Crowd and procession hypothesis testing for large-scale archaeological sites

1st Kristin Chow
Computer and Information Science
University of Pennsylvania
kchow@seas.upenn.edu

2rd Aline Normoyle
Computer Science
Swarthmore College
alinen@cs.swarthmore.edu

3nd Jeanette Nicewinter
Art History
Northern Virginia Community College
jnicewinter@nvcc.edu

4th Clark L. Erickson
Anthropology
University of Pennsylvania
cerickso@sas.upenn.edu

5th Norman I. Badler
Computer and Information Science
University of Pennsylvania
badler@seas.upenn.edu

***Abstract*—Our goal is to construct parameterized, spatially and temporally situated simulations of large-scale public ceremonies. Especially in pre-historic contexts, these activities lack precise records and must be hypothesized from material remains, documentary sources, and cultural context. Given the number of possible variables, we are building a computational system SPACES (Spatialized Performance And Ceremonial Event Simulations), that rapidly creates variations that may be both visually (qualitatively) and quantitatively assessed. Of particular interest are processional movements of crowds through a large-scale, navigationally complex, and semantically meaningful site, while exhibiting individual contextual emotional, performative, and ceremonially realistic behaviors.**

***Index Terms*—virtual reality, crowd simulation, crowd authoring, processions, archaeology, anthropology**

I. Introduction

Human history is often defined in terms of aperiodic, catastrophic, or confrontational events that disrupt populations, cultural development, or governance. At the other extreme, the daily life of individuals is largely anonymous and driven by survival, social role, and community. In between, however, are periodic, large-scale group events such as celebrations, pilgrimages, rituals, or theater. For many prehistoric societies, the ceremonial complex where such events occurred was the center of the world, or *axis mundi* of the cosmos, writ small as an architectural microcosm that was specially built for this purpose [1]. Today, much of the original scope, structures, usage, and phenomenology (e.g., the human experience of space) has been lost. Archaeologists and anthropologists attempt to reconstruct this phenomenology by synthesizing diverse sources, such as written accounts, unearthed artifacts, viewsheds, soundscapes, and archaeoastronomy. Beyond the pure phenomenological experience lies a presumed underlying narrative or purpose of a ceremonial complex: the social context or "story" that motivates constructing such spaces in the first place. Who were the people who used these spaces? How did the participants themselves experience the scope, intent, and emotional impact of public ceremonies, rituals, and celebrations? Through virtual and augmented reality, we can communicate the most likely hypotheses to others in a way that induces "cultural presence" [2]. What better way to experience the ethos of a bygone culture than by being embedded in its most public ceremonial practices?

We describe the requirements for and approaches to a system capable of simulating various human aspects of such public ceremonies and rituals called SPACES (Spatialized Performance And Ceremonial Event Simulations). To ground SPACES in an actual context, we base our experiments in the large-scale pre-Columbian Incan site of Pachacamac, located adjacent to modern Lima, Peru [3]. In particular, we are interested in the interaction between notable, unique events, such as processions and performances along with the daily routines that would have comprised baseline activities. Thus, our crowds require specific movement structures as well as localized and location-specific behaviors and emotions. Furthermore, crowds must be appropriately dressed and use a variety of instruments, icons, and objects as appropriate to the ceremony or performance. Such requirements are not typically addressed by usual crowd simulations which prioritize path finding, steering, collision avoidance, and goal achievement. Rather, what the individuals do becomes significant in rendering multiple possible realistic reconstructions of the hypothesized human utilization of a space.

Processions, in particular, have structure and goals that must combine individual behaviors and overall group goals. Processions require parameters that describe formation (single-file, pairs, rough groups, etc.), semantically-relevant behaviors along the route (dancing, singing, music production, parading of significant icons, etc.), and group emotion or performances (somber, joyous, reverent, distraught (funeral processions), etc.; see [4]). There is also evidence based on contemporary examples of processions that ancient peoples may have made (days) long treks from their homes to the communal center, may have participated in "line-dance" celebrations, traveled to pilgrimage sites of religious importance, and (presumably) queued for various activities such as food distribution, personal hygiene, animal management, entry to and exit from theaters,

978-1-7281-5604-0/19/$31.00 ©2019 IEEE
DOI 10.1109/AIVR.2019.00069

dances, and other spectacles, and conferring of items or blessings by religious personnel (e.g., analogous to taking holy communion). Ceremonial processions frequently have participants carrying items of ritual significance, playing instruments, and walking, dancing, or marching along a prescribed path [5].

The goal of SPACES is to construct parameterized, spatially and temporally situated, virtual simulations of large-scale public ceremonies. The activities at Pachacamac lack precise records and must be hypothesized from material (artifactual, spatial, architectural, and geophysical) remains, documentary sources from more recent times, and cultural context. Given the number of possible variables, SPACES must allow users to rapidly create variations that may be both visually (qualitatively) and quantitatively assessed. This approach is fundamentally different from a singular "movie reconstruction", as explorations of numerous alternatives may be needed to determine the most probable, or most compatible with the existing evidence.

Although crowd simulation using computer graphics is well developed, the bulk of the effort has been directed toward important but relatively low-level control issues such as navigation through a space, collision avoidance with obstacles and other people, and realism in trajectory choices [6]. The organization of "higher-level" aspects of crowd movement is frequently left to user discretion, artistic decisions, or other creative goals [7]. For example, the Menge [8] framework simulates pedestrians using customizable components that allow a programmer to tailor it to a specific "high-level" domain. For specific built environments, crowd simulations produce traffic simulation, egress/ingress flow assessments, and emergency evacuation studies (e.g., Cassol et al. [9]). These simulations often are unconcerned with the motivations, activities and roles of the individual participants, as they focus on pedestrian movement efficiencies. Our vision for SPACES centers on hypothesized human activities in built environments. While passage from place to place, navigation, and collision avoidance are important, our focus requires us to be flexible about which specific activities occurred, where they occurred, how long they lasted, and basic human physiology needs (motivations and/or desires) that necessarily affect or alter behaviors.

Large-scale public ceremonies often take place in multiple heterogeneous activity areas such as plays or spectacles on stages or platforms; eating and drinking places; ceremonial loci including altars, oracles, baths, sacrificial wells, residences of deities, power objects; and so on. Such heterotopia [10] may support behavior types and distributions that vary considerably across the ceremonial complex and sharply contrast with the everyday mundane and profane world. While games may contain animated non-player characters controlled through pre-determined scripted behaviors or rule-based reactions to user avatars or game moves, developers often program such behaviors to form plausible background characters rather than interactive or accurate portrayal of ceremonial events. Clear exceptions are sport simulations, where team behaviors are tied to player actions and the rules of the game, and warfare genres where the player often leads the activities of a much larger group or army of followers. The appearance of multiple heterotopia, in which "otherworldly" places overturn conventional normality, in games is rare because games typically fall into a distinct interactive genre such as role-playing, quests, warfare, or simulated evolution.

Considerable literature on 3D modeling and animation of virtual humans in cultural contexts exists, e.g., Senecal et al. [11]. Approaches to context-sensitive human activity simulation include: activities dependent on rules or events [12], semantics embedded in the environment [13]–[15], smart events [16], behavior trees [17], and interactive storyboards [18]. For example, Maim et al. [13] use semantic environment annotations help agents navigate to specific doors or regions whereas Sung et al. [14] uses them to select behaviors in a region. Allbeck's CAROSA system [15] provides semantic tags on places and activity probabilities in areas, as well as adding overall agent schedules and opportunistic behaviors. A seminal work in modeling queues provides important empirical background data for single file processions [19].

II. Simulation components

The major components of SPACES are:

- A 3D terrain from topographical datasets, geo-referenced for solar, lunar, and planetary alignments, viewshed (line-of-sight) assessments, and natural illumination.
- 3D models representing the known architecture, e.g., plazas, altars, walled compounds.
- 3D models representing hypothesized buildings and spaces, based on precise maps of standing architecture, archaeological excavations, knowledge of cultural architectural and site planning practices, and comparison to better-preserved examples.
- Sources for human-controlled illuminants such as bonfires, hearths, torches, doors, and windows.
- Static and dynamic sound sources, such as voices, music, instruments, noisemakers, dance and footsteps, animal sounds, and ambient noise (wind, ocean waves).
- "Social logic" of space based on architectural mapping and terrain: doors, gates, paths, passageways, corridors, streets, and avenues; Restrictions to navigation may also be affected by class, status, age, or gender.
- Functions of spaces based on archaeological evidence or analogy to cross-cultural evidence, such as human vs. animal occupancy; storage, performance, or audience areas; approximate occupancy limits; or timing/scheduling of use throughout the year.
- Approximate numbers of performers, participants and/or audience; occupancy time, arrival and departure frequency or rate limits defined by entry/exit constraints.
- Known or assumed human activities: essential (working, eating, drinking, defecation, sleeping); passive ceremonial (watching performances); active ceremonial (dancing, marching, singing, sacrificing, carrying sacred objects or offerings, theatrical performance, musical performance);

supportive (cooking, brewing, serving, delivering, unloading, and storing supplies, maintenance, cleanup, and waste removal, policing, guarding).
- Scheduling and duration of events, as probability distributions, for the human activities noted above.
- Rates of movement speed for animals and humans, dependent on activity (to determine transition times from place to place); possible queuing (waiting) times will arise from the simulation itself.
- Population diversity (males, females, children, animals) and any constraints on them (e.g., keep family units together, separate males and females, segregate children, sequester animals, etc.).

Since much of this data is speculative, SPACES requires a robust simulation engine and data rich environment that:

- Provides the essential phenomenology to experience place, space, landscape, and ceremonies in real-time;
- Provides a flexible user interface to set parameters, tags, and distributions relevant to the event and context, by spatial extent and time, and respectful of activity tags, social categories, or other tagged information;
- Provides a crowd movement algorithm that uses the constraints to move agents through and between spaces on the hypothesized schedule and travel routes while producing realistic travel times, queuing behaviors, crowd formation, animal husbandry, and family unit coherence;
- Provides real-time graphics of the 3D model of the ceremonial complex and surrounding landscape via a modern game engine, such as Unreal [20];
- Provides a customizable set of metrics to assess quantitative measures for the simulation as defined by subject-matter experts (archaeologists, anthropologists, historians, geographers, and psychologists);
- Provides an automated procedure to vary inputs across parameter variants, with or without graphics visualization, to facilitate locating local minima/maxima with respect to one or more of these evaluation metrics.

III. Pachacamac: People and Places

We ground SPACES in the specific ceremonial and pilgrimage activities from the ancient site of Pachacamac. Details are obtained from a combination of mapping, GIS, excavations, artifacts, eyewitness accounts (from conquistadors and other ethnohistorical sources), and scholarly accounts about modern Andean pilgrimage, oracles, and festivals. Based on these sources, we can hypothesize about the mix of activities and people at Pachacamac in ancient times (See Table I).

We assume that a substantial population lived full time at Pachacamac (e.g., priests, Aclla, cooks, administrators, royal families of the coast, servants, guards, artisans, farmers, and others). We also assume that many people lived here part-time or for short periods of time (e.g., caravan drivers, rotating groups of laborers for construction and maintenance, visiting dignitaries, pilgrims, and others). During the Inca empire, many people were taken from their communities and worked their lives serving the Inca state and religion. For example,

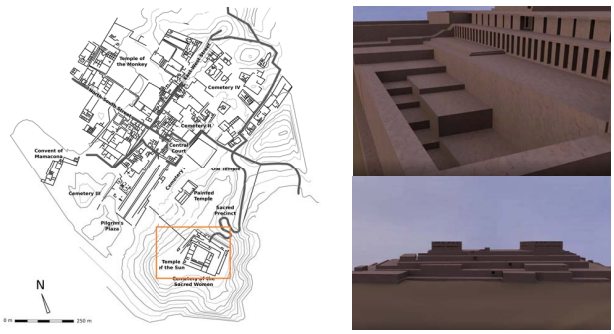

Fig. 1. Digital reconstructions. Left. the location of the sun temple in Pachacamac. Site map is based on [22]–[24]. Right. Two views of the sun temple, visualized in Unreal Engine.

the Mitmaq were entire groups of people brought by the Inca to perform municipal tasks and the Mit'a were corvee labor given as tribute to the Inca state. Acllas, or "Chosen Women", were sequestered women by the Inca state who served the Sun Temple (Table I).

Pachacamac has tens of thousands of rooms, but we do not know the function of each. We assume that open "public" spaces were used for rituals with larger audiences and participation. The so-called Pilgrims Plaza is the best example (see Fig. 2). The Aclla would have lived and slept in the Convent of Mamacona (Fig. 3) and worked there or in the Sun Temple (Fig. 1). Large areas between the two walls north of the center of the site are unexplored but limited excavation has shown areas of artisans (metalworkers, potters, and weavers).

Our approach to such crowd simulation combines macroscopic authoring based on roles, activities, and locations (similar to [21]). For example, we can specify distributions of people performing various activities throughout the day. These heterogeneous crowd motions can be authored interactively and subject to user-specified spatial and temporal localization constraints. These high-level behaviors can then be combined with detailed, localized behaviors which are embedded in the environment, similar to [12], [15], [16]. Detailed behaviors can correspond to either daily life activities or important unique events, such as ceremonies and processions. This agent behavior architecture enables background and principal agents to interact, for agents to oscillate between passive observers and active participants, and to support a mixture of specific, important events alongside ambient behaviors. Furthermore, the simulation can run at multiple time-scales, supporting festivals which might last days, weeks, or months, and can support level-of-detail so that agents out of view need not be simulated with high-detail.

IV. Discussion

Animating the human occupants of a large-scale pre-historic archaeological site requires a flexible and expressive simulation system for trying, viewing, and evaluating many alternative hypotheses of use and function. Rather than producing a single "finished" animated movie, the SPACES project seeks to emphasize parametric exploration of anthropological possibilities. In particular, contextualized human behaviors appropriate

Role	Tasks	Locations
Pilgrims	participated in festivals, carried/interned dead; gave offerings, visited oracle	Pilgrim's plaza, cemeteries, temple complex
Priests	receive offerings, rituals, fasting, consult oracle	Pachacamac temple complex, Sun Temple
Guards	guard sacred precincts	Pachacamac temple complex, Sun Temple
Acllas	Prepare high status textiles, participate in rituals, prepare special bread, brew chicha	convent, Sun Temple
Fishermen	fishing, transporting goods	Pacific coast, on-site distribution
Mitmaq/Mit'a	Making adobe bricks; Building/maintaining temple walls	off-site, temples
Painters	Mix paints, paint walls	off-site, temples
Field Laborers	Tilled fields, tended irrigation systems, harvested crops, transported food to storehouses	off-site, on-site distribution

TABLE I
EXAMPLES OF PEOPLE AND ACTIVITIES OF PACHACAMAC

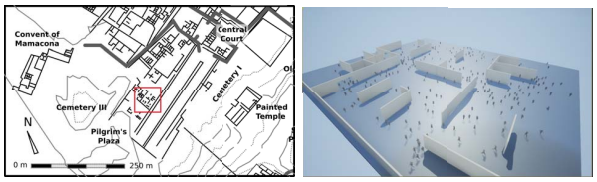

Fig. 2. Pilgrim's Plaza. Left. Location of the Pilgrim's Plaza. Right. A recreation of the smaller inset's floor plan, with a proof of concept crowd simulation in Unreal Engine.

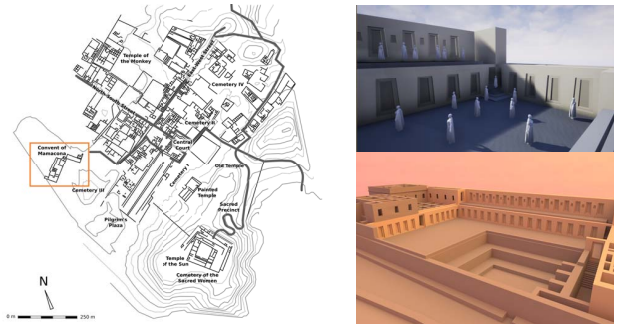

Fig. 3. Convent of Mamacona, the "House of Chosen Women". Left. Location of the convent. Right. Digital reconstructions in Unreal Engine (top) and Maya(bottom).

to large gatherings, ceremonies, and celebrations leads to our particular emphasis on processions. Within a particular procession, individual movements, sounds, carried items, and emotional content must visually characterize the intent and attitude of the participants. Pachacamac presents an excellent case study for elaborating these requirements for meaningful, organized, and hypothesis-driven crowd simulations.

ACKNOWLEDGMENTS

We wish to thank the Center for Undergraduate Research and Fellowships (CURF). We also thank Susan Xie, Adam Malley, and Yifan You for their work creating digital assets.

REFERENCES

[1] L. A. Coben, *Archaeology of performance: theaters of power, community, and politics*. Rowman Altamira, 2006.
[2] D. Villani, C. Repetto, P. Cipresso, and G. Riva, "May I experience more presence in doing the same thing in virtual reality than in reality? an answer from a simulated job interview," *Interacting with Computers*, vol. 24, no. 4, pp. 265–272, 2012.
[3] M. Uhle and I. Shimada, *Pachacamac: A Reprint of the 1903 edition*. University Museum of Archaeology and Anthropology, University of Pennsylvania, 1903.
[4] F. Durupinar, U. Gudukbay, A. Aman, and N. Badler, "Psychological parameters for crowd simulation: From audiences to mobs," *IEEE Transactions on Visualization and Computer Graphics*, vol. 22, no. 9, pp. 2145–2159, September 2016.
[5] J. D. Moore, "'The Indians were much given to their Taquis': drumming and generative categories in ancient andean funerary processions," *Archaeology of performance: Theaters of power, community, and politics*, p. 47, 2006.
[6] N. Pelechano, J. M. Allbeck, M. Kapadia, and N. I. Badler, *Simulating heterogeneous crowds with interactive behaviors*. CRC Press, 2016.
[7] P. Kanyuk, "Virtual crowds in film and narrative media," *Simulating Heterogeneous Crowds with Interactive Behaviors*, p. 217, 2016.
[8] S. Curtis, A. Best, and D. Manocha, "Menge: A modular framework for simulating crowd movement," *Collective Dynamics*, vol. 1, pp. 1–40, 2016.
[9] V. J. Cassol, S. R. Musse, C. R. Jung, and N. I. Badler, *Simulating Crowds in Egress Scenarios*. Springer, 2017.
[10] M. Foucault, *The order of things: An archaeology of the human sciences (1st American ed.)*. New York: Pantheon Books, 1971.
[11] S. Sénécal, N. Cadi, M. Arévalo, and N. Magnenat-Thalmann, "Modelling life through time: cultural heritage case studies," in *Mixed Reality and Gamification for Cultural Heritage*. Springer, 2017, pp. 395–419.
[12] B. Ulicny and D. Thalmann, "Towards interactive real-time crowd behavior simulation," in *Computer Graphics Forum*, vol. 21, no. 4. Wiley Online Library, 2002, pp. 767–775.
[13] J. Maim, S. Haegler, B. Yersin, P. Mueller, D. Thalmann, and L. V. Gool, "Populating ancient Pompeii with crowds of virtual romans," in *VAST: International Symposium on Virtual Reality, Archaeology and Intelligent Cultural Heritage*, 2007.
[14] M. Sung, M. Gleicher, and S. Chenney, "Scalable behaviors for crowd simulation," *Computer Graphics Forum*, vol. 23, no. 3, 2004.
[15] M. Kapadia, N. Pelechano, J. Allbeck, and N. Badler, *Virtual Crowds: Steps Toward Behavioral Realism*. Morgan & Claypool, 2015.
[16] C. Stocker, L. Sun, P. Huang, W. Qin, J. M. Allbeck, and N. I. Badler, "Smart events and primed agents," in *IVA: International conference on Intelligent Virtual Agents*. Springer, 2010, pp. 15–27.
[17] A. Shoulson, N. Marshak, M. Kapadia, and N. I. Badler, "Adapt: the agent developmentand prototyping testbed," *IEEE Transactions on Visualization and Computer Graphics*, vol. 20, no. 7, pp. 1035–1047, 2013.
[18] M. Kapadia, S. Frey, A. Shoulson, R. W. Sumner, and M. H. Gross, "Canvas: computer-assisted narrative animation synthesis." in *SCA: Symposium on Computer Animation*, 2016, pp. 199–209.
[19] S. Lemercier, A. Jelic, R. Kulpa, J. Hua, J. Fehrenbach, P. Degond, C. Appert-Rolland, S. Donikian, and J. Pettre, "Realistic following behaviors for crowd simulation," in *Eurographics*, vol. 31, no. 2, 2012.
[20] https://www.unrealengine.com, "Unreal Engine 4," accessed September 30, 2019.
[21] A. Normoyle, M. Likhachev, and A. Safonova, "Stochastic activity authoring with direct user control," in *i3D: Symposium on Interactive 3D Graphics and Games*, 2014, pp. 31–38.
[22] G. Matsumoto, "Pachacamac GIS Project: A practical application of geographic information systems and remote sensing techniques in andean archaeology," Master's thesis, Southern Illinois University at Carbondale, 2005.
[23] P. Eeckhout, "Change and permanency on the coast of ancient peru: The religious site of pachacamac," *World Archaeology*, 2013.
[24] D. Pozzi-Escot, Ed., *Pachacamac: EL Oráculo en el horizonte marino del sol poniente*. Banco Central del Perú, Lima, 2018.