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Agent-Based Modeling in Historical Settings

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Graz, May 2018

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Abstract

The ability to visualize and interact with known concepts in new ways has always been important for the process of discovery in science. Not only to renew interest in already known and well-researched fields, but also to discover new aspects and develop different perspectives on an already established knowledge base. For archeology and the application of virtual environments, the purpose of a digital recreation of a historical site, on the basis of factual archeological evidence, is not only to preserve cultural heritage but also to help advance the research done in the field of archeology. There have always been certain historical uncertainties and unknowns. A visualization and simulation of an archeological virtual environment can support the evaluation of academic hypotheses about these historical uncertainties. The inclusion of virtual humans in an archeological virtual environment and the simulation of human interaction and behavior are therefore crucial for understanding historical events, certain mannerisms, and behaviors, and also increase the immersion that such an environment generates.

In this work, the design for an algorithm to simulated variable human behavior is presented, that can be used by archeologists, and applied to different archeological virtual experiences. This algorithm uses an agent-based modeling approach, that calculates the basic agent behavior at runtime, and exposes parametric behavior variables to the user in an easy to use fashion.

The deployment of this algorithm is demonstrated in two separate historical simulations.

To test the usability, immersion, and the potential research value of the these simulations, a study with archeologists was conducted. The results of this first study are promising. Participants felt very curious about the simulations, and thought that the simulations were easy to use. They also noticed some issues and many articulated ideas for possible improvements. The potential research value of these simulations was clearly recognized by the target group.

This work is a showcase for the potential of agent-based modeling in historical settings, and the developed human behavior algorithm is an appropriate and promising tool for the use in virtual environments in the field of archeology.

Kurzfassung

Die Fähigkeit, bekannte Konzepte auf neue Weise zu visualisieren und mit ihnen zu interagieren, war immer ein wichtiger Prozess in der Wissenschaft. Nicht nur, um das Interesse an bereits bekannten und gut erforschten Bereichen zu erhöhen, sondern auch um neue Aspekte zu entdecken, und unterschiedliche Perspektiven auf eine bereits etablierte Wissensbasis zu entwickeln. Der Einsatz von virtuellen Umgebungen in der Archäologie, dient nicht nur dem Erhalt eines kulturellen Erbes durch den digitalen Nachbau von historischen Stätten, sondern auch der Forschung selbst. Es gab immer gewisse historische Unsicherheiten und Ungewissheiten. Eine Visualisierung einer auf archäologischen Fakten basierenden virtuellen Umgebung, kann die Analyse von wissenschaftlichen Hypothesen über diese historischen Unsicherheiten unterstützen. Die Einbeziehung virtueller Menschen in eine solche Umgebung, und die Simulation von menschlicher Interaktion und menschlichem Verhalten können dazu beitragen, ein grundlegendes Verständnis über historischer Ereignisse und menschliche Verhaltensweisen zu vermitteln, und die Glaubhaftigkeit einer solchen Umgebung wesentlich verbessern.

In dieser Arbeit wird der Entwurf eines Algorithmus zur Simulation von parametrisch veränderbaren menschlichem Verhalten vorgestellt, der von Archäologen verwendet und auf verschiedene archäologische virtuelle Umgebungen angewendet werden kann. Dieser Algorithmus verwendet

einen agentenbasierten Modellierungsansatz, der das Verhalten eine menschlichen Agenten zur Laufzeit einer Simulation berechnet, und einem Benutzer verhaltensverändernde Variablen auf einfache Weise zur Verfügung stellt. Der Einsatz dieses Algorithmus wird in zwei unterschiedlichen historischen Simulationen demonstriert.

Um die Benutzerfreundlichkeit und den potenziellen Wert der Simulationen für archäologische Forschung zu testen, wurde eine Studie mit Archäologen durchgeführt. Die Ergebnisse dieser ersten Studie sind vielversprechend. Die Teilnehmer erklärten, dass sie die Simulationen sehr neugierig machten, und dass die Simulationen einfach zu handhaben waren. Sie bemerkten auch einige Probleme und viele artikulierten Ideen für mögliche Verbesserungen. Der potenzielle Wert dieser Simulationen für archäologische Forschung wurde von der Zielgruppe klar erkannt.

Diese Arbeit ist ein Beispiel für das Potenzial von agentenbasierter Modellierung in historischen Umgebungen, und der entwickelte Algorithmus ein geeignetes und vielversprechendes Werkzeug für den Einsatz in virtuelle Umgebungen im Bereich der Archäologie.

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Finally, I want to thank my family and friends for their unwavering support throughout this work. Without their love, continuous patience and motivation, none of this would have been possible. I especially want to thanks my 3½-year-old son Heinz, for understanding and supporting me during the process of writing this work, even if I could not always play with him when he wanted me to.

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1 Introduction

The ability to visualize and interact with known concepts in new ways has always been important for the process of discovery in science. Not only to renew interest in already known and well-researched fields, but also to discover new aspects and develop different perspectives on an already established knowledge base. Today digitalization and virtual environments are used in a variety of scientific fields. Medicine (Galas & Hood, 2009), education (Pirker, 2013; Wilding, 2015) and archeology (Pavlidis, Koutsoudis, Arnaoutoglou, Tsioukas, & Chamzas, 2006; Sanders, 2013) are only a few examples of scientific areas where digitalization and virtualization are gaining influence and starting to impact the future direction of their respective fields and scientific study. The possible impact and advantages of virtual environments in medical applications for example, was recognized very early on (considering the major advances of virtual environment and virtual reality technologies over the last decade) for the important role these technologies could play in health care. Already in 2003 considered application of those technologies were numeral. Riva (2003) recognized several possible application of virtual environments and virtual reality, for example for medical education or surgical simulation and planning. Today this trend continues in other medical fields like radiology, where computational biology and imaging informatics are major trends in the digitalization of medical imaging (Li et al., 2013).

Further examples for the use and impact of digitalization and virtual environments can be found in education and in the way people use and learn through these technologies. One of the major strengths of a virtual environment is arguably the visualization itself and the immersion it generates, which is an important factor in natural sciences like chemistry or physic, where the ability to visualize and manipulate three-dimensional objects and scenes can be very helpful (Trindade, Fiolhais, & Almeida, 2002). Although it is important to note that students usually learn more if the method of instruction matches their own style of learning, which means that students with a high spatial aptitude tend to acquire a better conceptual understanding than those without it. Nevertheless, learning approaches that emphasize the interactive use of three-dimensional visualizations to enhance the conceptual understanding of different topics are gaining popularity with students and can help reach different pedagogical objectives (Pirker, 2013).

When it comes to the field of archeology and the application of virtual environments therein, it can be argued that one of the main contributions of digitalization has been the use of different methods of three-dimensional reconstruction or recreation of archeological objects, artifacts, buildings, landscapes and sites of the past (Fdez, 2017; Hermoza & Sipiran, 2009; Noh & Sunar, 2009; Teichmann, 2010). Still existing or not, but nevertheless known thanks to archeological or different historical (and even artistic) sources, these reconstructions or recreations serve not only to visualize the past but also to better understand it. In relevant literature the term used to describe these reconstructions, and the methods used to develop them, is called *virtual archeology* (Reilly, 1991; Rigby, Melaney, & Rigby, 2014; Virtual Archeology, 1990). Although it is a definite necessity to build and recreate historical scenes on the basis of factual archeological evidence (Beacham, Denard, & Niccolucci, 2006; Beacham, Niccolucci, Denard, &

et al., 2009), there are always certain historical uncertainties and unknowns. As an extension of the concept of virtual archeology, projects have been evolving to go beyond the reconstruction of architecture or artifacts: human interaction with the environment and therefore the modeling and simulation of virtual crowds, is also an important part of the ongoing research (Sequeira, Morgado, & Pires, 2014). This is why simulations of autonomous agents and their behavior are also becoming a part of the techniques and methods that are employed by historians and archeologists.

Simulating a historical scene or heritage site and the human population that inhabited it accurately, is certainly the first step, but beyond the visualization and simulation of an already known set of fact-based historical conditions, a parameter-driven approach can provide additional utility. A parameter-driven crowd simulation, composed of autonomous agents, that is based on archeological and historical data, where certain hypothesized situations can be tested and evaluated, can help to contrast known and unknown historical data and therefore provide a new perspective on the past. This is why within the framework of this work the main goal will be the simulation of two historical scenarios within a virtual environment, that are populated by a virtual crowd, comprised of a number of single, parameter controlled agents. In the next section the motivation and additional goals for the simulation of these agents are discussed in more detail.

1.1 Goals and Motivation

Within the scope of this thesis, the main contribution are:

1. the design and implementation of an agent-based crowd simulation algorithm, that is applicable to different historical scenes, for the pur-

pose of testing archeological hypotheses, through the visualization of scenario dependent historical uncertainties. This algorithm simulates and supports a variable sized crowd of agents that:

- can traverse flat ground and stairs, both at variable speeds
- can avoid certain obstacles
- are animated during traversal of different surfaces
- can reach their predetermined goal and show situation depended behavior
- can deviate from their predetermined goal if so inclined

2. the design, implementation and evaluation of two historical scenarios (Pnyx and Marketplace), that apply that algorithm to drive a human behavior simulation

These two historical simulations also expose different, changeable parameters at runtime, for example:

- walking and animation speed
- behavior depicted through different animations
- number of animations for specific behaviors
- the ability to vote
- time for lingering at points of interest
- chance for lingering at point of interest

The purpose for this is to give a user or researcher the ability to evaluate certain assumption and hypotheses about these historical scenarios. The target audience of these simulations are mainly archeologists and students but also museum visitors. Special emphasis is on the creation of a user-friendly environment and an easy to use input method for all simulation parameters. This is especially important because ease of use helps to increase the participation when it comes to the adoption of these simulations (e.g. for the use in a virtual reality application in a museum). It is also important that the underlying algorithm used in these simulations is flexible and adaptable enough so that it can be used by archeologists without the need or necessity for advanced programming skills.

1.2 Structure

This thesis is essentially structured into four different parts: (1) related work, (2) design, (3) implementation, and (4) evaluation. An overview of the structure and the iterative approach for the design and implementation part of this work can be found in Figure 1.1.

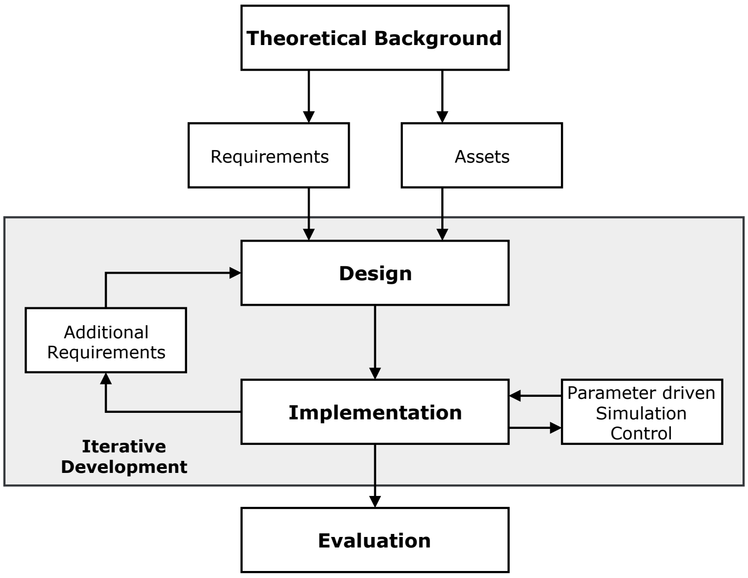


Figure 1.1: Structure of this work: theoretical background, requirements and assets as the basis for the iterative approach for the design and implementation of the simulations. The last part features the evaluation of the simulations

Chapter 2 focuses on related work, digitalization, and virtual environments in archeology, different approaches on how to simulate virtual agents within these environments, and different methods for building and developing believable crowd behavior. In Chapter 3, the design of two simulations that integrate an agent-based algorithm is discussed. The chapter focuses on the requirements and design decisions regarding the placement, movement and control mechanism of a single agent, and includes thoughts on the implications this has on a simulated crowd as a whole. An architectural overview of the project will also be presented. Chapter 4 looks at the implementation of this project, discusses certain scripts and code details. This also includes a short overview of implementation details for the behavior algorithm and the changes that had to be made to apply the algorithm to two different simulation scenarios. Moreover, possible future improvements are mentioned. In Chapter 5, the findings of the evaluation that was conducted, and the feedback that was gathered, are discussed. Methodology, participants, and procedure will be described and the results presented. Chapter 6 will give a short overview of the lessons that were learned during the span of this work, Chapter 7 present ideas for possible future work, and Chapter 8 will give a conclusion of this work.

2 Background and Related Work

Several authors describe subjects that deal with digitalization and virtual environments in archeology, or aspects of cultural heritage by means of simulating historical data, either as a way to showcase no longer existing sites and artifacts (Hermoza & Sipiran, 2009; Noh & Sunar, 2009; Teichmann, 2010), or to teach and educate about certain aspects of history (Clark et al., 2002). The first major part of this chapter will give a short overview of how archeology uses digitalization to scan and build virtual representations of historical artifacts and sites. This includes a introduction on photogrammetry and an example of a three-dimensional research methodology in archeology. Additional sections will take a deeper look at virtual environments in archeology. The focus will be on how virtual environments are built, and how they help to set the stage for the simulation of human elements. Furthermore, a short look at how museums realize the potential of these new technologies for the development of edutainment content and services for their visitors will be given. The major second part of this related work chapter will look at concepts of crowd behavior modeling and different approaches and methodologies that are used in the simulation of humans in historical settings. This part will emphasize what goals archeologists and historians have (and what methods they employ), when they fill virtual environments (based on archeological data) with appropriate agents. And how their behavior and certain elements of human interaction, impact the immersion that comes from the inclusion of the visualization of virtual human agents. An overview of this chapter can be found in Figure 2.1.

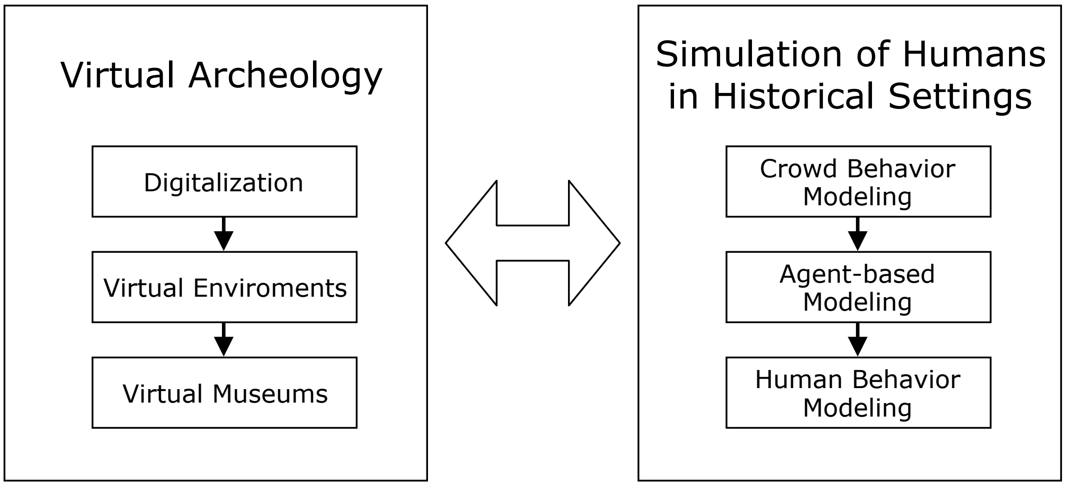


Figure 2.1: Overview of the two main parts of this chapter

2.1 Virtual Archeology

The term virtual archeology was first introduced by Paul Reilly (Reilly, 1991; Virtual Archeology, 1990), in 1990. As a computer scientist and archeologist Reilly used this term to describe the use of computer-based simulations of archeological excavations. Reilly discussed two possibilities: visualizing with the help of a computer, the total amount of data obtained from the fieldwork, and using the technologies applied in the computer games production for scientific goals. But the implications and the definition of the term have changed since then, as stated by Hookk (2014) *"time has gone; many applied sciences introduced computer technologies, and the possibility to unify and accumulate, to analyze and to demonstrate data appeared"*. Hookk goes on to explain that today almost all scientific research in the field of archeology supposes the application of computers and digital technologies and comes to the conclusions that *"since the time of Paul Reilly's definition, the meaning of the term virtual transformed from imaginary to existing in our understanding"*. And although nowadays, the term is predominantly associated with the use of three-dimensional computer graphics or geophysical data imaging for archeological research (Reilly, 2015) the main characteristics of virtual archeology can be summarized (Hookk, 2014) as the use of computer technologies for:

- archeological prospection
- archeological data processing
- archeological modeling
- archeological and historical reconstructions
- visualization of the results of all of the above

Since virtual archeology spans a variety of subjects, only the most important ones for the conceptional understanding of digitalization and development of archeological virtual environments will be discussed. In general, the recording and visualizing of cultural heritage is a multidimensional process (Pavlidis et al., 2006). And although five main processes can be identified in digital recording (these processes are shown graphically in Figure 2.2) the main focus of the next sections will be on the first and fourth part of this processes, which are *digitization in three dimensions* and *visualization and dissemination of three-dimensional data*. This includes how archeological data is used to build virtual representations of heritage sites and historical scenes, and furthermore how museums are adapting to these new possibilities.

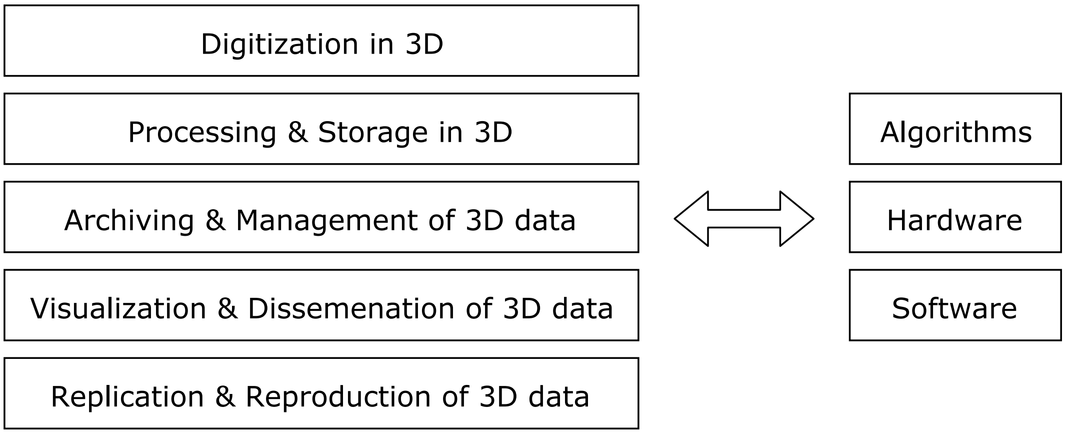


Figure 2.2: Recording of cultural heritage: five main processes of digital recording from Raykovska, Bevan, and Vasiliev (2015)

2.1.1 Digitalization

Since the last two decades digitalization has influenced almost all sciences (Hilbert & Lopez, 2011), archeology being only one of the fields of study affected by this trend (Evans & Daly, 2006). Interestingly, research in this domain was mainly led by computer scientists, who focused on optimizing realism of three-dimensional digital representations of artifacts or monuments (Mueller, Vereenooghe, Vergauwen, Gool, & Waelkens, 2017). Or the use of virtual archeology for educational purposes (Sanders, 1999), leading to the popularization of three-dimensional modeling and virtual environments as means to disseminate cultural heritage. That is why a charter for the computer-based visualization of cultural heritage has been proposed (Beacham et al., 2009), whose main purpose is to *"establish internationally-recognized principles for the use of computer-based visualization by researchers, educators and cultural heritage organizations"*, as a set of guidelines for the scientific community. One of the implicit reasons for these guidelines concerns the validity of the use of three-dimensional modeling as a valid approach for solving challenging research questions in archeology. One of the main technologies for three-dimensional modeling in archeology is photogrammetry. This will be discussed in the next section.

Photogrammetry

With the advent of high-resolution digital cameras and fast, multi-core computers, photogrammetry has rapidly become one of the standard documentation techniques in archeology and architecture (Raykovska, Bevan, & Vasiliev, 2015), and published case studies that use photogrammetry abound (Baptista, 2013; Giuliano, 2014; Harrower et al., 2014; Martínez, Ortiz, Gil, & Rego, 2013; Spring & Peters, 2014). The fundamental features that have made photogrammetry obviously more attractive over similar three-dimensional recording techniques are, as stated in Doneus et al. (2011) and Reu et al. (2013):

- high accuracy
- low cost
- ease of use
- fundamentally a image-based 3D recording technique

The last item is important because it means that models can be stored as two-dimensional image sets, thereby making archiving and monitoring data integrity more intuitive. If three-dimensional data is required, images can be matched and geometry generated through pattern matching and other techniques (Hermoza & Sipiran, 2009), but there is no requirement that any project has to be stored as anything other than images with the associated metadata. Also, an important advantage is that because the interior orientation (distortion characteristics) and exterior orientation (camera position and pose) are known, the images used for photogrammetry can be used for other types of measurement as well. Additional features that are identified in these photos can easily be mapped into real-world coordinates. This last point is very important when addressing the challenge of integrating different forms of data into one digital reconstruction of a building or archeological site (F. Remondino & Rizzi, 2010; Remondino, Spera, Nocerino, Menna, & Nex, 2014). A good example of this technology, how it is implemented and the implications it has, is demonstrated in a paper from Raykovska et al. (2015), where the process of photogrammetry (as seen in Figure 2.3 and Figure 2.4) and the inherent technical challenges are well documented.

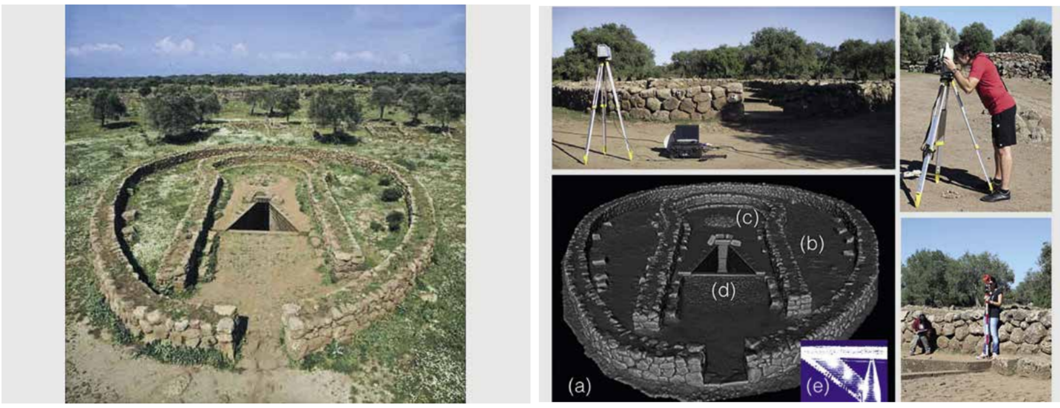
(a) (b)

Figure 2.3: Photogrammetry in progress as depicted in Raykovska, Bevan, and Vasiliev (2015), (a) the apse of the St. Petka Church, (b) the west wall of the St. Petka Church

In this paper from Raykovska et al. (2015), the photogrammetric process is demonstrated and shows that computational photographic techniques can produce a three-dimensional end product that, in most cases, exceeds manual recording techniques. Raykovska et al. (2015) also mention that one of the most important advantages was that the whole recording process did take less than two weeks and was done with volunteers that had almost no training in photography. Another good example of photogram-

Figure 2.4: Medium density, colored point cloud of the St. Petka Church from Raykovska, Bevan, and Vasiliev (2015)

metry can be found in this attempt by Hermon and Niccolucci (2015), to set the foundation for a three-dimensional based research methodology in archeology. This work by Hermon and Niccolucci details theoretical and implementation aspects of such a research methodology through a concrete case study. This case study not only emphasizes the importance of properly documenting archeological excavations, and having such records available for further research, but also demonstrates how such an approach can be valid, and help solve open research questions in archeology. This study concerns the archeological site of Santa Cristina, Sardinia, Italy where a three-dimensional model of the surface and underground has been developed to answer certain archeological research questions. There are about two dozen sites on the island of Sardinia that are exhibiting very similar features. In most archeological publications these sites are called "sacred wells" which, although there is no concrete evidence for this assumptions, implies that some form of ritual could have been performed there. The aim of the three-dimensional model (shown in Figure 2.5) and additional virtual representations of the interior of the structure is to understand the social actions that took place at the site and how these may have influenced the architecture of the complex. Hermon and Niccolucci, through a visual comparison between all structures categorized as ”sacred wells”, come to the conclusion that there was no rule or a strict canon on how these sites were build and *”while in some cases a ”crowd” may have been present in a dedicated space [...] in others human activity was limited to the underground space”*.



(a) (b)

Figure 2.5: (a) the complex of the Santa Cristina archaeological site, (b) three-dimensional documentation at the site and the resulted model, both depicted in Hermon and Niccolucci (2015)

This study demonstrated how a three-dimensional based research approach can be valid, and help solve open research questions in archeology. But beyond the scanning of artifacts and architecture with different computational photographic techniques to produce and recreate archeological data, it is also important to discuss the methods and technologies to visualize all this data. This will be discussed in the next section, where the process how to get from a real-world object or scene to a virtual representation is described.

2.1.2 Virtual Environments

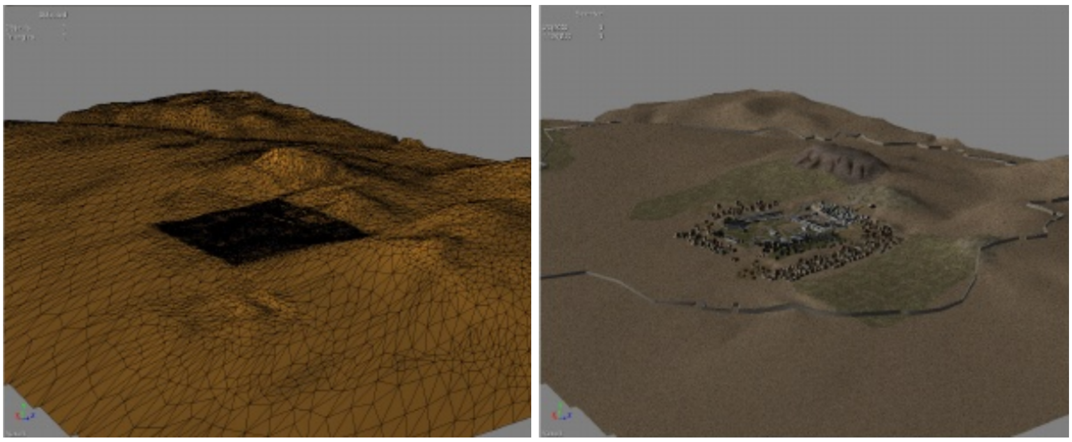
The visualization of archeological data and the technologies that are typically applied for this process consist mainly of specialized software tools (Teichmann, 2010), games (Calef, Vilbrandt, Vilbrandt, Goodwin, & Goodwin, 2002) and game-related software. As stated by Beale and Reilly (2017) *"innovators in this field have proven that games and interactive media are highly effective as a means of engaging with complex archaeological concepts and processes and have begun to use a variety of tools and approaches"*. These include the production of immersive and interactive experiences (Emery & Reinhard, 2015; Galeazzi & Franco, 2017; Kevin Kee et al., 2009; Morgan, 2009), the use of mixed reality and pervasive gaming (Eve, 2017), and the use of open source and simple to use tools for producing non-linear interactive stories (Copplestone & Dunne, 2017). Example for the use of specialized or game-related software for the representation of virtual environments in archeology can be found in a variety of places. For example, Ubisoft[1] the company responsible for the creation of the game Assassin's Creed Origins developed a *"discovery tour mode, which allows players to travel around the environment with game elements removed, replaced by guided tours written by historians and Egyptologists"* (Assassin's Creed Origins, 2018). But before further examples can illustrate how software is used to showcase virtual environments based on archeological data, a technical baseline for how these environments are build has to be established and will therefore be discussed in the next section.

[1]Ubisoft. (2018). Official website. Retrieved from https://www.ubisoft.com.

Building an Archeological Virtual Environment

A good technical case study for the reconstruction of an archaeological site can be found in Sideris (2008) and Sideris (2007), where seven procedures and phases for building an archeological virtual environment are presented. A short summary of those steps is outlined below:

1. First the time and space of a given area have to be defined. In this context, space is easier because it can be defined with great certainty whereas time is almost always an approximation (mainly because of the coarseness of ancient chronology). The appearance of the environment and buildings is also included when space and time are defined. In most cases, this starts with a digital terrain model (as depicted in this Figure 2.6). Depending on archaeological and geophysical data, this model is then modified frequently (Sidiropoulos & Sideris, 2003).



(a) (b)

Figure 2.6: Digital terrain model as shown in Sideris (2008), (a) in shaded wire frame, (b) with building and texture integration

2. The second step includes documentation composed of data caption by three-dimensional scanning and photogrammetry, pictures of ruins and landscapes, excavation data and, if available, studies of earlier reconstruction.

3. The third step is essentially the combination and evaluation of the first two steps, which means looking at all the data and trying to interpret it. Here a decision needs to be made which proposed reconstruction to use, and to justify it according to all available information and the criteria of the London Charter (Beacham et al., 2009; Hermon & Niccolucci, 2015).

(a) (b)

Figure 2.7: (a) model of the Tholos of Epidaurus ,(b) model of of the Stoa of Zeus Eleutherios, both from Sideris (2008)

4. In the fourth step, the proper building of three-dimensional models (examples are depicted in Figure 2.7) is started. Here hardware and software capabilities come into play and certain trade-offs have to be made. If architectural forms need to be simplified this has to be done without affecting the final viewer's impression of realism (Champion, 2004; Ogleby, 2007). Textures are added and varying image-based

techniques may help with additional realism (Gaitatzes, Christopoulos, & Papaioannou, 2005; Gaitatzes, Christopoulos, & Roussou, 2001).

5. In the fifth step the digital terrain model (shown in Figure 2.6) and all the building are integrated and a horizon in the circumference of the area added (two-dimensional). This horizon may include distant structures and surrounding geomorphology.

6. The sixth step represents the addition of all the details necessary to contextualizes the virtual environment. This can include lighting, sounds, small walls, steps, enclosures, light structures, statues, and trees.

(a) (b)

Figure 2.8: Model and scene from Sideris (2008), (a) wire frame model of a virtual character, (b) the ostracism voting scene in the Athenian Agora involving multiple virtual characters

7. The last step concerns the creation of virtual characters (an example can be seen in Figure 2.8), that should be designed and animated according to the given scenario. Their behavior essentially transforms the virtual environment, gives it a plausible socio-cultural context and

intensifies the experience for spectators (Jacobsen & Holden, 2007; Sadzak, Rizvic, & Chalmers, 2007).

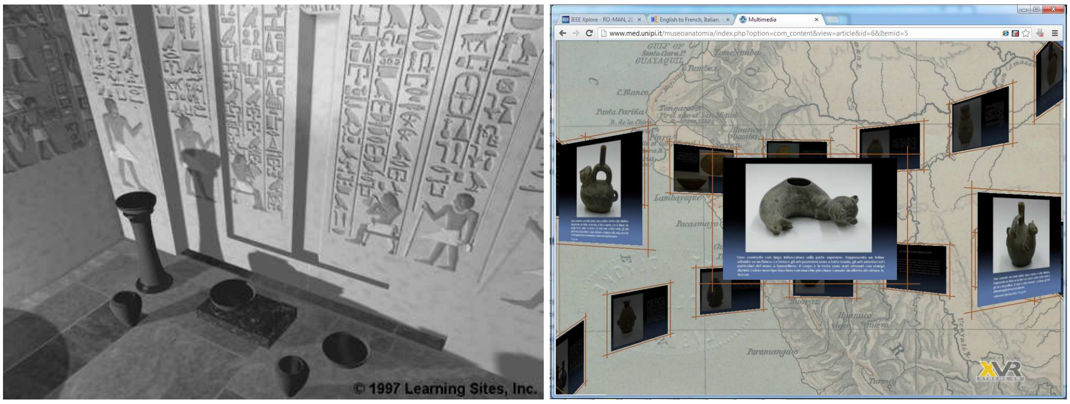
These steps established a baseline for the creation of virtual environments in cultural heritage and archeology and furthermore illustrate the processes involved with transferring archeological knowledge and methodology into a virtual environment. As previously mentioned, the underlying technology for these environments is often found in modern game-engines (George Lepouras & Vassilakis, 2004; Teichmann, 2010), but although they are often valued for their greater versatility, usability, maturity, and simulation capabilities (Calef et al., 2002), when it comes to the exhibitions of virtual archeological environments there is still a mix of specialized software and game-related software used today. In the next section, the focus will be on the dissemination of archaeological knowledge in museums (real museums, virtual museums, games). This section will present how archeological artifacts and sites within virtual environments are shown to audiences and visitors.

2.1.3 Virtual Museums

As mentioned in the work by Bruno et al. (2010), where a methodology for digital archeological exhibitions is discussed, virtual environment technologies have been used in the field of cultural heritage for almost two decades. When it comes to cultural heritage the main advantages of immersive visualization and three-dimensional reconstruction of archaeological sites and finds comes in the form of the safeguard and the protection of the remains of the past. Museums have started to realize this and the potential of new technologies for the development of edutainment content and services for their visitors. Virtual environment technologies promise to offer a vivid and enjoyable experience to the museum's guests (Roussou, 2008). But because museums are interested in the digitizing of their collections not only for the sake of preserving the cultural heritage, but to also make that content accessible to the wider public in a manner that is attractive, other technologies, like virtual reality, but also augmented reality and Web3D are widely used to create virtual museum exhibitions, both in a museum environment through informative kiosks and on the World Wide Web (Styliani, Fotis, Kostas, & Petros, 2009).

There are many examples of current projects that either create museum-like experiences in existing games (Urban, Marty, & Twidale, 2007), build virtual exhibition in real museums (Scucces, Carrozzino, Evangelista, & Bergamasco, 2012), or offer a complete virtual museums to begin with (Jones & Christal, 2002; G. Lepouras, Katifori, Vassilakis, & Charitos, 2004). These projects can be seen in various places, examples include the exhibit on *"Malay culture at the Fort Malaya Museum"* in the online game Second Life (2018) shown in Figure 2.10 as depicted in Urban et al. (2007), or early web based virtual depictions of the *"Chapel of Ka(i)pura, Saqqara, Egypt"* in Sanders (2013), the more modern web based interactive multimedia catalog in Scucces et al. (2012), both shown in Figure 2.9, and of course virtual interactive exhibitions in real museums like the *"Doric temple of Ancient Messene in Greece"* as described in Roussou (2008) and also shown in Figure 2.10.

Although virtual museums are very popular and they offer the possibility for *"supporting collaboration among the users of virtual museums"* (Baloian et al., 2017), very few implementations of virtual museums offer support for such activities. In this work by Baloian et al. (2017) the value of collaboration in virtual museums is established through the classification of collaborative curation activities. As an example of this approach, a virtual museum



(a) (b)

Figure 2.9: Examples of virtual museums shown in works from Sanders (2013) and Scucces, Carrozzino, Evangelista, and Bergamasco (2012), (a) the Chapel of Ka(i)pura, Saqqara, Egypt, rendering created for the Dallas Museum of Art exhibition on Egyptian art, (b) interactive multimedia catalog showing a selection of an archeological collection

(a) (b)

Figure 2.10: (a) exhibit on Malay culture at the Fort Malaya Museum in the game Second Life shown in Urban, Marty, and Twidale (2007), (b) real Museum with a virtual reality environment, where museum visitors use a haptic interface, to reconstruct a section of the Doric temple of Ancient Messene in Greece, depicted in Roussou (2008)

devoted to Armenian cross stones is presented. In this scenario, different curators can place stones and rearrange the original setting of stones, all at the same time. Different current users activities are displayed in different colors, to support the collaboration between curators (as shown in Figure 2.11).

Figure 2.11: Curators collaborative environment from Baloian et al. (2017)

But despite the great popularity of virtual museums, virtual exhibitions on the web, in real museums and even games, the previously mentioned human elements and historical accurate depiction of human behavior is missing in these examples, which is why in the next section of this work different aspects of virtual humans, and simulated human behavior in virtual environments will be discussed.

2.2 Simulation of Humans in Historical Settings

Simulations of humans in historical setting helps to not only give people a basic understanding of historical events, certain mannerisms, and behaviors, but also conveys a sense of immediacy (Roussou, 2008), especially in virtual reality environments (like in Figure 2.10). The immersive elements that come from the inclusion of the visualization of human interaction and behavior should not be underestimated. At the same time the difference between a past natural society and an artificially created one has to be taken into account and properly explored as stated in this work by Barceló (2012) *"with the possibility of simulating past social systems, a new methodology of social and historical inquiry becomes possible [...] the value of creating artificial societies is not to create new entities for their own sake, but observing theoretical models performing on a test-bed. Such a new methodology could be defined as exploratory simulation"*.

Barceló goes on to explain that exploratory research based on social simulation can typically contribute in a variety of ways:

- implicit but unknown effects can be identified
- possible alternatives to a performance observed in nature can be found
- the functions of given social phenomena can be carefully observed
- "Sociality" that is "Agenthood" orientated to other agents can be modeled explicitly

Barceló states that the cause of human action in the past cannot be known in the present. But that by simulating societies that may have existed somewhere and at some point in time, an understanding of social activities in the past in terms of a "pure" system can be approached and analyzed. An example for such a system can be found in the next section.

Case Study: Virtual Romans in Ancient Pompeii

A good example and case study for a simulated society can be found in a work by Maim et al. (2007), where the ancient city of Pompeii has been virtually reconstructed based on archeological data (shown in Figure 2.12). Crowds of virtual Romans have been introduced in its streets and houses to simulate life before the eruption of volcano Mount Vesuvius in 79 A.D.: *"Pompeii was a Roman city, destroyed and completely buried during an eruption of the volcano Mount Vesuvius. We have revived its past by creating a three-dimensional model of its previous appearance and populated it with crowds of Virtual Romans"* (Maim et al., 2007).

(a) (b)

Figure 2.12: (a) and (b), a crowd of Virtual Romans in a reconstructed part of Pompeii from Maim et al. (2007)

In this work by Maim et al. (2007), the process of simulating ancient Pompeii life in real-time, based on archeological data, is described. From the procedural generation (based on shape grammar rules) of a city model containing semantic data (like land usage, building age, and window/door labels, that can trigger special crowd behavior), to the real-time simulation of a large number of virtual Romans. In a first step, a high and low-resolution model of the city are built. The first one for the actual visualization, the second one for the semantic data that is used in the crowd simulation. The semantic data for the behavior mapping and also a navigation graph for the crowd itself are both rendered offline, whereas the rendering of the scene itself and the behavior of single Romans (that is based on the location within the scene), are done online at runtime. With the help of additional information provided by archeologist, they included location data for rich and poor districts, which is also *baked* into the semantic data. That data dictates which Romans are assigned to what part of the city. All this information is included in the navigation graph in an offline preprocessing steps. By this means behavior at runtime is triggered by graph vertices (shown in Figure 2.13) that are used to contain a series of variables that can be used for parameterization later.

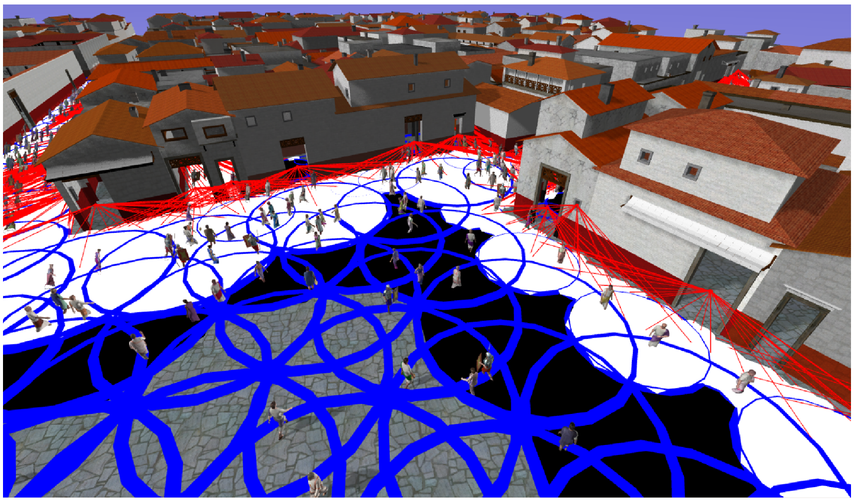


Figure 2.13: Graph vertices are marked with special behaviors: "look at" (in white), "stop looking at" (in black), and "target point" (in red) from Maim et al. (2007)

E.g. when a virtual Roman looks through a window or door, it also receives a target point where to look (computed at the center of the door or window). During the crowd simulation itself, Maim et al. (2007) also differentiate between short and long-term behavior. Long-term would be for a virtual Roman to buy something and keep the item until the end of the simulation, whereas short-term behavior would be the before mentioned look through a door or window. All this leads to a simulation where crowds exhibit specific behavior relative to their location. The segmentation into an offline and online part for the behavior does also mean that the performance impact from simulating a great number of virtual Romans during runtime is not as big as it would have been otherwise. Between 2000 and 4000 virtual Romans have been successfully simulated in this recreation of ancient Pompeii within acceptable performance numbers. The end result of this work can be seen in Figure 2.14.

Figure 2.14: Crowds of Virtual Romans in a street of Ancient Pompeii from Maim et al. (2007)

Now, to gain a deeper understanding of how virtual humans can be developed, the next section will focus on different categories of crowd behavior modeling, and also look at how the goals for simulating virtual humans can impact the approach and the methodology used to create them.

2.2.1 Crowd Behavior Modeling

High-quality crowd simulations are very important for many virtual environment applications in different disciplines, like education, entertainment and also archeology, but offers many challenges centered mainly on the trade-offs between rich behavior, control and performance (Sung, Gleicher, & Chenney, 2004). As stated by Luo et al. (2008) the research on crowd behavior modeling can be classified into two categories:

- The first approach to simulating crowds, looks at groups of virtual humans as collections of uniform entities, which follow simple rules and use those rules to react to events within their environment. Examples of this approach are the automata model described in Burstedde, Klauck, Schadschneider, and Zittartz (2001) and particle system model used in the works of Brogan and Hodgins (1997) and Helbing, Farkas, and Vicsek (2000).
- The second approach for simulating crowds treats groups of virtual humans more like real humans, in other words like individuals that have powerful decision-making capabilities. An often used approach for this category is the agent-based model (Nguyen, McKenzie, & Petty, 2005; Pelechano, O'Brien, Silverman, & Badler, 2005; Shendarka & Vasudevan, 2005; Ulicny & Thalmann, 2005), where a single agent represents a single human in a crowd. Because of significant increases

in processing power over the last decades this model has become very popular.

The first category deals mostly with the automata model and the particle system model. Simulations based on these models present topics like pedestrian traffic, like in this work by Burstedde et al. (2001), group navigation and animal behavior shown in Brogan and Hodgins (1997), or crowd stampede induced by escape panic shown in Helbing et al. (2000). And although there are works in the field of archeology that outline crowd simulation based on particle models, for example in this work by Heigeas, Luciani, Thollot, and Castagné (2003), in most cases these approaches are dropped in favor of an agent-based model. This has various reasons, one of the most prominent ones being the fact that the simulation of humans in virtual archeological environments is not only done to evaluate academic hypotheses or study past human behavior, but to a large degree for the immersive elements that come from the inclusion of the visualization of human interaction and behavior. This means that single virtual humans need to be represented by actual human models, that look, move and behave like real humans would have in the depicted historical environment. Now, of course the visual representation of virtual humans has little to do with the underlying model that is responsible for their behavior, but in many cases for crowd simulations, within cultural heritage sites or other archeological virtual environments, the behavior necessary, to develop a believable scene, needs to be complex, and often diversely allocated to different types of agents. Not every virtual human or agent can be treated the same, or has the same behavior, individual differentiators like age, social status, economic status and gender can all be factors in archeological depictions of virtual humans and important distinguishing elements between them. This is why, for the purpose of understanding how crowd behavior modeling is applied to most virtual archeological environments, the next section will focus on agent-based modeling rather than on particle system or automata modeling.

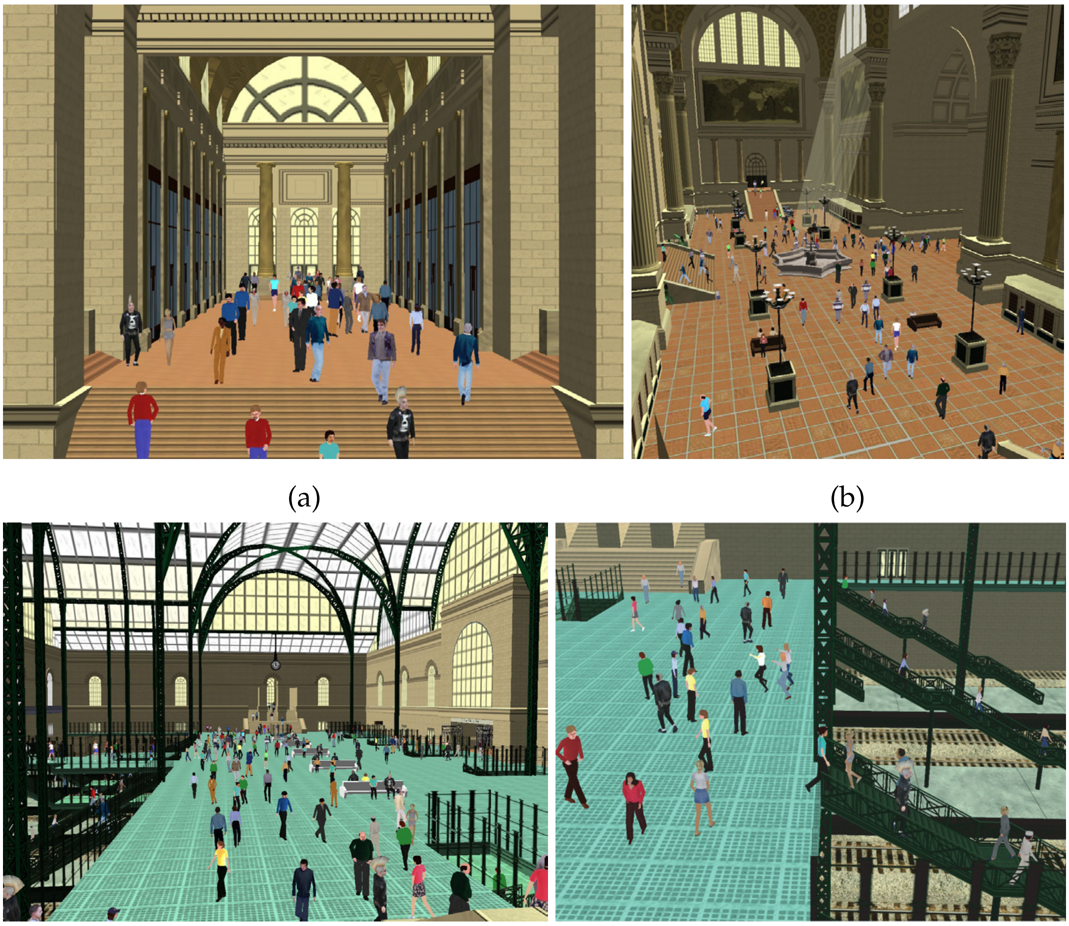
2.2.2 Agent-based Modeling

Agent-based modeling (Agent Based Model, 2018) is a simulation technique that has seen numerous applications in different fields of sciences. This technique can be applied to flow simulation, organizational simulation or market simulation and is essentially a system, where as stated in this work from Bonabeau (2002) *"autonomous decision-making entities called agents"* assess situations in their surroundings, and make decisions based on a specific set of predetermined rules. What those rules are, and what actions agents can take, and which behavior they show, depends entirely on the simulation they are deployed in. When looking at agent-based modeling in archeology (where agents are predominantly represented by human entities), there are only a few examples where the quality of the simulation of human inhabitants equals the quality of the reconstructions of the virtual environment they are a part of. That does not only pertain to the work that goes into visualizing these virtual humans, but above all the quality of the simulation that determines their behavior patterns. Only if the quality of the simulation meets a high standard, it can start to help test archeological hypotheses about sites in ancient times and their inhabitants.

2.2.3 Human Behavior Modeling

One of these examples for agent-based modeling, or one of its subcategory *human behavior modeling* (where autonomous agents are presented as human entities), was already previously discussed in the work from Maim et al.

(2007). Another can be found in the work from Shao and Terzopoulos (2006). In this paper from Wei Shao and Demetri Terzopoulos, the use of the artificial life model from D. Terzopoulos (1999) to build *"comprehensive, detailed models of individual autonomous pedestrians"* that *"span several modeling levels, including appearance, locomotion, perception, behavior, and cognition"* is discussed. An example from this work can be seen in Figure 2.15.



(a) (b) (c) (d)

Figure 2.15: (a), (b), (c), (d), large-scale simulation of human activity in the reconstructed Pennsylvania Station from Shao and Terzopoulos (2006)

In principle, Shao and Terzopoulos (2006) propose a similar idea to Maim et al. (2007), where through the inclusion of semantic data, that is either embedded in the three-dimensional models of the scene itself, or part of the navigation maps, the virtual crowd can navigate the environment more efficiently. Their virtual environment contains a collection of four different maps (Shao & Terzopoulos, 2005a, 2005b):

- a *topological map*, where nodes and edges represent the walkable regions and accessible paths between them
- two *perception maps*, where stationary and mobile objects (that includes other agents) are represented
- the *path map*, that is built for each region of the virtual environment, consist of 2 parts, a quadtree map and a grid map. The quadtree map enables long-range path planning for agents, while the grid map is for short-range paths (a short-range example would be the navigation around a bench for the purpose of sitting on it)
- a *specialized objects map*, that contains information about the environment that cannot be baked into the *perception maps*, examples include:
  - where an agent can wait in line
  - purchase points
  - entrances
  - exits

This virtual environment model lays the groundwork for the autonomous agents. These agents receive information about the environment they are in, can analyze situations, plan certain action, and thus behave in a relatively natural manner. This detailed behavior is made possible by including *"appearance, locomotion, perception, behavior, and cognition sub-models"* into the basic agent model. A short summary of how these behavior details are achieved in a single agent can be read below:

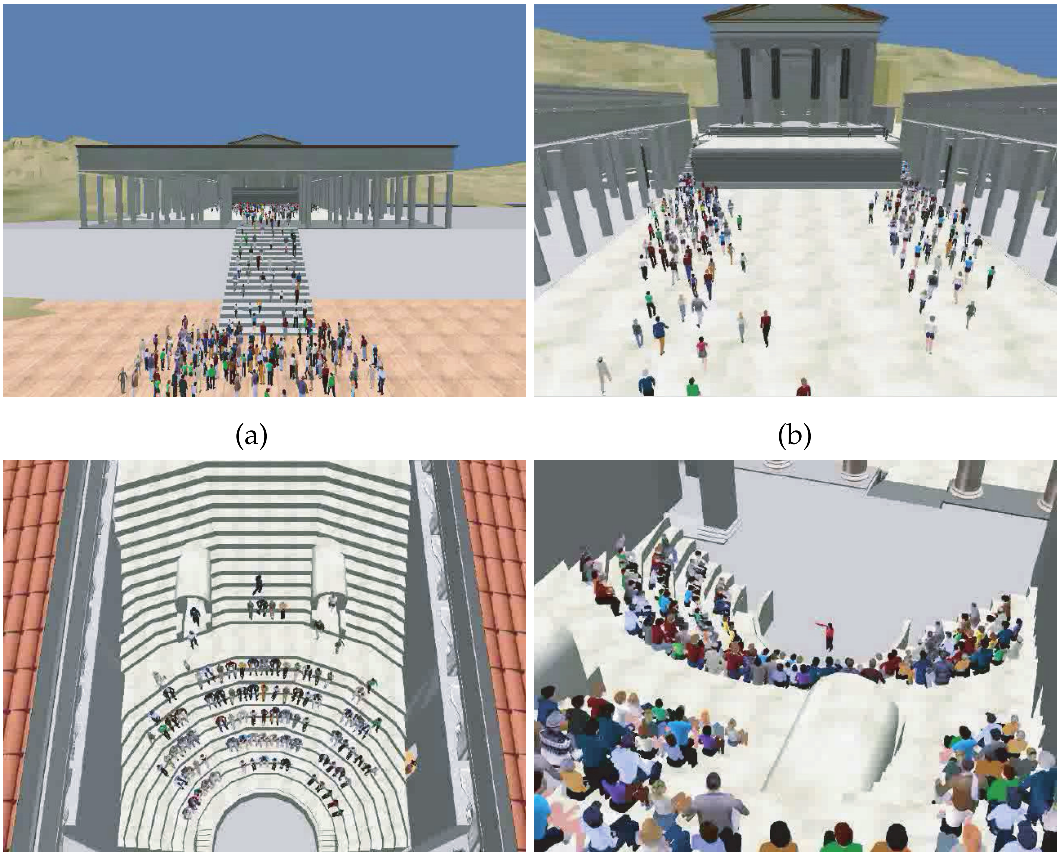
- for the agent appearance and locomotion, a human animation package called *DI-Guy*[2] is used, that essentially provides textured human models that have a range of basic skills like walking, jogging or sitting
- for the perception part of the agents, the hierarchical world model is used extensively to understand the environment (through multiple perception maps), but the specialized objects map is also taken into account for recognizing certain objects or other agents
- for the agent behavior, every perception of a single agent is linked to an appropriate action. The idea is to use simple behavior routines as building blocks to develop a complex set of higher-level behavior. A strategy similar to the one show in Terzopoulos, Tu, and Grzeszczuk (1994). This enables single agents to not only move around freely, avoid collisions, and go where they want, but the addition of *"non-navigational, motivational routines"* also enables them to sit on unoccupied seats, queue at a line, or approach a point of interest and watch what is happening. Furthermore, the inclusion of an *"action selection mechanism"* allows to trigger a behavior, that is depended on internal and external stimuli. If an agent is thirsty or hungry, it will abandon its current task and seek out a source of food. If more than one of these needs accumulate, they are queued, and processed in the order of their importance
- The last step is cognition, where a model from Funge, Tu, and Terzopoulos (1999) is used to give the agents the ability to have short and

[2] DI-Guy. (2018). Realistic human characters for extraordinary visual simulation. Retrieved from https://www.mak.com/products/visualize/di-guy.

> long-term plans. This requires a memory model, that enables agents to *"memorizes, update and forget"* their respective goals. In summary, it can be said that this cognition model leads to the ability of single agents to achieve very complex goals, that can be split into simpler ones, possibly intersected by *"non-navigational, motivational routines"*, ultimately reach their destination, and showing very diverse and life-like behavior while doing it.

As a demonstration and case study for their work Shao and Terzopoulos (2006) apply their *"pedestrian simulation system"* in two distinct scenarios. The first one is a virtual reconstruction of the New York Pennsylvania Station, which was destroyed in 1963. They created *"lengthy animations of numerous pedestrians in large urban environments without manual intervention"*. This more modern archeological site can be seen in Figure 2.15. The second one is a virtual reconstruction of the Great Temple in the ancient Nabataean city of Petra, and the theater inside. For this second scenario (that can be seen in 2.16), Shao and Terzopoulos (2006) had to augment the behavior of their agents to better fit the theater environment inside the Temple.

Interestingly, the results of the second simulation compelled archaeologist authorities on Petra to lower certain estimates they had made, concerning the number of people the theater should have been able to hold originally, since in the simulation only 200 agents could enter, be seated, and exit the theater in a realistic time-frame. This is a concrete example of how the simulation of humans in virtual environments, can help to advance the research done in the field of archeology, and therefore help to better understand the past. In the next section, a summary of this chapter is presented, and a comparison of the two main examples (Maim et al., 2007; Shao & Terzopoulos, 2006) for simulating virtual humans in historical settings is shown.



(a) (b) (c) (d)

Figure 2.16: (a) agents walk into the Temple theater, (b) agents use the stairs on the east and west on the lower Temenos, (c) agents enter the auditorium and start choosing seats, (d) agents are attending and listing to a speaker. Depicted in Shao and Terzopoulos (2006)

2.3 Summary

In this chapter important aspects of virtual archeology and methodologies for simulating humans in virtual environments were discussed. To gain an understanding of the foundations of virtual environments, populated by virtual humans in archeology, a certain knowledge base had to be established. How to get from an archeological object or historical site to an actual virtual and simulated representation of that object or site. To that end, digitalization through photogrammetry was noteworthy, because it represents a fundamental technology for the virtual representation and recreation of archeological data. Furthermore, a short overview of how virtual environments in archeology are built, and how these are then presented in museum environments, was presented. This is especially important, because when it comes to exhibitions, museums (virtual and real) are not only interested in the safeguard and the protection of the remains of the past, but also want to offer a vivid and enjoyable experience to the museum guests. They accomplish this through the use of a variety of new technologies and possibilities, including virtual reality, augmented reality and Web3D. The second half of the Chapter dealt with simulation aspects of human behavior in virtual archeological environments. Here categories and concepts of crowd behavior and especially agent-based modeling were discussed. Special emphasize was given to how these concepts are applied, and help answer important archeological research questions. Two concrete examples were shown (Maim et al., 2007; Shao & Terzopoulos, 2006) that both represent a very detailed approach to human behavior modeling, where parts of the basic agent intelligence is uncoupled and put into a separate offline preprocessing step, that *bakes* semantic data into the geometry and navigation maps. These maps are then used by the human agents to show location-specific behavior. This leads to simulations where single agents show complex and believable behavior patterns. When comparing these two approaches, certain differences become apparent. These differences revolve around the question of what to put into the (offline) preprocessing step, and what to do during the (online) runtime part of the simulation. Also, one main difference is that Maim et al. (2007) support some parameterization, while Shao and Terzopoulos (2006) prefer a hands-off approach. A detailed comparison can be found in Table 2.1.

Simulation Comparison	**Maim et al. (2007)**	**Shao and Terzopoulos (2006)**
Geometry	Procedural (shape grammar rules)	Traditional modeling
Preprocessing	Semantic data (for geometry), navigation graph, graph vertices	Semantic data (for geometry), topological map, two perception maps, navigation map, specialized objects map
Simulation and Behavior	Location dependent, long and short term behavior, behavior parameterization though variables in the graph vertices possible	Highly detailed through the use of appearance, locomotion, perception, behavior, and cognition submodels, no manual intervention
Deployment Flexibility	Virtual agent behavior is restricted to prepossessed scenario	Virtual agents are demonstrated in two different scenarios with only small changes to the underlying behavior model

Table 2.1: Comparison of two virtual human behavior simulations (Maim et al., 2007; Shao & Terzopoulos, 2006)

But, while the results of these examples represent major advances in regards to the simulation of human behavior in historical settings, none of them focuses on an agent-based approach that calculates the basic agent intelligence at runtime, or exposes parametric behavior variables to the user of the simulation in an easy to use fashion. This is why in Chapter 3 the design of such an approach will be demonstrated.

3 Design and Requirements

A common knowledge base for concepts of digitization and visualization of virtual environments in archeology, as well as human behavior modeling in those environments was established in Chapter 2. This knowledge is now used to create two historical virtual experiences, that are inhabited by a number of virtual agents presented as humans. These human agents are guided by a specific set of rules and can be influenced by a user through a number of different parameters.

Since this project is partly based on a previous work, it is important to first establish the onset situation and analyses the original concept. Through literature findings made in the previous chapter, especially the lessons learned from the comparison of the work from Maim et al. (2007) and Shao and Terzopoulos (2006), shown in Table 2.1, a set of requirements for an individually designed human behavior algorithm is created. After the definition of all objectives and requirements for the human behavior algorithm, and the definition of the requirements of the two simulations that use that human behavior algorithm, a short overview of the architecture is presented.

3.1 Requirements and Objectives

In this section, all objectives and requirements will be collected and presented. But first, the concept this work extends on, and its archeological virtual environment will be explained and analyzed.

3.1.1 Pnyx Simulation Analysis

This work is partly based on a concept for an archeological virtual environment described in Holter and Schäfer (2018). The goal of this concept was to demonstrate how *"game engines and virtual reality enable the creation of innovative, dynamic research environments with which the multisensory experience of ancient spaces can be approached"* (Holter & Schäfer, 2018). Holter and Schäfer used archeological data from Thompson (1982), to digitally recreate the Pnyx, the public space of the assembly in Classical Athens (5th–4th centuries BCE). During this Classical period of Athens, the hill of the Pnyx was a location for public assembly, where citizens met regularly and listen to speeches, debated and subsequently voted on important issues. As stated by Holter and Schäfer (2018) *"This form of political communication was central to the functioning of the democracy of Classical Athens, and it is intricately bound up with the space itself"*. Holter and Schäfer evaluated the archaeological evidence as well as suggested reconstructions, to determine how to best digitally reconstruct the Pnyx and the surrounding topography. Through this process, that included the study of many descriptions and two-dimensional drawings, an evidence-based archeological model was created. This rendering of the visual reconstruction of the Pnyx, allowed a better understanding of the communication between Demosthenes (the speaker in this historical scenarios) and the crowd on the platform, and how well each could interact with the other. To better analyze this interaction between Demosthenes and the crowd, and *"the effectiveness of this central element of political communication"*, Holter and Schäfer also included an acoustic simulation on the basis of physically correct aural impressions of different points in the virtual environment of the Pnyx. This method is called auralization (Vorländer, 2008) and is normally used to optimize acoustics in already existing constructions, but is also applied to approach acoustics of historical sites (Weinzierl, Sanvito, Schultz, & Büttner, 2015). Since this acoustic simulations runs outside of the archeological virtual environment of the Pnyx, the different points (for the acoustics simulation) are placeholders. This will be taken into account for the requirement analysis. The aforementioned evidence-based archeological environment of the Pnyx was integrated and embedded into the game engine *Unity*[1]. This game engine is used extensively in the game development industry and has several subsystems that allow the creation of a multitude of scenarios. From the correct physical simulation of gravity or wind, to many visual aspects of a digital reconstruction like textures, lights or animations. All this is directly handled by the engine itself and does not have to be developed individually. These aspects are greatly appreciated by archaeologists, because they can begin to recreated the digital environment immediately. For the concept of their virtual research environment of the Pnyx, Holter and Schäfer integrated a customizable interface into the virtual environment, that can be used to manipulate various parameters during runtime. These parameters include different locations of the speaker (Demosthenes), certain acoustic properties (like the mood of the crowd), weather and time of day. However the depicted human models, their position, movement, and behavior is completely static in that, except for certain predetermined animation states,

[1]Unity3D. (2018a). Cross-platform game engine developed by unity technologies. Retrieved from https://unity3d.com/.

there is no actual human crowd behavior simulation, or movement of any kind. This virtual archeological research environment, and the customizable interface of this original concept are shown in Figure 3.1).

(a) (b)

Figure 3.1: (a) original static crowd and virtual environment of the Pnyx, (b) early version of a user interface from Holter and Schäfer (2018)

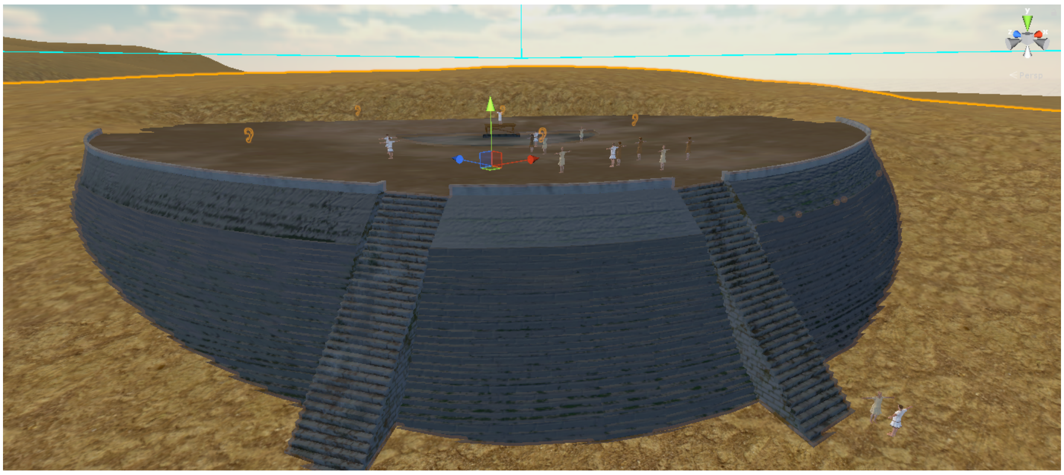
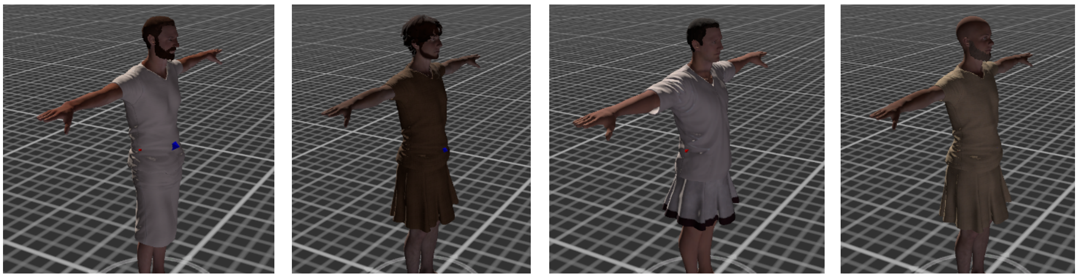


Figure 3.2: Terrain and platform model (including textures) of the Pnyx structure

The original concept of the Pnyx simulation consists of the following components (depicted in Figure 3.2 and Figure 3.3):

- digital terrain model
- structure of the platform
- 4 different human models (male, placeholders)
- textures for the terrain, structure and the 4 models
- a set of "speech" animations for Demosthenes (the speaker)
- a set of basic animation (walking, clapping, talking, etc.)



(a) (b) (c) (d)

Figure 3.3: (a) model of Demosthenes (the speaker), (b), (c), and (d) three different possible audience members

3.1.2 Objectives and Target Group

The two main objectives, that can be determined from the analysis of the original concept from Holter and Schäfer (2018), the literature findings made in Chapter 2, especially the lessons learned from the comparison of the work from Maim et al. (2007) and Shao and Terzopoulos (2006), shown in Table 2.1, are:

1. Design of an agent-based crowd simulation algorithm, that can be applied to different archeological virtual environments by archeologists in the Unity engine
2. Deployment of this algorithm in two separate historical simulations (Pnyx and Marketplace), that demonstrate the parameter-driven nature of the algorithm, through a user interface that is easy to use and understand

The target group for these simulations and the underlying algorithm are graduated archeologists and archeology students. Both simulations are developed to demonstrate the parameter-driven nature of the algorithm and help archeologists to evaluate assumption and hypotheses about the depicted historical scenarios. The algorithm should be easy enough to use and understand, to be applied to different historical scenarios by archeologists. Each simulation should have an easy to use interface for scenario dependent human agent control.

3.1.3 Requirement Analysis

As mentioned in the previous Section 3.1.1, in the original virtual environment the models of all humans, their position, movement, and behavior, are completely static, and there is no actual human behavior simulation happening. The goal of this project is to extend, expand, and improve this concept through the inclusion of a basic human behavior simulation. The idea is to fill this static virtual environment with a believable crowd of humans, that should behave according to certain rules, but also respond to external parameter inputs. For the Pnyx simulation, a variable and diverse number of human agents should start at a point in front of the Pnyx structure and make their way onto the platform. There, they should autonomously find a free spot and listen to the speech given by Demosthenes. Demosthenes should be able to start at an arbitrary place somewhere on the site, and make his way to the speaker platform, before starting his speech and interacting with the crowd. Once a human agent reaches its destination on the platform, that agent should choose and display a random behavior pattern. A number of external parameters should be able to change the crowds behavior towards Demosthenes. Also, a basic voting system should be present. Since one of the goals of this work is to build a flexible algorithm for depicting and simulating basic human movement and behavior, an additional second scene that simulates a simple historical Marketplace is developed. This scene is primarily developed to showcase the flexibility of the basic human behavior algorithm, and while it uses the same human models, the scene and depicted environment itself is not based on archeological data or an original historical site. In this Marketplace simulation a different set of parameters will be exposed. Because both simulations use a flexible game engine, the visualization of different uncertainties (that come from the underlying archeological data) becomes possible, by exposing different parameters to the user, thereby enabling further archeological research. Unity also enables development of potential virtual reality versions of the Pnyx and Marketplace simulations. Through a custom and easy to use interface that is integrated into the simulations, the user can freely manipulate various variables while experiencing the scene. That allows the researcher that created that scenario, to modify the scene, choose from a range of different options, and adjust research questions accordingly. This user interface will be kept very simple, to support the easy integration of all parameters in a potential virtual reality version of these simulations. Implementation details for all modules that are discussed in this chapter, and their deployment in the two simulations is shown in Chapter 4. An evaluation of both simulations (Pnyx and Marketplace) can be found in Chapter 5. This evaluation presents how archeologists and students asses the usability of the parametric input possibilities and immersion of both scenes. A general description of the basic simulation scenarios, the human agent behavior capabilities, and the parameters that a user can change, are summarized in the next sections.

The Pnyx simulation

In the Pnyx simulation the human agents need to make their way onto the platform, find a free space there and show a behavior towards Demosthenes (shown in Figure 3.4).

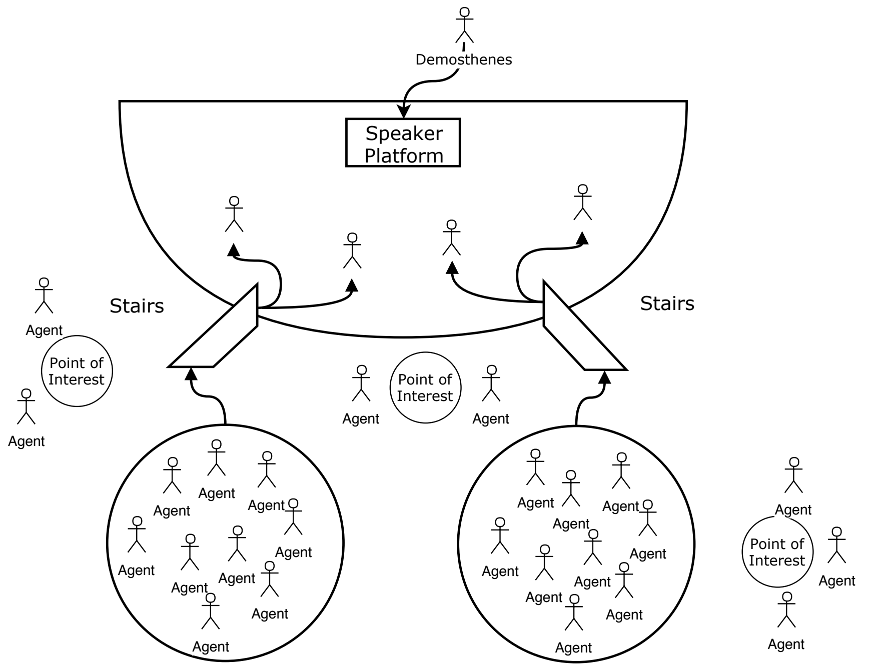


Figure 3.4: Pnyx simulation concept: agents need to find their way onto the platform, find a spot, look at Demosthenes and display a behavior

Human agent behavior capabilities, and the parameters that a user can change are:

- basic movement and traversal of all human agents from a variable point in front of the Pnyx onto the platform, this includes Demosthenes and the audience
- human agents need to be able to find a free, unoccupied space on the platform
- if so inclined, human agents should be able to change their primary goal of getting to the platform and listing to Demosthenes, and linger on certain points of interest instead
- human agents need to show a basic variable behavior when listing to Demosthenes
- when listing to Demosthenes, the behavior of single human agents should be changeable by the user through external parameters
- a basic voting system, to agree or disagree with Demosthenes should be triggerable through external user input
- the user of this simulation should be able to control all parameters in an easy to use fashion

The Marketplace simulation

In the Marketplace simulation agents enter the market, traverse through the market in a random fashion, if a human agent is drawn to a point of interest (e.g. seller) the agent looks for a free space around that point and lingers there. After losing interest, the agent moves on and continues its original path through the market (shown in Figure 3.5).

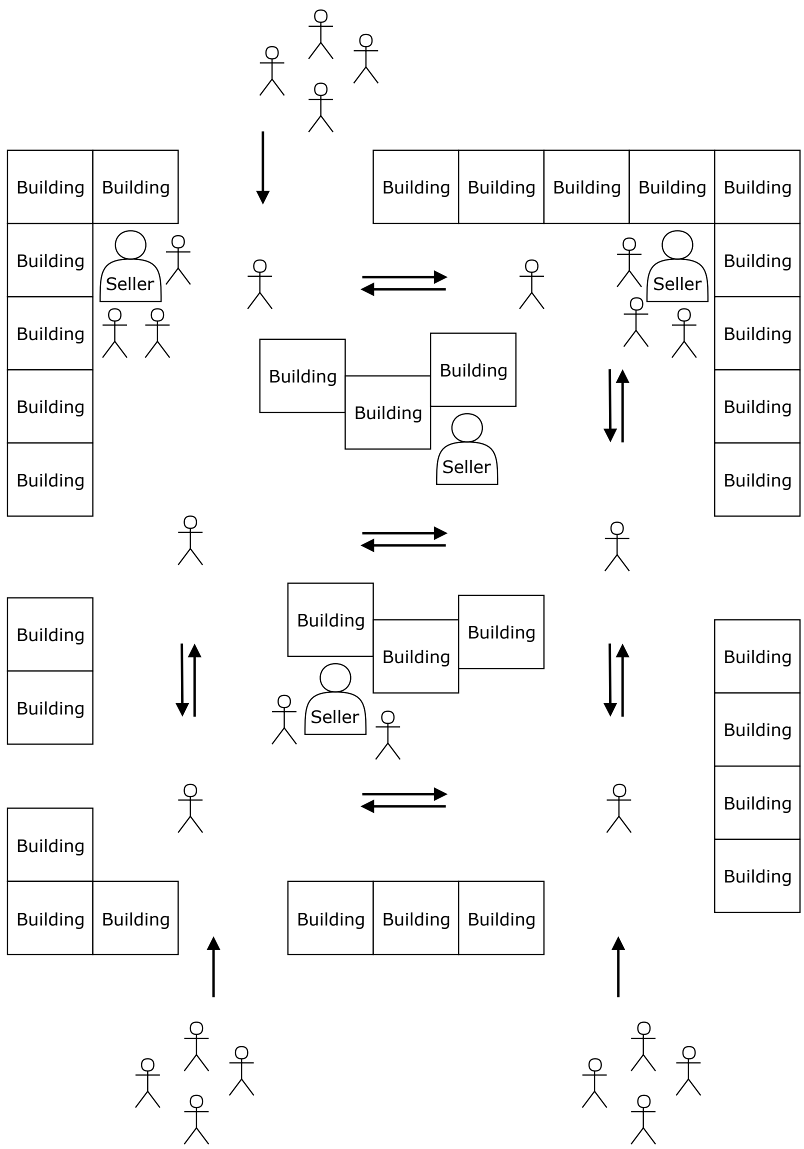


Figure 3.5: Marketplace simulation concept: agents traverse through the market, if an agent passes an interesting seller, it lingers at this point of interest and displays a behavior, after a time it moves on and continue on the original path through the market

Human agent behavior capabilities, and the parameters that a user can change are:

- different sellers should be present and try to invite members of the passing human crowd
- human agents should walk within this Marketplace and between single market stands in a self-determined fashion
- if human agents are interested, they should be able to linger in front of a seller and interact with him
- if human agents are no longer interested, they should be able to leave a particular market stand and resume their original route through the Marketplace
- certain parameters like movement speed, the chance and time frame for lingering at market stands, and the behavior that is shown towards sellers, should be controllable through user input
- the user of this simulation should be able to control all parameters in an easy to use fashion

Both simulations should immerse a user into the depicted environment, and also expose all parameters necessary to facilitate interactivity in a scene through an easy to understand user interface.

3.1.4 Functional Requirements

The concepts described in the Section 3.1.3 will now be discussed in more detail. The functional requirements have been designed with the target group (described in Section 3.1.2) in mind. Regarding the simulations and the underlying algorithm for the human behavior, the following functional requirements can be concluded:

Basic movement and behavior

- The basic movement and behavior of a single human agent should be configurable to the requirements of the given scenario
- The agent is either given a variable number of navigation points (these can also be randomized) during the setup process of the scenario, or the agent chooses its next point within a certain environmental radius of its current position
- Added to the different behaviors that an agent exhibits when it reaches a predetermined destination, the agent can choose between additional behaviors when reaching points of interest
- Agent behavior for the Pnyx includes:
  - different behaviors towards Demosthenes
  - different behaviors at points of interest
  - the ability to vote
- Agent behavior for the Marketplace includes:
  - different behaviors towards sellers at points of interest
  - after losing interest in talking with a seller, human agents can return to their previous navigation path

Online parameters

During the runtime of both simulations a number of parameters should be exposed to the user (e.g. researcher), including:

- the basic movement speed of human agents, this is especially important for testing certain assumptions or research questions, because, for some conclusions or a quick test of certain changes, a realistic walking or behavior speed is unnecessary.
- the ability to slow down or completely pause the simulation

- the ability to deactivate the user interface completely
- the ability to choose the number of animations used for the different behaviors available
- for both simulations, the behavior of human agents, when standing on the platform in front of Demosthenes, or when talking to a seller in the Marketplace, should be directly adjustable in three levels:
  - behavior 'interested in what Demosthenes or sellers have to say', randomly chosen between a selection of at least two distinct animations
  - behavior 'skeptical towards Demosthenes or seller', randomly chosen between a selection of at least two distinct animations
  - behavior 'annoyed towards Demosthenes or seller', randomly chosen between a selection of at least two distinct animations
- for the Pnyx simulation three additional parameters for the human agents on the platform will be available:
  - Behavior 'randomized', completely randomized behavior pattern for the entire crowd in front of Demosthenes
  - Behavior 'dependent on distance', dependent on the distance that a particular agent has to Demosthenes, a specific predetermined behavior will be chosen, this is important because when a researcher wants to simulate the limited range of the voice of Demosthenes, this enables a visual representation of an interested crowd in the front and a skeptical or annoyed crowd in the back of the platform
  - Behavior 'voting', the crowd of human agents can vote, the results will be shown visually through distinct animations for 'yes' and 'no' and also depicted numerically in the user interface
- for the Marketplace simulation the following additional parameters

will be available:

  - the chance an agent has to be interested in lingering when passing a seller
  - the time an agent will spend when talking with a seller
  - the possibility to completely disperse the crowd of human agents in front of a seller

Offline parameters

Parameters that are not available at runtime, should be configurable during the setup process of the simulations. These parameters include:

- the number of instantiated human agents
- a parameter that affects general movement speed and the time for lingering
- the specific location of navigation points
- the specific location of points of interest
- the specific mesh for the possible calculation of navigation points at runtime

Human agents should be able to traverse navigation points in order, or completely randomized. Additional functionality should include the ability of single human agents to chose their own navigation points on the current terrain they are traversing, within a certain radius of their current position. Since this will require the ability to find free spaces on the terrain (at runtime), the possible performance impact could be high. This is why this feature is optional and can be exchanged for predetermined navigation points.

3.1.5 Non-Functional Requirements

The concepts described in the Section 3.1.3 will now be discussed in more detail. The non-functional requirements have been designed with the target group (described in Section 3.1.2) in mind. Regarding the simulations and the underlying algorithm for the human behavior, the following non-functional requirements can be concluded:

Usability

The simulation environment for both scenes must be easy to use for the target group (archeologists). Through good usability, user frustration can be avoided and the motivation to actually use the simulations enhanced. This also applies to the underlying algorithm that must be easy to use and understand by archeologists.

Flexibility

The simulations should be easily changeable and variable enough to support different research scenarios. E.g. the auralization placeholder points on the Pnyx platform for the acoustic simulation mentioned in Section 3.1.1, should be possible destination points for human agents. The underlying algorithm should be able to be integrated into different historical scenarios.

Extensibility

Both simulations should be expandable through the addition of content. The underlying algorithm should be able to support additional human behavior patterns.

Performance

The simulations should run at an acceptable frame-rate to ensure fluidity of movement and uninterrupted engagement with the environment. Performance intensive parts of the algorithm should be made optional.

Scalability

The number of human agents in a given scenario should be variable, and should not have a major impact on the performance.

Compatibility

The algorithm and the exposed parameters displayed in the user interface should be easy to integrate into potential virtual reality versions of both simulations. For this reason the interface itself should be a simple text overlay to support such an integration.

3.2 Technologies

The technologies that will be used for this project are the Unity engine[2] and the integrated development environment Visual Studio[3]. Unity is available for many platforms and is free for education use. It is easy to learn, allows rapid prototyping, has a large selection of free assets in the Unity asset store[4], and has a large number of tutorials and online documentation available.

[2]Unity3D. (2018a). Cross-platform game engine developed by unity technologies. Retrieved from https://unity3d.com/.

[3]Visual Studio. (2018). An integrated development environment from microsoft. Retrieved from https://www.visualstudio.com/.

[4]Unity3D. (2018c). Unity asset store. Retrieved from https://www.assetstore.unity3d.com/.

However, Unity is not open source, it is expensive when more features are required than are available in the free version, and the mentioned documentation is in most cases severely out of date. But Unity includes the option for easy navmesh *baking*, which enables the rendering of an offline navigation map, that is indispensable for proper path traversal and obstacle avoidance for potential human agents. For this reason and because the original virtual environment concept from Holter and Schäfer (2018) is based on Unity, it is an obvious choice for the development environment for the simulations. Visual Studio will be used because it has excellent Unity integration. This means that writing and debugging scripts is easy to manage, and script errors that are revealed during simulation testing can easily be found and corrected.

3.3 Architecture

This project consists of a number of different modules that will be implemented in Unity. Except for the parts mentioned in the Pnyx simulation analysis, everything will be built from scratch. The parts that will be implemented (shown in Figure 3.6) consist of:

- **Instantiate Agents:** a module to instantiate all human agents (with a variety of offline parameters) within each simulation
- **Basic Agent Behavior and Control:** the algorithm responsible for the behavior and control of a single human agent
- **User Interface:** a module that draws the overlay of the user interface on the screen, different for each simulation scenario
- **Global Communication:** a module for communication between the modules mentioned above

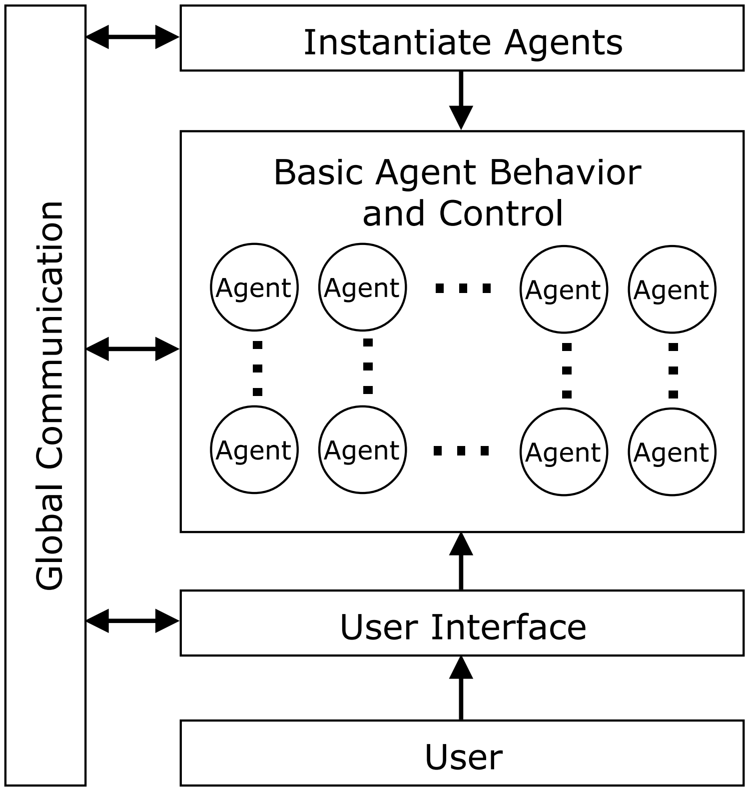


Figure 3.6: Interaction between different parts of the Unity simulations

These modules will be employed in both simulated scenarios.

3.4 Summary

This chapter discussed all objectives and requirements for the Pnyx and Marketplace simulation, as well as the underlying algorithm that is responsible for the basic behavior of human agents. The requirements were found through the combination of the analysis of the original concept from Holter and Schäfer (2018), literature findings made in Chapter 2, and especially the lessons learned from the comparison of the work from Maim et al. (2007) and Shao and Terzopoulos (2006), shown in Table 2.1. The main technology discussed in this chapter concerns the Unity engine. Unity is free for educational use, has a large selection of free assets, and enables the development of desktop and virtual reality versions of the same simulation. Furthermore, it supports easy navmesh *baking*, which is indispensable for proper path traversal and obstacle avoidance for human agents. For these reasons, and because the original virtual environment concept from Holter and Schäfer (2018) is based on Unity, it is an obvious choice for the development environment.

Within the scope of this work, the designed algorithm will be implemented and used to drive two distinct simulations. The Pnyx simulation and the Marketplace simulation, both will be a showcase for the adaptability and flexibility of the underlying algorithm. The Pnyx simulation will include basic human agent movement and behavior patterns, with appropriate parameters exposed to the user. The Marketplace simulation will have different goals for the human agents and expose different parameters to showcase the adaptability of the algorithm.

Special emphasis will be on the usability, in terms of the simulation controls, and how a user from the target group can change human behavior parameters in these simulations. This emphasis includes the general flexibility of the designed algorithm, e.g. variable point destinations for human agents (which is important for the acoustic simulation points), and certain performance considerations during development. Also, for compatibility reasons, the user interface depicting all changeable human behavior parameters, will be kept simple to allow integration into a potential virtual reality version of these simulations. In the next chapter, implementation details for all the modules mentioned in Section 3.3 will be discussed.

4 Implementation

In this chapter, the implementation details for all the modules discussed in Chapter 3 are discussed. These modules were designed to meet the specifications outlined in Section 3.1.4. An overview of the algorithm deployed in the Pnyx and Marketplace simulations and scripts details for the different module implementations will be shown.

4.1 Development Environment

For the development of this project Unity[1] was used. All programming for the necessary logic for game-objects and other simulation parts was done in C# in Visual Studio[2]. The Unity editor was specifically used for the allocation of scripts to game-objects and placement of game-objects. Except for the parts used from the original concept environment from Holter and Schäfer (2018) for the Pnyx simulation, and a number of historical

[1]Unity3D. (2018a). Cross-platform game engine developed by unity technologies. Retrieved from https://unity3d.com/.

[2]Visual Studio. (2018). An integrated development environment from microsoft. Retrieved from https://www.visualstudio.com/.

building parts[3] from the Unity asset store[4] for the Marketplace simulation, no additional resources were used. Technical features of Unity include scene rendering on graphics hardware either with DirectX[5] or OpenGL[6] (for Windows or MAC/Linux respectively), support for NVIDIA PhysX[7] for physics calculations, and animations through its own animation system Mecanim[8].

4.2 Implementation Details

In this section, the individual modules, their purpose, and implementation are discussed in detail. First, the general components, like the user controller, or instantiate agents scripts, that are the same for both simulations, are presented. Subsequently, the behavior algorithm for the human agents is described, including the changes that had to be made for the different simulation scenarios (Pnyx and Marketplace). Additional discussed components include the user interface and a script for global communication.

[3]Ink Phantom Studio. (2018). Polylised - medieval desert city. Retrieved from https://assetstore.unity.com/packages/3d/environments/historic/polylised-medieval-desert-city-94557.

[4]Unity3D. (2018c). Unity asset store. Retrieved from https://www.assetstore.unity3d.com/.

[5]DirectX. (2018). Microsoft direct3x overview. Retrieved from https://msdn.microsoft.com/en-us/library/windows/desktop/ff476080.

[6]OpenGL. (2018). Opengl overview. Retrieved from https://www.opengl.org/.

[7]PhysX. (2018). Nvidia physx overview. Retrieved from https://developer.nvidia.com/gameworks-physx-overview.

[8]Unity3D. (2018b). Mecanim animation system. Retrieved from https://docs.unity3d.com/462/Documentation/Manual/MecanimAnimationSystem.html.

4.2.1 User

A potential user (e.g. researcher) is placed in the simulation at a predetermined place. In the Pnyx simulation, this is in front of the Pnyx structure, among the crowd of human agents, that were instantiated at the start of the simulation. In the Marketplace simulation, the starting point for the user is inside the market itself. The simulations are seen through a first-person perspective, with the standard WSAD + mouse movement scheme described in Table 4.1. A first-person (rather than a third-person) perspective is used to support potential virtual reality versions of the simulations.

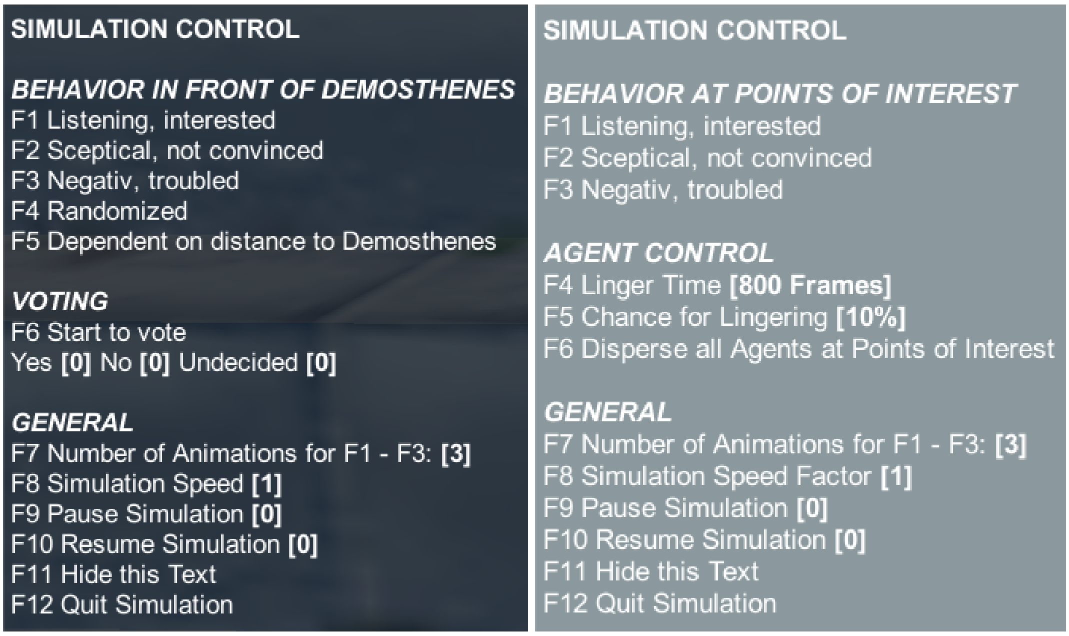
W	Move Forward
S	Move Backward
A	Slide Left
D	Slide Right
Space	Jump
Mouse X	Look Left and Right
Mouse Y	Look Up and Down

Table 4.1: Movement scheme within the simulations

The user avatar in both simulations consists of a standard character controller, a first-person controller script, a Rigidbody component for physically correct movement, and an audio source for standard sound clips that are played when the user walks or jumps. Additional to the standard components, a script for displaying the user interface, and a script for the global communication is attached to the user avatar game-object.

4.2.2 User Interface

The user interface is the main source of information (for the user) on how to interact and influence the human agents that are moving through the simulation environment. It describes different parameters, what they do, and how to change them. It is displayed as a simple text overlay. This overlay is different in each of the simulations because the exposed parameters are different for each of the simulations. Both overlays are drawn in the bottom left corner of the screen. It is text based and kept very simple and flexible, to support the adaption of the displayed parameters for potential virtual reality versions of the simulations. A depiction of the basic user interface can be seen in Figure 4.1.



(a) (b)

Figure 4.1: User interface overlay, (a) for the Pnyx simulation, (b) for the Marketplace simulation

Additionally, the frames per second are calculated and displayed in the upper left corner of the screen. The basic human agent control and the general simulation controls are both routed through a global communication script, as described in the next section.

4.2.3 Global Communication

This module is an important necessity because variables within one script of a game-object do not 'live' outside of the instances of that particular object. This means that for information to pass through, from one script that is attached to a game-object, to another script of a game-object, it becomes necessary to implement the Unity equivalent of a singleton pattern. This is what the global communication module represents, a very small, simple implementation of a singleton pattern. It restricts the instantiation of a class to exactly one object. In this case, this script holds a number of different parameters that are important for the control of both simulations. These parameters include variables for voting, the general simulation speed, number of animations, lingering time and chance for lingering. This module is responsible for communication and the pass-through of parameter values between the human agent behavior algorithm, user input, and the user interface overlay.

4.2.4 Instantiate Agents

This module enables a variable number of human agents to spawn around an original human agent. This original agent is hand-placed by a user, and represents the template that is used for duplication. Additional (offline) parameters that are available here include the number of agents that should be spawned, the spawn radius all duplicates will spawn within, a random movement speed boolean with an associated range (so that all agents have different walking speed), and a general simulation speed factor that directly impacts all movement and animation when the duplicates are instantiated. Although this general simulation speed factor can also be changed anytime at runtime, this enables researchers to specify it before the simulation starts, which can be beneficial depending on the scenario. This is demonstrated in the following code snippet:

```
...
void CreateGroup()
{
    originPoint = original_agent.transform.position;

    for (int i = 0; i < agent_count; i++)
    {
        if (random_speed)
        {
            agent.speed = Random.Range(sim_speedup_factor * min_speed,
                                       sim_speedup_factor * max_speed);
        }
        CreateAgent();
    }
}

void CreateAgent()
{
    xx = Random.Range(-spawnRadius, spawnRadius);
    zz = Random.Range(-spawnRadius, spawnRadius);
    Vector3 point = new Vector3(originPoint.x + xx, originPoint.y, originPoint.z + zz);
    Instantiate(original_agent, point, transform.rotation);
}
...
```

This module can subsequently be used for all available agent templates on different spots within the simulation environment (shown in Figure 4.2 and Figure 4.3). This enables a user (e.g. researcher) to use all available human agent models to populate a scene, with an exact number and exact placement for different groups of human agents.

Figure 4.2: Instantiation in the Pnyx simulation, human agent templates and their duplicates

Figure 4.3: Instantiation in the Marketplace simulation, human agent templates and their duplicates

4.2.5 Human Agent Behavior

The following scripts for the respective Pnyx and Marketplace simulations represent the algorithm that is responsible for the agent behavior logic. Different behavior patterns are utilized, depending on the scenario of the simulation. The same basic algorithm is used in the Pnyx as well as the Marketplace simulation. The differences in these scripts, come from the different requirements of the two scenarios and are explained below. Before that, a detailed look at the animation system that is responsible for the behavior expressions of human agents, and the Unity navmesh system that ensures basic obstacle avoidance capabilities for all human agents, is presented.

Animation

Human agent behavior is always depicted through the use of different animations. This works with the help of a runtime animation controller. This controller enables the use of different animations, and more importantly the use of different animation transition during runtime. Depending on the behavior a human agent has to display, certain animations have to transition into other animations. This has to happen as a smooth as possible to not break the user immersion in the depicted environment. For this to work properly, a number of animation transition had to be configured. These animation transitions, and not the animation states themselves, are then triggered directly from the necessary scripts. Without the animation transition, the direct use of an animation stage that is switched to another animation stage within a script would lead to a result that is very jarring, stiff and abrupt.

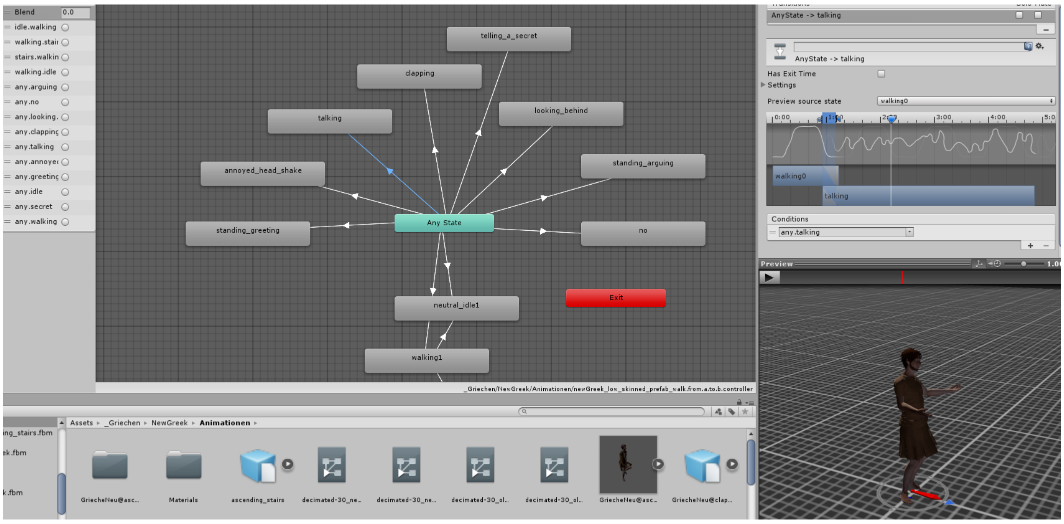


Figure 4.4: Runtime animation controller and corresponding animation transitions

This is why animation transitions for every available animation were developed (shown in Figure 4.4). These animation transitions were then used to show corresponding behavior for the human agents.

Navmesh

For a single human agent to be able to properly traverse a given terrain model and have basic obstacle avoidance capabilities within the simulation environment, that agent needs a navmesh agent component in Unity. Additionally, a navmesh for that simulation environment and all non-traversal objects has to be *baked*. This is an essential preprocessing step, that is done once for every simulation environment, to ensure that human agents know where they can and cannot go. A depiction of the navmesh for both simulations can be seen in Figure 4.5 and Figure 4.6.

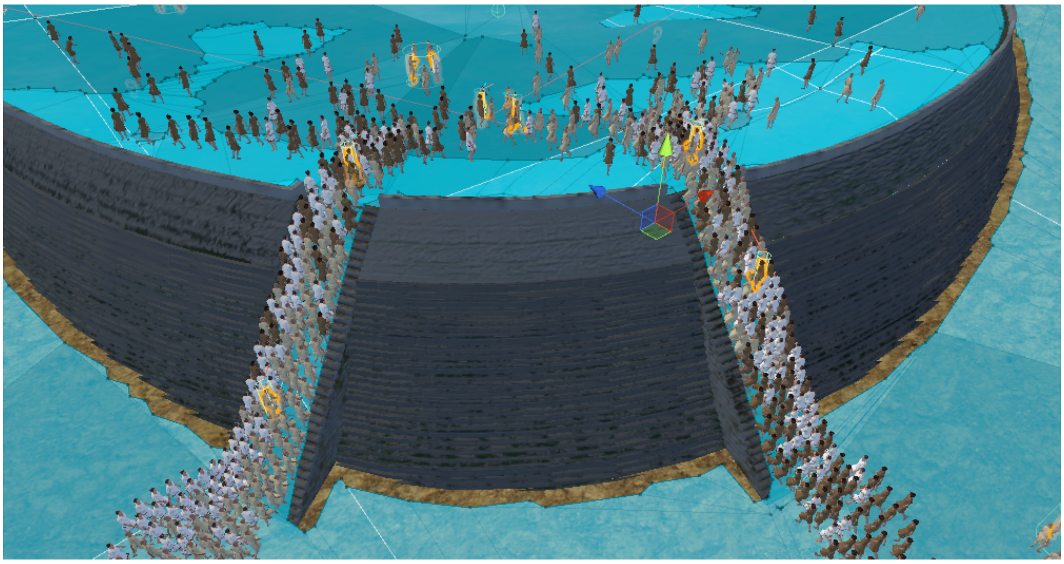


Figure 4.5: The navmesh for the Pnyx: traversable areas for human agents are shown in blue

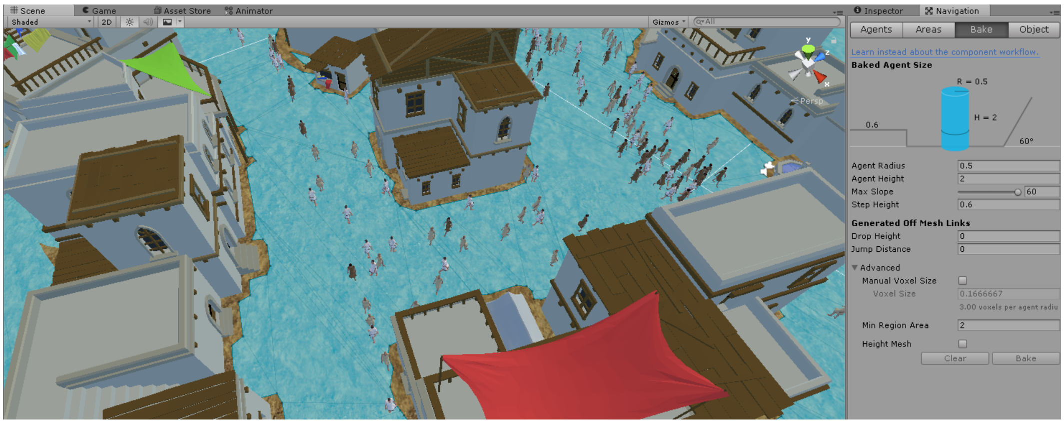


Figure 4.6: The navmesh for the Marketplace: traversable areas for human agents are shown in blue

Pnyx

A short overview of the different parts of the algorithm for the Pnyx simulation is described in the following. This includes what a human agent can do inside the Pnyx scenario, and which parameters a user can influence during the runtime of the simulation.

For the Pnyx simulation, basic actions for human agents include:

- go to the next navigation point (while exhibiting a walking or stair traversal animation)
- when the platform of the Pnyx is reached, find a free place within the confines of the platform
- if that place has been occupied in the time it took to get there, look for a new free place in the surrounding area of the current location
- when the destination is reached, turn towards Demosthenes and show a randomly chosen behavior (animation)
- if, on the way to your destination, a discussion between other agents interests you, join the conversation

For the Pnyx simulation, basic parameters for the user to influence include:

- the human agent behavior on the platform, in front of Demosthenes, in five categories:
  - listening, interested
  - skeptical, not convinced
  - negative, troubled
  - randomized
  - dependent on the distance to Demosthenes

- the number of animations used for these different behavior categories can be changed between one, two or three different animations
- a basic voting mechanism, currently with a randomized chance distribution
- human agent speed, for traversal and animations, during the runtime of the simulation
- the ability to slow down, pause and resume the simulation
- the ability to deactivate the user interface

Here, an important aspect for a implementation discussion is the ability of agents to find a free space on the platform. First all agents traverse a number of predetermined navigation points, during which they chooses the right animation transitions for either walking or traversing stairs (shown in the Figure 4.7).

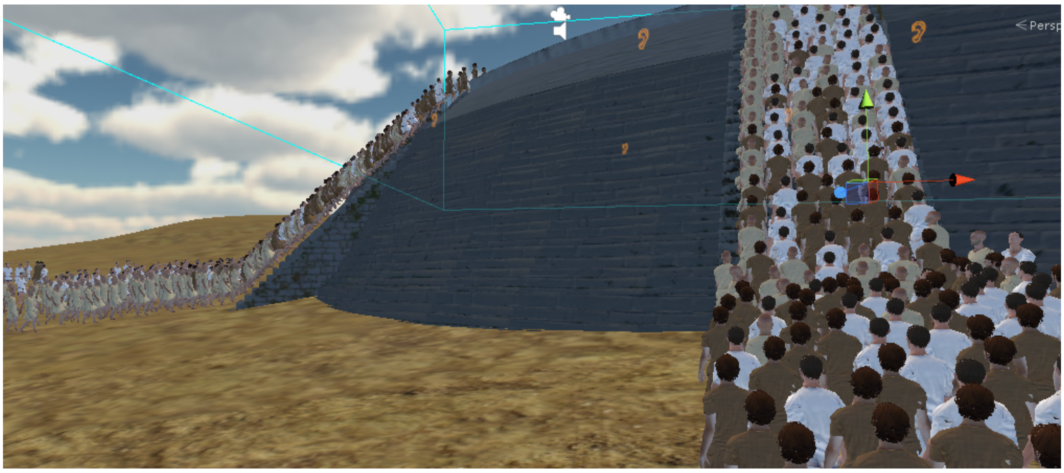


Figure 4.7: Agents walk to the stairs, switch animations, and traverse the stairs to reach the platform

After the agent reaches the platform (shown in Figure 4.8), a random point within a certain radius of the current location is selected on the platform mesh of the Pnyx.

Figure 4.8: Agents try to find a free place on the platform

How an agent finds this random point on that platform is shown in a short code snippet below:

```
void choosePoint(float range, string mesh)
{
    float xx, zz;
    int i=0;
    while (i < 1)
    {
        xx = Random.Range(-range, range);
        xx = xx * 5;
        zz = Random.Range(-range, range);
        zz = zz * 5;
        Vector3 position = new Vector3(agent.transform.position.x + xx,
                                       agent.transform.position.y,
                                       agent.transform.position.z + zz);
        RaycastHit hit = new RaycastHit();
        if (Physics.Raycast(position, Vector3.down, out hit))
        {
            if (hit.collider.tag == mesh)
            {
                agent.destination = new Vector3(agent.transform.position.x + xx,
                                                hit.point.y,
                                                agent.transform.position.z + zz);
                i++;
            }
        }
    }
}
```

A vector position is randomly chooses within a certain radius of the current agent location. A ray is cast vertically through the target mesh at the random vector position and checked against a hit. If this position is found to be on the target mesh, this position is designated as the agents new destination. Subsequently, this point is chosen as the next point in the navigation path of the agent. In the case of the Pnyx simulation, this is the agent's final destination (agents that have reached that point can be seen in Figure 4.9).

Figure 4.9: All human agents have found their place on the platform in front of Demosthenes and show different behavior patterns

To comply with the performance requirement outlined in Chapter 3, the method `choosePoint()`, at least in the current implementation, is not used on a regular basis for agent path-finding (only in this case on the Pnyx platform). This is because ray-casting on large meshes, done multiple times in short succession, inherently requires a lot of performance, especially when used often within a single agent behavior script, let alone by a great number of agents at once.

An overview of how all these agent rules and possible user inputs interact is shown in 4.10.

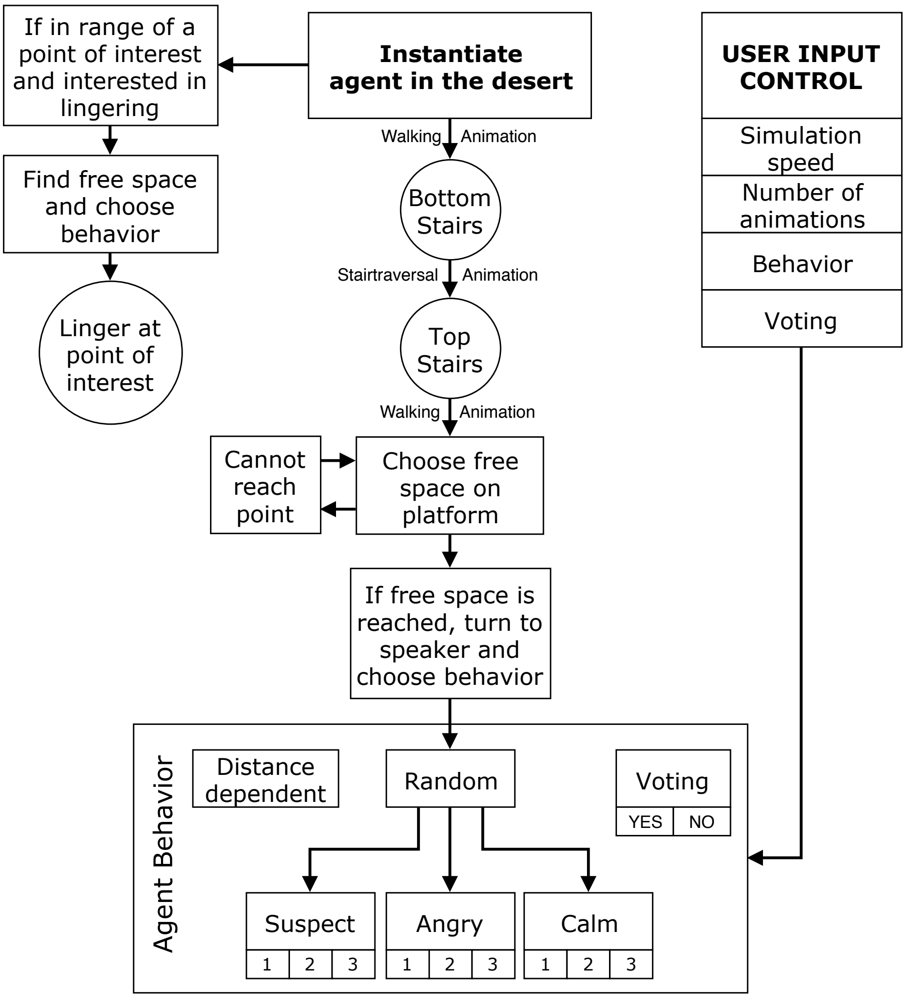


Figure 4.10: Basic agent behavior patterns and possible user interjections for the Pnyx simulation

Additional behavior routines and essential functions of the user input control, that are used in the Pnyx as well as the Marketplace simulations, will be shown during the implementation discussion in the next section.

Marketplace

A short overview of the different parts of the algorithm script for the Marketplace simulation is described below. This includes what a human agent can do within this Marketplace scenario, and which parameters a user can influence during the runtime of the simulation.

For the Marketplace simulation, basic actions for human agents include:

- go to the next (randomized) navigation point (while exhibiting a walking animation)
- if during the exploration of the market a seller interests you, turn to what interests you and stay there for a while
- during your stay, choose a behavior towards the seller
- after your stay, resume your randomized path through the Marketplace

For the Marketplace simulation, basic parameters for the user to influence include:

- the human agent behavior, at points of interest, in three categories:
  - listening, interested
  - skeptical, not convinced
  - negative, troubled
- the number of animations used for these different behavior categories can be changed between one, two or three different animations
- the time an agent lingers at points of interest (currently adjustable between 100, 200, 400 and 800 frames)
- the chance an agent has to be interested in a seller (currently adjustable between 10%, 20%, and 50%)
- the option to disperse all human agents from all points of interest at once

- human agent speed, for traversal and animations, during the runtime of the simulation
- the ability to slow down, pause and resume the simulation
- the ability to deactivate the user interface

An overview of how all these agent rules and possible user inputs interact is shown in Figure 4.11.

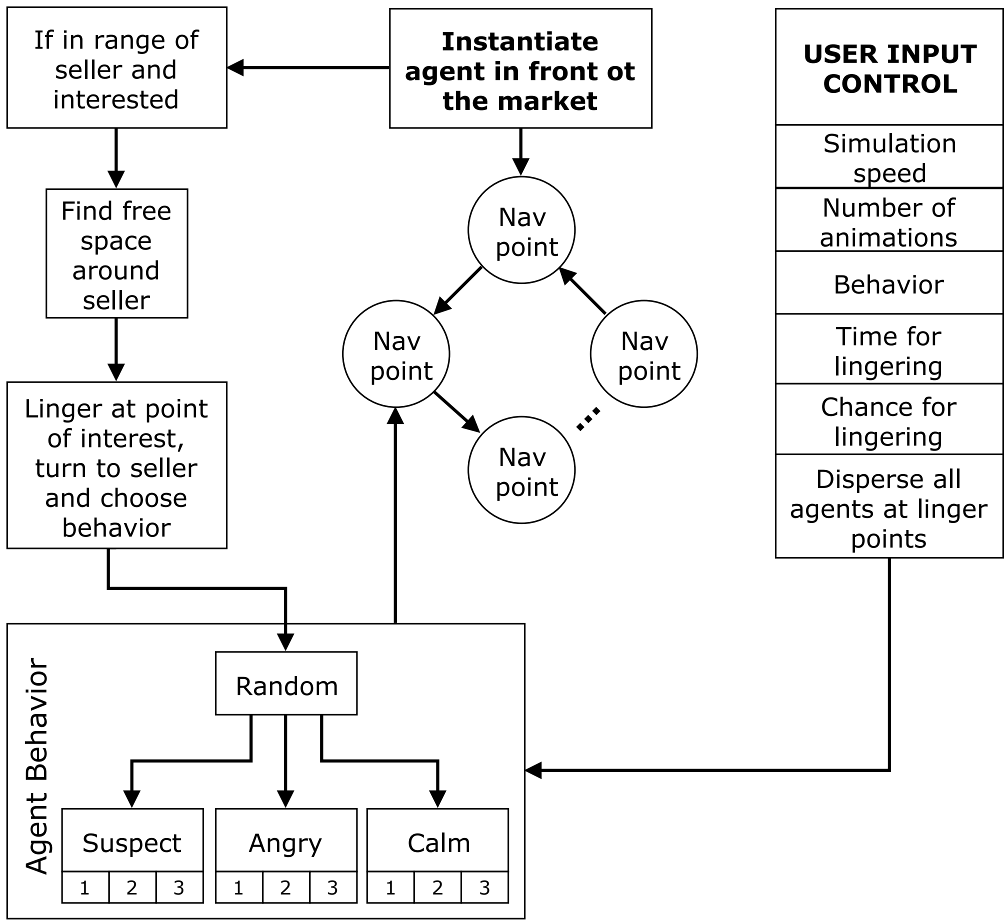


Figure 4.11: Basic agent behavior patterns and possible user interjections for the Marketplace simulation

A very important aspect of the detailed implementation discussion is the ability of human agents to decide to linger at a point of interest (as depicted in Figure 4.12).

Figure 4.12: A number of agents lingering at a point of interest

Although this behavior can also be exhibited by human agents in the Pnyx simulation, in the Marketplace simulation human agents can resume their original path through the market (can be seen in Figure 4.13) after a specific, user adjustable time-frame. Also adjustable is the chance a human agent has to be interested in a seller. Also, the user has the ability to disperse (reset) all lingering agents at all points of interest, so that subsequently all agents resume their original navigation path.

Figure 4.13: A number of agents walking through the market

A few short code snippets, that show how an agent is drawn to a point of interest, and how basic user input control is managed, are shown below:

```
void linger()
{
    float distance_1;
    float big_range = 0.15f;
    float small_range = 0.05f;
    distance_1 = Vector3.Distance(agent.transform.position, linger_point_1.position);
    if ((distance_1 < 3.5f) && (distance_1 > 3.25f) && (static_random_high_chance == 1))
    {
        anim.Play("walking1", anim.GetLayerIndex("Base Layer"));
        chooseLingerPoint(small_range);
        direction_point = linger_point_1;
        dest_reached = true;
        want_to_linger = true;
    }
    ...
}
```

In this short code snippet the basic concept of how an agent determines if a point of interest is close, and what chance that agent has of actually picking that point, is shown. The `linger()` method calculates the distance between the agent and a potential point of interest, and through a given chance the agent determines if it will stay at that particular point or not.

```
void control()
{ ...
    if (Input.GetKeyDown(KeyCode.F5))
    {
        switch (chance_factor)
        {
            case 1:
                chance_factor = 2;
                break;
            case 2:
                chance_factor = 5;
                break;
            case 5:
                chance_factor = 1;
                break;
            default:
                break;
        }
        Global.chance_factor = chance_factor;
        static_random_high_chance = Random.Range(0, 10/chance_factor);
        return;
    }
    ...
}
```

In the method `control()`, this chance can be adjusted through a keystroke, in this case by pressing F5. The same basic concept is used in the method `chooseBehavior()`, where through pressing F1, one of three possible animations (for the behavior state 'interested') is randomly chosen and performed by the agent at a point of interest.

```
void chooseBehavior()
{
    int random;
    if (Input.GetKeyDown(KeyCode.F1))
    {
        random = Random.Range(0, number_of_animations);
        switch (random)
        {
            case 0:
                anim.SetTrigger("any.idle");
                break;
            case 1:
                anim.SetTrigger("any.greeting");
                break;
            case 2:
                anim.SetTrigger("any.looking.behind");
                break;
            default:
                break;
        }
        return;
    }
    ...
}
```

This concludes the discussion about implementation details. The depicted modules and script snippets, for both the Pnyx and the Marketplace simulations, are essential for understanding the basic behavior implementation for human agents.

4.3 Summary

For this project, two distinct simulations were implemented (Pnyx and Marketplace), both with a slightly changed human agent behavior algorithm, adapted for these different scenarios. Most problems with the implementation of the algorithm were performance related. This mostly had to do with the number of agents used. The highest number of agents that could be achieved (for the Pnyx simulation), without comprising the performance (30 FPS), was 600 (Hardware: Intel Core i5 5300U, 8 GB RAM, Intel HD 5500 GPU). Additionally, ray-casting that is done multiple times, by multiple agents on a large target mesh (like the Pnyx platform) can also lead to performance problems. For the Marketplace simulation, navigation points where therefore predetermined and randomized, subsequently there were no performance problems in this regard. The number of agents used in this scenario was 185. This number was chosen, to give the size of this simulation scenario a proportional number of human agents.

The user interface for both simulations was intentionally kept simple, not only to fulfill the compatibility requirement (e.g. parameters depicted in the interface should be easily portable to potential virtual reality versions), but also to help simulation usability. The discussed use of ray-casting for runtime calculation of destination points, has been made optional, primarily to fulfill the performance requirement. But also for flexibility reasons, so that users (e.g. researchers) are able to setup their own destination points (e.g.

for the auralization; to be able to hand-place potential acoustic simulation points).

Additional implementation work would include more differentiators for human agents, additions to offline and online parameters, for example, different behavior patterns for human agents with different social or economic status, or additional gender-related behavior. Also, additional information explaining the user interface and its different parameters in more detail could be helpful for the user. The evaluation part of this work in Chapter 5, could also offer information for additional implementation tasks. All the different modules depicted in Figure 3.6 from Chapter 3 were implemented.

5 Evaluation

In this chapter, the results from a first study of the Pnyx and Marketplace simulations are presented. For this study of the two distinct simulations, a version of both simulations was distributed to all participants for testing. The participants were graduated archeologists, archeology students, and computer science students. This first study of the simulations is focused on general usability, immersion and possible benefit for archeological research. In the following section, the research methodology, procedure, participants, and results of this study are discussed.

The two simulations that are evaluated, were designed with a focus on the usability of the user interface and the simulation controls, flexibility of the human agent behavior through parametrization, general performance, scenario immersion, and research value.

5.1 Research Methodology

To test and evaluate the Pnyx and Marketplace simulations, a version of both simulations was distributed to all participants for testing, and a survey with a pre-questionnaire and a post-questionnaire was used. The abbreviation used in this chapter include: ″CES″ = ″Computer Emotions Scale″, ″SUS″ = ″System Usability Scale″, ″SD″ = ″standard deviation″, ″M″ = ″mean″.

- Pre-questionnaire
  - Personal information about the participants
  - Previous experience with similar simulations and games
- Post-questionnaire
  - Simulations specific experience and comments
  - General usability of the simulations
  - Emotional state during the testing of both simulations

Both simulations were evaluated with one group of people. This group consisted of graduated archeologists, archeology students, and computer science students. This group was tasked with testing both simulations. No additional information about the simulations was given.

5.2 Procedure

The current version of both simulations was sent to every participant. After a pre-questionnaire, that included a few personal questions and questions about previous experiences with similar simulations, participants were asked to experience both simulations. They were also encouraged to use the user interface overlay to change different simulation parameters.

- The Pnyx simulation consists of a scene where 600 agents walk onto the platform of the Pnyx to listen to a speaker. The participants were asked to explore the simulation and to change a number of simulation parameters (for agent behavior or general simulation variables)

- The Marketplace simulation consists of a small city district with a number of sellers, while 185 agents walk through this market. The participants were asked to explore the simulation and to change a number of simulation parameters (for agent behavior or general simulation variables)

In the post-questionnaire the participants were asked to evaluate usability, immersion, and possible archeological research value of these simulations.

5.3 Materials

This evaluation included 22 question, including the standardized SUS (Brooke, 1996) questionnaire, and the CES (Kay & Loverock, 2008) questionnaire. The SUS is based on the Likert-scale (from 1 = strongly disagree, to 5 = strongly agree). The CES use 10 standard indicators, that range between 1 (none of the time) to 4 (all of the time). Some of the questions are in an open-ended format. A detailed overview of these questions is shown in the next sections.

5.3.1 Pre-questionnaire

The pre-questionnaire included a few personal questions and questions about previous experiences with similar simulations, games and experience with standardized input controls.

- Personal Information
  - The personal information that was asked included questions about age, gender, profession, and the highest level of education
- Previous Experience
  - In this question category, previous experiences with similar simulations, as well as the experience with standard input methods like keyboard and mouse, are asked. Furthermore, experience with computer games is also asked

5.3.2 Post-questionnaire

In the post-questionnaire the participants were asked to evaluate the simulations in regard to general usability, immersion and possible benefit for archeological research. This also included the SUS and the CES questionnaire.

- Simulation specific Questions
  - In this part of the questionnaire, specific simulation related questions were asked, for example, what participants liked or disliked, which of the two simulations they did like more, a number of details about possible problems with the simulations or the controls, and possible missing features of the simulations. Participants were also asked if they would use these simulations on a regular basis, and if so, what they would use it for
- System Usability Scale
  - The SUS is a tool used for evaluation that provides 10 measures with a fixed pre-defined scale. It measures user satisfaction, usability effectiveness, and usability efficiency (Brooke, 1996)

- Computer Emotions Scale
  - The CES is is a tool used for measuring different emotions from a user, after using new computer software. Emotions like curiosity, satisfaction, anxiety, and anger are measured (Kay & Loverock, 2008)

5.4 Participants

There were a total of 10 (3 female, 7 male) participants, between 25 and 34 (M = 29.6; SD = 2.65) years old, 8 of these participants are graduated archeologists or archeology students, 2 are computer science students. The 8 graduated archeologists and archeology students represent the target audience for both simulations. The 2 computer science students were invited to participate as application experts, to get different opinions of the simulations. 7 of the 10 participants stated that they play computer games. Most of these 7 prefer to play action or role-playing games. Games that participants had played included: "Fallout", "Tomb Raider", and "Assassins Creed". Most of the participants are very experienced with standard input methods for games or simulations (M = 3.9; SD = 1.45). Only half of them had previous experience with archeological or historical virtual environments (M = 2.1; SD = 1.37). When asked about experience with parameters driven simulations, the results were a little higher (M = 2.9; SD = 1.6).

5.5 Results

The results presented here are a mixture of open-ended answers, experiences, and comments from the participants. Answers from the SUS are based on the Likert-scale (from 1 = strongly disagree, to 5 = strongly agree). Answers from the CES use 10 standard indicators, that range between 1 (none of the time) to 4 (all of the time).

The general reactions from the participants after testing both simulations were good. When the participants were asked what they thought, the first impressions ranged from *"good, enjoyable, interesting, fun"* to *"fine, confusing, a little bit spooky"*. What Participants liked about both simulations was: *"being part of the scene, being able to manipulate the scene, free movement, voting"*. Additional participant comments about the simulations included: *"nice layout, certain points of interest catching the eye immediately, moving of crowd seemed realistic, game like intuitive controls, real time change of parameters and seeing their impact, simulations were coherent and on point"*.

Usability

The answers are based on the Likert-scale (from 1 = strongly disagree, to 5 = strongly agree). The mean rating for the SUS was 74,25 (SUS grading: Good) with a standard deviation of 20. 7 of 10 participants strongly agreed, that both simulations were easy to use (M = 4.7; SD = 0.48). The participants did not think that a technical person was necessary to use these simulations (M = 1.5; SD = 0.71). The opinions on the integration of the various function within the simulations were mixed (M = 3.33; SD = 1). The participants did not find many inconsistencies within the simulations (M = 2.3; SD = 0.82), and felt very confident while using the simulations (M = 4.4; SD = 0.70). The navigation in both simulations, for all 10 participants, was characterized as easy.

Performance

None of the participants had any performance problem. Although, when asked about the parametrization, one participant noticed something interesting: *"Good Idea, but mostly useless. E.g. the time frame of 800 frames was way to low, to observe differences, when the system runs with 250 fps"*. Since the simulations where developed on older hardware (Intel Core i5 5300U, 8 GB RAM, Intel HD 5500 GPU), a frame dependent timescale was never a problem, and certain parameters were configured accordingly during development. But this clearly shows the need for a performance independent timescale. Fortunately, the point raised by this participant can easily be rectified by changing this parameter during the setup stage of the simulation scenario (or through a frame rate limit).

Emotions, Immersion and Research Value

In general, the participants stated that they liked the simulations. Half of the participants liked the Pnyx simulation more, while the other half liked the Marketplace simulation more. The reasons given from both half's of the participants were the same: *"because it feels more believable/realistic, looks better, the parameter effects were clearer to distinguish"*. On participant said: *"i much enjoyed the impression of having a crowd around me walking to the same event as I am, to experience a lively scene"*. Another stated: *"quite interesting as the crowd seemed to move autonomously, nice environment created, felt a bit like the old CounterStrike"*. When asked about using these simulations on a regular basis 6 of 10 participants said yes. The reasons that were stated for the possible use of these simulations included: *"research into these spaces, discovering life in different times, museum exhibitions"*.

The participants emotions were measured using the CES. The 10 standard indicators range between 1 (none of the time) to 4 (all of the time). The focus of the measured emotion was curiosity, satisfaction, anxiety, and anger, a statistical overview of the results can be seen in Figure 5.1, 5.2, 5.3, and 5.4.

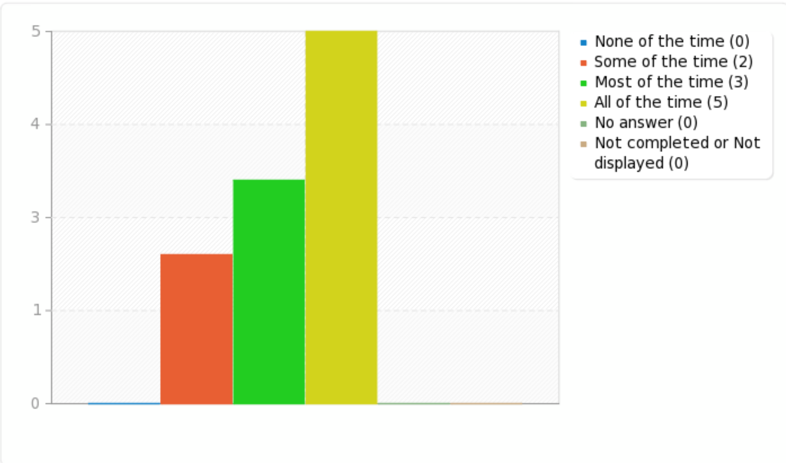


Figure 5.1: Statistic for measured curiosity (M = 3.3; SD = 0.82)

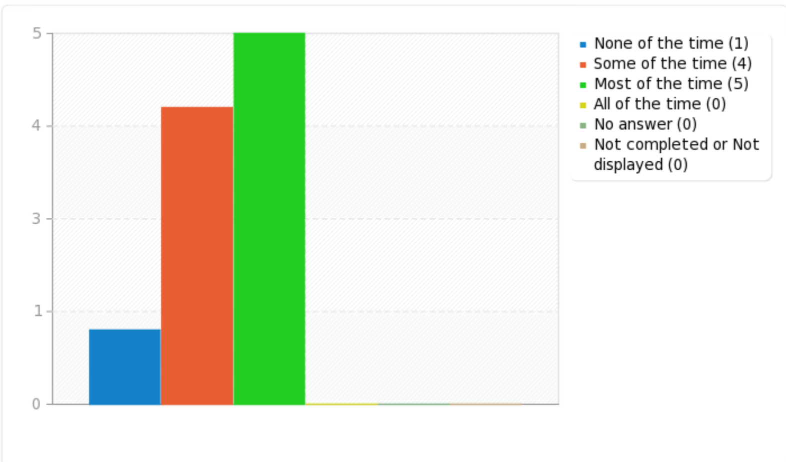


Figure 5.2: Statistic for measured satisfaction (M = 2.4; SD = 0.70)

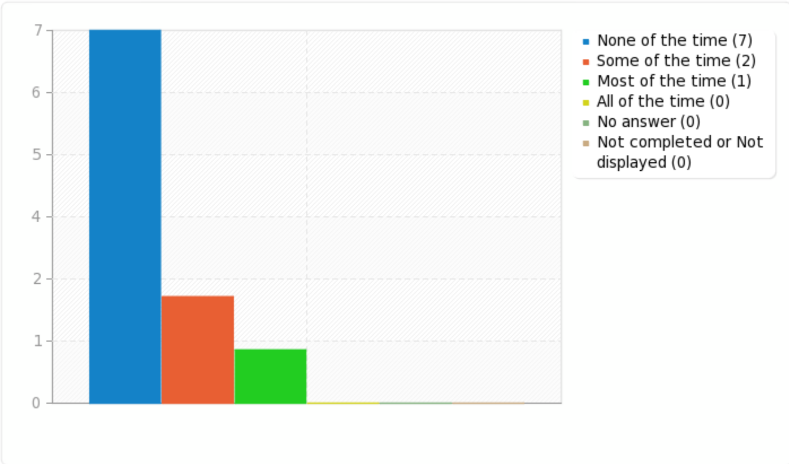


Figure 5.3: Statistic for measured anxiety (M = 1.4; SD = 0.70)

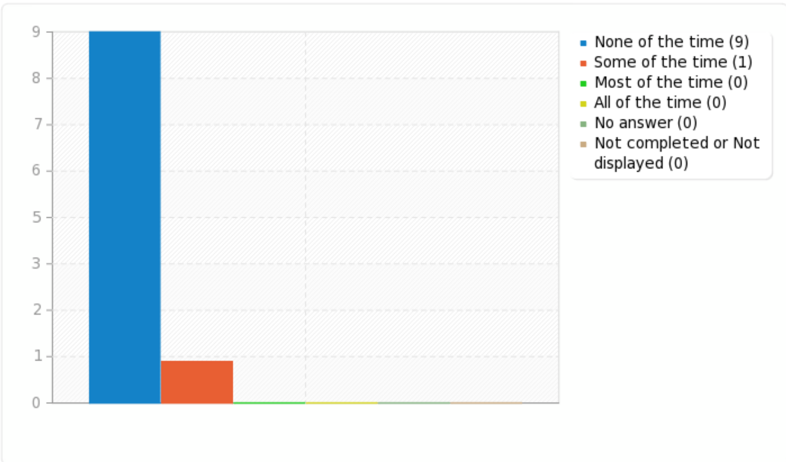


Figure 5.4: Statistic for measured anger (M = 1.1; SD = 0.32)

Problems and Missing Features

Although none of the participants had any technical problems, participants noticed that: *"parameter effects only work in specific places, there are not enough difference between animations for different behaviors, there is not enough lingering* *time for agents, animations are stiff, there is some weird path-finding going on"*. One participant stated that: *"some aspects led to a feeling of less accuracy, e.g. in market situation would have expected the people to linger longer, which would lead to larger groups; when entering Pnyx at some point so many people were on the stairs, it felt too full and fast to be a representation of how the stairs should be climbed"*. Another commented that: *the greek people look not very different from each other"*. In general the participants recognized a number of missing features, that included: *"more contextual information about the simulations, additional parameters for different voting distributions, longer lingering times, women for the human agent model pool, vegetation"*.

5.6 Discussion

In general, the evaluation results were very informative. Most participants felt very curious about the simulations and thought that the simulations were easy to use. Anxiety and anger, while using the Pnyx or Marketplace simulations, were low, while the satisfaction felt during the simulation experience was higher than average. What participants liked about both simulations include:

- *being part of the scene*
- *being able to manipulate the scene*
- *free movement*
- *voting*
- *moving of crowd seemed realistic*
- *game like intuitive controls*
- *real time change of parameters and seeing their impact*

Also, the participants did not think that a technical person was necessary, and felt very confident while using the simulations. But the need for more information about different simulation parameters displayed in the user interface was clearly recognized, also the integration of the various control mechanism for agent behavior was received with mixed reactions. Also, most participants mentioned that higher fidelity models and animations would be good improvements for future versions. In summary, the results of this study were clear and lead to a list of possible improvements, that include:

- more and clearer information for the simulation specific user interface
- more diverse models (gender aspects)
- better animations, and more animation states
- more significant differences for most parametric behaviors
- additional parameters, e.g. a parameter for different voting distributions
- performance independent timescale

These possible improvements will be looked at in more detail in Chapter 7. In the next chapter, the lessons learned during the literature research, development and this first study will be discussed.

6 Summary and Lessons Learned

This chapter presents a summary, and the lessons learned during the literature research, development phase, and the conducted study of the two simulations. Some of what is presented here, especially possible improvements, will also be discussed in Chapter 7.

6.1 Theory

During the literature study of this work, a short overview was given, of how archeology uses digitalization to scan and build virtual representations of historical artifacts and sites. With special emphasis on how these virtual environments are built, and how they help to set the stage for the simulation of human elements. Furthermore, a look at how museums realize the potential of these new technologies, for the development of edutainment content, and services for their visitors, was presented. The major second part of this the literature study presented information about concepts of crowd behavior modeling and different approaches and methodologies that are used for the simulation of humans in historical settings. Through literature findings made in Chapter 2, especially the lessons learned from the comparison of the work from Maim et al. (2007) and Shao and Terzopoulos (2006), it became apparent that agent-based modeling is a good approach for simulating humans in virtual archeological environments. During the research of these two case studies, and through a subsequent comparison made in Table 2.1, certain design decisions for the algorithm depicting the agent-based behavior became clear. This especially concerns the decisions regarding which parts of the basic agent behavior should be preprocessed during the setup stage of the simulations, and which parts should be processed during the runtime of the simulations. This trade-off influences the complexity of the agent behavior, the flexibility of the underlying algorithm for the behavior, runtime performance of simulation developing the algorithm, and the time it takes to adapt that algorithm for a new scenario.

6.2 Development

Unity was used as the main development environment for this work. The main reasons for this were because Unity supports easy navmesh *baking*, which is indispensable for proper path traversal and obstacle avoidance for human agents. It also enables easy development of desktop and virtual reality versions of the same simulation. This was also an important consideration for the user interface, that was intentionally kept simple and text based, to support the adaption of the displayed parameters for a potential virtual reality version. For these reasons, and because the original virtual environment concept from Holter and Schäfer (2018) was based on Unity, it was an obvious choice for the development environment. Through the design and development phase of this work an iterative design and development approach was used. This was an important decision, that helped the development of a prototype of the Pnyx simulation, that was subsequently improved over time. This was very useful for testing and evaluating different concepts, in regard to which part of the human agent behavior should be done during the runtime of the simulations, and which part during the setup of the simulation scenario. The Marketplace simulation was developed after the Pnyx simulation was finished, to showcase the flexibility of the behavior algorithm. Both simulations use the same basic behavior algorithm, slightly adjusted for the respective scenario.

To reach a certain level of flexibility for the algorithm, and ensure its applicability for different scenarios, every part of the agent behavior, except for the location of navigation points and points of interest, had to be calculated during runtime. Although this ensures a high level of flexibility for the algorithm, it also requires more performance during runtime. Flexibility, performance and scalability were all important requirements for the algorithm and the simulations, but in this case flexibility had the highest priority. Performance was still taken into account through hand-placing navigation points, instead of calculating them at runtime (the calculation is still available but optional). Usability and compatibility was ensured through easy simulation controls, and an easy to use interface, that can be ported to potential virtual reality versions of the simulations. This algorithm and the two simulations represent a solid foundation for future improvements and extensions for this approach of simulating human behavior in historical scenarios.

6.3 Evaluation

The evaluation used a mixture of standardized questionnaires like the SUS for the usability testing, or the CES for measuring emotions, as well as a number of simulation specific questions. In general, the evaluation results very informative. Most participants felt curious about the simulations and thought that the simulations had intuitive controls and were easy to use. The mean rating for the SUS was 74,25 (SUS grading: Good) with a standard deviation of 20. The results of the evaluation were unambiguous for the most part. Participants felt very immersed in both simulations, they liked being part of the scene and simultaneously being able to manipulate the crowd and seeing the impact, all while moving freely through the depicted scenario. When asked about using these simulations on a regular basis 6 of 10 participants said yes. They also clearly recognized the possible use of these simulation for research and exhibitions. But this study also clearly showed some usability issues, a lack of variety in human agent models and behavior, and the need for a performance independent timescale. These issues show a clear road-map for potential future work, which will be discussed in the next chapter.

7 Future Work

The main aspect of this chapter will be the suggestions for future improvements of this work. These suggestions come from the observations the participants made during the evaluation part of this work, those include usability suggestions, and content and fidelity improvements of the simulation scenarios. The last section will discuss the integration of the behavior algorithm into the work of Holter and Schäfer (2018).

7.1 Evaluation Results

As previously mentioned in Chapter 5, the results of the evaluation were clear and the participants articulated a number of possible improvements to both simulation scenarios:

- more and clearer information for the simulation specific user interface
- more diverse models (gender aspects)
- better animations, and more animation states
- more significant differences for most parametric behaviors
- additional parameters, e.g. a parameter for different voting distributions

And although a more diverse human agent model pool (e.g. women and children) would be a good addition to the diversity and immersion of possible future simulation scenarios, and additional animation states would ensure that the agent behavior is more distinguishable, both were not the focus of this work. The goal for future improvements should be to develop a better interface for the different simulation scenarios, that displays more detailed information to the user, a performance independent timescale for certain parameters, and additional human agent behavior capabilities.

7.2 Behavior Algorithm

The observations made during the evaluation phase lay the groundwork for possible improvements for the simulation scenarios, which in turn also affect the underlying algorithm. But beyond the suggestions of the participants of the conducted study, a number of addition archeological requirements can be added to the list of future improvements. These include the implementation of more differentiators for human agents, for example, different behavior patterns for human agents with different social or economic status, or additional model dependent behavior (e.g. for women or children).

7.3 Algorithm Integration

In a next step, the underlying algorithm of the Pnyx and Marketplace simulations will be integrated into the work of Holter and Schäfer (2018). Since Holter and Schäfer originated the concept for the Pnyx simulation, the progress made in their work has been mainly focused on the fidelity (models, textures, vegetations, lighting) of the Pnyx scenario.

A current depiction of that progress can be seen in Figure 7.1.

Figure 7.1: Current depiction of the Pnyx scenario from Holter and Schäfer (2018)

The integration of the algorithm that was developed in this work will be a valuable addition, and, through the simulation and parametrization of human agent movement and behavior, will add to the immersion of this visualization of the Pnyx. In the next chapter, a short conclusion of this work will be presented.

8 Conclusion and Outlook

Developing an immersive virtual environment of a historical site, that is based on archeological data, is a challenging task. This process involves digitization technologies (e.g. photogrammetry) to scan and build virtual representations of historical sites. Building such an environment is a meticulous process that involves multiple procedures. The resulting virtual environment established the foundation of a digitally recreated historical site and sets the stage for the simulation of human elements. From the different approaches that were researched for this task, agent-based modeling was chosen. There are two reasons for this. The first is that the simulation of humans in virtual archeological environments is not only done to evaluate academic hypotheses, or to study past human behavior, but for the immersion that comes from the inclusion of believable virtual humans. A single virtual human needs to be represented by an actual human model, that looks, moves, and behaves like a real human would in the depicted historical environment. The second reason is that the behavior necessary, to develop a believable scenario, needs to be complex, and often diversely allocated to different types of human agents. Not every virtual human has to have the same behavior. Individual differentiators like age, social status, economic status, and gender can all be factors in archeological depictions of virtual humans, and important distinguishing elements between them. This is why agent-based modeling was chosen as the foundation for the algorithm developed in this work. This algorithm was developed to give archeologists a flexible tool for simulating basic human behavior in different virtual environments.

As a showcase for this algorithm, the Pnyx and Marketplace simulations were developed to demonstrate how this algorithm can be used to implement parametrically changeable human agent behavior. Through the development of this work and the conducted study with the target group (archeologist), a number of conclusions can be drawn. All functional and most non-functional requirements were meet. For the non-functional requirements certain trade-offs had to be made.

Flexibility of the algorithm and its adaptability for different scenario had the highest priority, which meant that scalability and performance, while still important and addressed, were secondary. Performance was taken into account through hand-placing navigation points, instead of calculating them at runtime, which not only saves performance, but also removes the need for certain preprocessing steps (e.g. target mesh resizing). Scalability was not completely attained, because after all possible performance optimization was completed, the number of human agents in a given scenario is still inherently hardware dependent. Extensibility was ensured through the use of Unity and the adaptability of the algorithm itself. Compatibility was achieved through the consistent use of a first-person perspective, and a simple user interface, that can be ported to potential virtual reality versions of the simulations. The usability results of the evaluation can be categorized as good (SUS: M = 74,25; SD = 20). Participants did not think that they needed help, and felt very confident during testing. And although both simulations were generally well-liked, some issues were identified by almost all users. These included problems with the user interface, the need for additional scenario dependent information, and behavior specific additions for the algorithm, to ensure a higher human agent behavior diversity. Nevertheless all participants recognized the potential use for these simulations.

This work is a showcase for the potential of agent-based modeling in historical settings. Possible future improvements to this algorithm are planned and will add to the capabilities and immersion of this parametric human behavior simulation approach.

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