geometry instancing* (Dudash, 2007). Similar to the old Hollywood trick to copy and paste multiple copies of the same group of people to form large crowds, geometry instancing renders a small set of models multiple times while providing a unique set of parameters for each model. Parameters may include position, orientation, etc. The psychological and perceptual implications (i.e. “Clone Attack!”) are subject to active research (McDonnell, Larkin, et al., 2008).

Still, geometry instancing alone is not sufficient to render such extremely dense crowds. However, once the observer is in the crowd, the crowd density actually becomes a benefit. In this case it suffices to render only a few hundred entities that are closest to the observer. Overhead views, on the other hand, pose a completely different challenge, since millions of entities have to be displayed, yet the resolution can be drastically decreased up to the point where the visualization can be performed via a GPU-based particle system (Kipfer, Segal, & Westermann, 2004; Krüger, Kipfer, et al., 2005).

The transition phase of an observer moving from an overhead view into the crowd is the hardest part and we are currently investigating strategies for this case. Initial experiments lead us to believe that a hybrid system involving both triangulated models at various levels-of-detail (Larkin, Paris, et al., 2010) and billboards might be suited best to cope with the challenge of rendering more than 2 million pilgrims.

5 Visualization Environment and Usage Scenarios

In this section we describe the KAUST Visualization Laboratory, which is a high-end visualization environment run by the Visualization Core Lab. It is an ideal test bed for all visualization purposes and fit to present the results of our research to a broad audience of people.

5.1 CORNEA

The lab features a fully immersive 3D virtual reality environment, CORNEA, which is an advanced version of the original four-sided immersive environments developed in the early 1990s. CORNEA is now the brightest and highestresolution CAVE environment in the world, and one of only two six-sided installations in the world to employ 24 digital projectors each with 4K resolution to create 100 million pixels of stereoscopic 3D visual information. CORNEA is also the first research environment to offer the integrated sound spatialization and variable virtual acoustics of Meyer Sound Matrix3 and Constellation.

Each side of the CORNEA cube is ten feet (three meters) across, and the environment can accommodate up to eight researchers or visitors at a time.

For the CORNEA audio system, 20 loudspeakers are mounted 18 inches outside the room and point into it. These loudspeakers provide audio support of visualizations. Miniature microphones inside the sonic environment pick up sounds for Constellation processing. They also pick up discussions and commentary from scientists to be monitored in the other facilities and recorded for archiving purposes.

5.2 Multipurpose Room (MPR)

With seating for up to 75, the Multipurpose Room (MPR) serves as the Visualization Laboratory's principal space for larger group meetings and intensive collaborative research sessions.

The front wall of the MPR is dominated by a 10'×20' Mechdyne PowerWall™ which employs eight Sony 4K projectors to provide a 32 million pixel stereoscopic 3D display. A ninth "utility" projector is used for 2D videoconferencing and presentation applications. Three large plasma screens are mounted on side walls for additional imaging option. HD cameras and wireless microphones are available for videoconferencing sessions.

Extensive, high-speed fiber optic lines interlink the MPR with the central computer cluster, the CORNEA environment, the Recording and Control Room and the main development room. The MPR can tap 51 potential sources, and distribute 31 of them out of the MPR to other visualization systems. For audio spatialization and acoustical enhancement, the MPR provides a fully immersive sonic environment as implemented through Meyer Sound's Matrix3 and Constellation technologies.

5.3 Showcase Systems

Furthermore, the Visualization Lab maintains a so-called *showcase*. It is intended to be an ad-hoc visualization lab where people walk in, grab a wireless tablet and start visualizing their data either from USB drives or their network-attached storage. Among other equipment, the showcase contains the following two visualization spaces.

NexCAVE is a scalable, modular 3D environment. As implemented at KAUST, it is configured as a 21-tile system using JVC X-pol video screens for visualization elements. Meyer Sound MM-4XP loudspeakers and a UMS-1P subwoofer provide surround sound. (see Fig. 7 for a photograph of the setup)

AESOP is a 40-tile display featuring 52” NEC narrow bezel panels that enable large scale, near-seamless HD images without use of projection.

5.4 Usage Scenarios

Planning. The 6-sided CAVE environment (CORNEA) is used, for planning and development of the Makkah region and the Masjed Al-Haram itself. A typical scenario would involve the planning commissioner and his team stepping into the fully interactive and immersive environment inside CORNEA. The research team would enable the visual display of information, including the terrain, urban landscape surrounding the mosque, and the Grand Mosque itself. Different layers of information such as roads, accommodation facilities, Hajj camp sites, etc. can be provided to the planning team. The planning commissioner and his team would then virtually implement different strategies for developing the area. 3D virtual buildings can be erected, terrain can be modified, roads can be planned and they can be visually perceived, analyzed, discussed and recorded as well. Modalities of interaction include touch-tablets (iPads etc.) and the gyro-mouse.

Training. A combination of CORNEA and MPR can be used to train volunteers and pilgrims alike on the Haj experience. A high-speed interconnect between the two spaces enables real-time streaming of content from the CORNEA onto the high-resolution MPR screen, while preserving the 3D stereoscopic effect. The MPR space can accommodate up to 75 people at a time, each wearing active 3D shutter glasses for a stereoscopic effect. An operator in CORNEA can lecture and navigate in and around the Masjed Al-Haram area, while the audience in the MPR can hear and see the operator, as well as visualize the navigational walk-through from the CORNEA on the high-resolution screen.

Figure 7. Our model of the Masjid al-Haram on the NexCAVE. Stereo was disabled for this picture, actual screen brightness is higher than apparent in this picture.

This provides a unique setup to train and familiarize individuals with the area. The sound equipment in the room adds to the realism by simulating the acoustical properties of the environment within the Masjed Al-Haram.

Interactive Crowd Control Disaster Prevention. The high-resolution 2D display wall (AESOP) is perfectly suited to simulate and visualize a very dense crowd of pilgrims in the mosque area. Users are able to direct crowd flow, simulate disaster response scenarios, and study the effect of changes in landscape and construction on the Hajj experience for the pilgrims. The simulation can also be visualized in our NexCAVE/CORNEA environments, providing a more convincing experience and feedback to the user.

6 Discussion and Future Work

Our first results are very promising as attested by the many visitors we have presented the project to in our visualization facilities. We are currently negotiating further support by authorities of the Kingdom of Saudi Arabia and hope to be soon able to improve our data accuracy and presentations.

In the future, we would like to properly account for changes in elevation in our crowd simulation and analysis framework to further extend the usability of this project. Furthermore, we will investigate the use of clustered GPUs (graphics processing units) to further accelerate the crowd simulation framework aiming at the ultimate goal, the interactive real-time simulation of more than 2.5 million pilgrims performing Tawaf and Sa’i.

7 Conclusion

We have presented our ongoing efforts to design a framework that can be used both for the education and training of Hajj and Umrah pilgrims as well as for the planning stage of the imminent restructuring of the area around Al-Masjed Al-Haram in Makkah. We described three crucial parts of this project, namely the modeling of the area around the Holy mosque including the mosque itself, a simulation and analyzation framework for pilgrims performing the Tawaf and the Sa’i, and we discussed the presentation of this data using the KAUST Visualization Laboratory.

Although more work needs to be done, our initial feedback from visitors to our visualization showroom indicate that the project is generally well received since the Hajj is not only the fifth pillar of the Islamic faith, but also a corner stone of the Saudi Arabian culture and tradition. Visitors from the region attested us that it is not only an important step towards the education of pilgrims but also offers possibilities in the documentation of the history of Makkah.

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