DEVELOPING ARTIFICIAL LIFE SIMULATIONS OF VEGETATION TO SUPPORT THE VIRTUAL RECONSTRUCTION OF ANCIENT LANDSCAPES

By

Eugene Ch'ng

A thesis submitted to
The University of Birmingham
For the degree of

DOCTOR OF PHILOSOPHY (PhD)

School of Engineering
Department of Electronic, Electrical & Computer Engineering
The University of Birmingham

September 2006

UNIVERSITY OF
BIRMINGHAM

University of Birmingham Research Archive

e-theses repository

This unpublished thesis/dissertation is copyright of the author and/or third parties. The intellectual property rights of the author or third parties in respect of this work are as defined by The Copyright Designs and Patents Act 1988 or as modified by any successor legislation.

Any use made of information contained in this thesis/dissertation must be in accordance with that legislation and must be properly acknowledged. Further distribution or reproduction in any format is prohibited without the permission of the copyright holder.

1st of 4 files

Introductory material and chapter 1

The remaining chapters and the appendices are in three additional files

Abstract

Research in ***Virtual Heritage*** has gained popularity in recent years. Efforts by the community of Virtual Heritage researchers to reconstruct sites considered worthy of preservation span from the historical "built environment", including the Pyramids at Ghiza and Virtual Reality Notre Dame, to natural heritage sites such as Australia's Great Barrier Reef and the Virtual Everglades at Florida. Other important efforts to conserve artefacts and educate visitors include Virtual Stonehenge, Pompeii and the Caves of Lascaux. Entire villages, cities and even caves have been constructed as part of virtual conservation efforts. These digital reconstructions have, to date, contributed significant awareness and interest among the general public, providing educational benefits to schoolchildren and new research opportunities to archaeologists and conservationists, to mention but two groups of beneficiaries. Today, to paraphrase the work of Professor Robert J. Stone, Virtual Heritage strives to deliver to a global audience, computer-based reconstructions of artefacts, sites and actors of historic, artistic, religious and cultural heritage in such a way as to provide formative educational experience through the manipulations of time and space. It is realised that the user experience and educational value of a Virtual Heritage site is crucial – the process of virtual reconstruction is as important as its outcome. The total experience therefore, hinges on the modelling accuracy, scientific credibility, and the interactive visualisation capability of a virtual site. However, many interactive media implementations in Virtual Heritage in the recent past have failed to make full use of the advanced interactive visualisation techniques available to researchers. In particular, an element that many end users might consider essential, namely the inclusion of "living" and responsive virtual agents are noticeably lacking in most all Virtual Heritage examples. The addition of these 'living' entities and environments could give Virtual Heritage applications a richer, more evolvable content, and a higher level of interactivity. Artificial Life (alife), an emerging research area dealing with the study of synthetic systems that exhibit behaviours characteristic of natural living systems, offers great potential in overcoming this missing element in current Virtual Heritage applications. The present research investigates the feasibility of constructing models of vegetation, exploiting new developments in Artificial Life implemented within a controlled Virtual Environment for application in the field of Archaeology. The specific area of study is the recently discovered and recently named *Shotton* river valley off the eastern coast of the United Kingdom – a region that once flourished during the Mesolithic Era prior to the post-glacial flooding of the North Sea.

To the two most important women in my life

My mother Geng Kim Tay
My wife Huey Yih Teoh

Acknowledgements

My utmost gratitude to my supervisor Professor Robert J. Stone, a visionary and veteran in his field, for his lasting advice and much needed support throughout the course of this research. Thank you for initiating the most interesting project I've ever had the chance to come across, and my deepest appreciation for making the PhD a possibility.

To Professor Vince Gaffney, thank you for providing the datasets of the Shotton River Valley and for your wonderful team of archaeologists, geo-archaeologists, and palaeo-environmentalists. Thanks to Mr. Simon Fitch and Dr. Benjamin Gearey for pointing out literatures related to the river valley and for your time and archaeological contributions in specific junctures of the project.

My gratitude to Mary Winkles for listening to my laments and, for all the help that made my PhD a worthwhile experience. Special thanks to Madeleine Comley for arranging the financial support for this research and for being such a wonderful person. A big thank you to Carolyn Toney for being such a good and cheerful friend. Thanks to Daniel Williams, David White, Robert Guest, James Cross, Doris Fan Yang, and all the lads in the Human Interface Technologies (HIT) Team for being chums.

Much thanks to my brother Eric for introducing me to the wonderful world of computers when I was ten, and for his wisdom (or laziness) in not teaching it to me so that I can be an independent learner to this day. To my younger brother Edwin, for being a wonderful and talented brother, your marvelous skills in the guitar has entertained me in both dull and happy days.

To my father and mother-in-law, Yong Cheng and Ching Ching Teoh, for your precious help in taking care of my baby. Without you, writing up the thesis would be a great difficulty.

To my parents, Eng Hoe and Geng Kim Ch'ng for all the hard years of labour in raising me up, for your prayers, faith, support and care, and for your unconditional and unwavering love even in difficult times. Thanks Mom, for helping with Chloe, without you I do not know how I can cope with writing up at the final stage of the thesis. I cannot thank you enough. To all my family members in Malaysia, Australia, and Canada, your love and care over the years have made me who I am today.

Most importantly, to my wife Huey Yih, for being ever so lovely, gentle, patient and kind. Thank you for the many laughter and smiles. Your unwavering love and support has made the entire PhD process enjoyable and in time, a success. It's all because of you. To my daughter, Chloe Erin Ch'ng, for being so beautiful and for the many years of joy to come.

List of Abbreviations

2D	Two Dimensional
2½D	Two and a Half Dimensional
3D	Three Dimensional
AD	Anno Domini Nostri Jesu Christi
AI	Artificial Intelligence
alife	Artificial Life
API	Application Programming Interface
bc	Before Christ
bp	Before Present
BSP	Binary Space Partition
CA	Cellular Automata
CAS	Complex Adaptive Systems
CG	Computer Graphics
GIS	Geographical Information Systems
HTML	Hypertext Markup Language
HTTP	Hyper Text Transfer Protocol
i3D	Interactive 3D
LOD	Level Of Detail
Ma	Million of years ago
MIME	Multipurpose Internet Mail Extensions
OOP	Object Oriented Programming
PC	Personal Computer
SG	Serious Gaming/Serious Games
URL	Universal Resource Locator
VE	Virtual Environment
VH	Virtual Heritage
VR	Virtual Reality
VRML	Virtual Reality Modelling Language
W3C	World Wide Web Consortium
WWW	World Wide Web
XML	Extensible Markup Language

Table of Contents

List of Illustrations

List of Tables

And God said, Let the waters under the heavens be gathered together into one place, and let the dry land appear; and it was so. And God called the dry land Earth, and the gathering together of the waters He called Seas; and God saw that it was good. And God said, Let the earth sprout grass, herbs yielding seed, and fruit trees bearing fruit according to their kind with their seed in them upon the earth; and it was so. And the earth brought forth grass, herbs yielding seed according to their kind, and trees bearing fruit with their seed in them according to their kind; and God saw that it was good.

Genesis 1: 9 – 12, Holy Bible (Recovery Version)

Chapter 1

Introduction

Virtual Reality (VR) or Virtual Environments (VE) have in recent years, been instrumental in the success of many research projects and industrial applications. According to Stone [1], "Virtual Reality refers to a suite of technologies that support intuitive, real-time interaction with three-dimensional databases". VR and VE have been useful not only for training simulators, such as in defence and medical applications, but also for enhancing interactive visualisation with scientific concepts that were once difficult to grasp. One of the more recent research application areas to benefit from the field is Artificial Life (alife). Langton [2] defines Artificial Life as "the study of synthetic systems that exhibit behaviors characteristic of natural living systems. It complements the traditional biological sciences concerned with the analysis of living organisms by attempting to synthesise life-like behaviour within computers and other artificial media. By extending the empirical foundation upon which biology is based beyond the carbon-chain life that evolved on Earth, Artificial Life can contribute to theoretical biology by locating life-as-we-know-it within the larger picture of life-as-it-could-be." Although Artificial Life is a relatively new field, the explosion in research opportunities arising out of the field have manifested themselves in a suite of extremely useful applications – not only in studies related to biological evolution, but also in the application of biologically-inspired principles for solving real world problems.

The fusion of Virtual Environments and Artificial Life will become a potentially useful model in future research for visualising archaeological reconstructions and predicting current or future vegetation patterns in large spatial-temporal landscapes. The benefits from years of developments in interactive 3D (i3D) hardware and software technologies, coupled with the emerging trends of scientific endeavours in the modelling and synthesis of life, have already witnessed successful applications in the convergence of the disciplines. This thesis investigates the feasibility of constructing models of vegetation alife in a controlled Virtual Environment for application in the field of Archaeology (and, possibly, other disciplines in which landscape vegetation pattern research is studied).

The research project presented here was initiated following the discovery of an ancient landscape in the southern regions of the North Sea during an oil prospecting exercise carried out by Petroleum Geo-Services (PGS) [3]. Initial investigations of the seismic datasets at the University of Birmingham's Institute of Archaeology and Antiquity's (IAA) high powered computing facility, the HP Visual & Spatial Technology Centre (HPVISTA) revealed a large river valley (Figure 1) – part of an ancient landscape that existed during the Mesolithic period (10,000 to 7,000 years before present (BP)), before the glacial melting and rising sea levels finally submerged the terrain and eradicated living organisms from the once habitable land bridge.

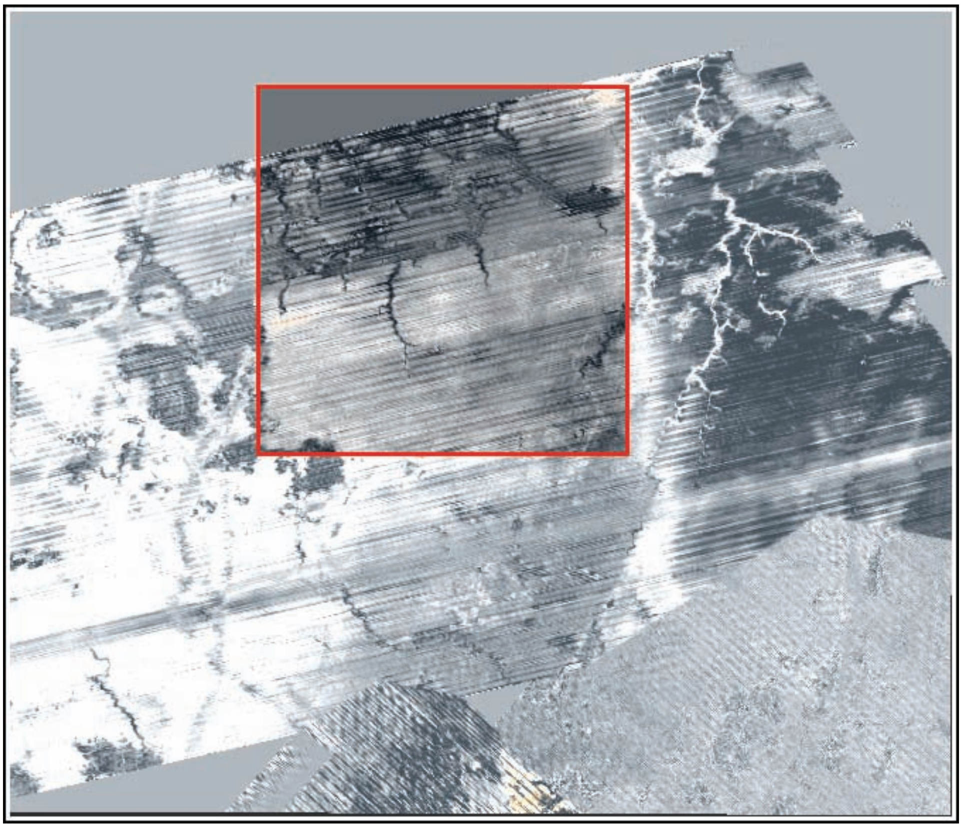

Figure 1. North Sea bed Seismic data acquired from Petroleum Geo-Services (PGS), Inset shows the Shotton River Valley (dark grey to black recesses)

The collaborative project between IAA and the School of Geography, Earth, and Environmental Sciences (GEES) that spawned this investigation [4] to reconstruct the river valley as it existed 10,000 to 7,000 ago was originally developed to address themes discussed with archaeologists working in the North Sea and within the maritime archaeology [5] along with representative of British Marine Aggregate Producers Association (BMAPA) as directed by English Heritage. One of the aims of the project between IAA and GEES is to 'provide a model of survival potential for environmental and archaeological deposits within the area of the Southern North Sea which can be used by the aggregate industry and curatorial groups for management purposes'. The project also supports one of English Heritage's objectives, which is to conduct research into the archaeology of the Quaternary Period to characterise the resource, to develop evaluation frameworks, predictive tools and mitigation strategies. Parts of the foundations leading to these aims can be answered by the investigation of new approaches for constructing models and the application of new archaeological information visualisation techniques in the research described herein.

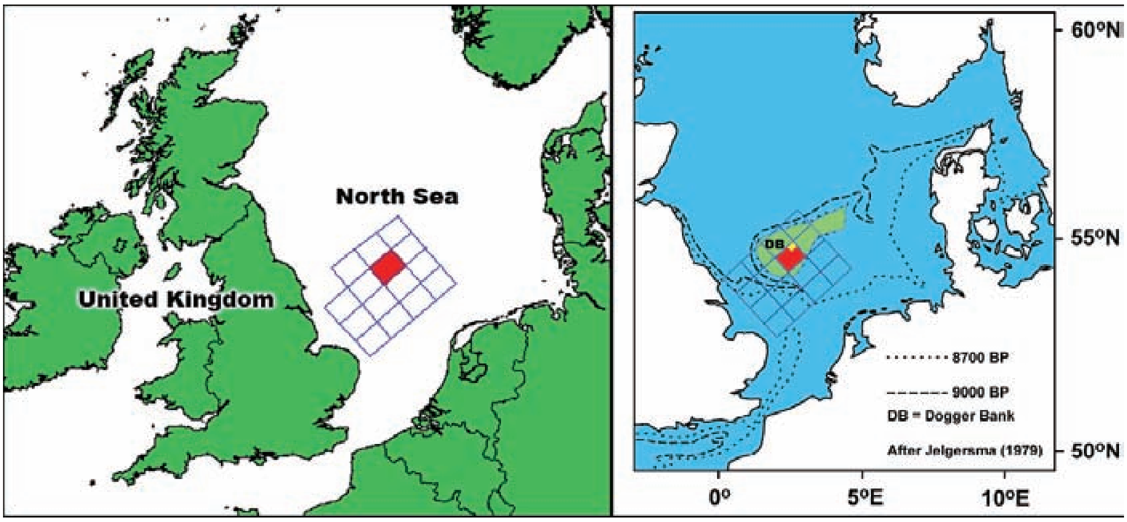

Figure 2. The study area and Holocene Shorelines showing the seismic source (red), the Shotton River Valley (yellow) in relation to the Dogger Bank

The river valley, formally named The Shotton River (after Prof. Fred Shotton – see Appendix A) is located in the region of the southern North Sea where the famous Dogger Bank [6-8] is situated (Figure 2). At 600 metres wide with an observed length of 27.5km, the river valley displays a trend of North West to South West. From an archaeological perspective, questions naturally arise as to the possible climate, ancient cultures, migration patterns, and hunter-gatherer settlements 10,000 to 7,000 years ago. What species of plants would have populated this landscape? How would vegetation species be distributed across the river valley via their ecological traits? Would plant growth alter the way living organisms inhabit these areas just as geological transformations alter plant growth? In its time, which regions of the river valley could have been a settlement area of early travellers? Are there technologies which could be exploited to enable us to explore this ‘lost’ landscape?

For addressing these questions, some fundamental requirements should be defined. One of the prerequisites is visualisation. Visualisation is a necessary element in archaeological interpretations. In order to visualise an ancient site appropriately that may be inaccessible due to the limitations of time and space, certain visualisation techniques are required. Furthermore, if a technique could allow users to ‘experience’ an archaeological site by ‘being there’, the process of interpretation could be greatly enhanced [9]. On the other hand however, to visualise a ‘lost’ site adequately requires information recovery of the site of study, perceptions made from accumulation of knowledge coupled with even the best imagination will not suffice. The quality of the recovered seismic datasets of the Shotton River Valley has provided a first step to achieving this goal. The subsequent step is the accessibility and exploitation of related knowledge obtained from years of archaeological studies and interpretations. These are abundant, but opinions and interpretations vary between subject matter experts. Having said that, major topics involving climatic and environmental settings proven by scientific techniques appear to generate agreement. It is well known in archaeological studies that the patterns of plant species forming on landscapes can determine the outcome of tools for subsistence, protection, shelter and direct and indirect (plant as animal food) food sources for ancient cultures [10] which may lead to approximate locations of hunter-gatherer settlements. Since that is the case, reconstructing vegetation formations can be considered a primary step for achieving the chain of effects leading to the target objectives.

Vegetation species and their preferences in different habitats and climates is a much studied area. Specifically, studies of past vegetation type from pollen cores in the British Isles are available [11, 12] and preferences of each vegetation species are well researched [13-20]. At this stage, it would seem that with the knowledge at hand and help obtained from subject matter experts, assembling the knowledge of plants and their preferences onto the recovered landscape should complete the picture. However, due to the fact that models for determining vegetation patterns on landscapes are continually being developed and compared for inconsistencies, strength, and limitations (e.g., [21-25]), it is immediately realised that as straightforward as it seemed, studies like these are difficult, for vegetations are living organisms that exist in a changing habitat with parameters such as species migration and ecological variance affecting species communities from time to time.

At this point, two crucial strategies in the present study area have been identified. In order to complete the picture, modelling and visualisation is required. The aim of this research is to evaluate novel modelling strategies for reconstructing the Shotton river valley with vegetations and to identify effective interactive media for visualising the outcome. From a survey of current trends in archaeological research [26-28] and in consideration of the involvement of state-of-the-art techniques, the scope of research can best be positioned in the field of Virtual Heritage.

1.1. What is Virtual Heritage?

Virtual Heritage (VH) has been defined as "the use of computer-based technologies to record, preserve, or recreate artefacts, sites and actors of historic, artistic, religious and cultural significance and to deliver the results openly to a global audience in such a way as to provide formative educational experiences through electronic manipulations of time and space" [29]. Efforts by the community of VH researchers to reconstruct sites considered worthy of preservation span from the historical built environment, including the Pyramids at Ghiza [30] and Virtual Reality Notre Dame [31], to natural heritage sites such as Australia's Great Barrier Reef [32] and the Virtual Everglades at Florida [33]. Other important efforts to conserve artefacts and educate visitors include Virtual Stonehenge [34] and archaeological relics recovered from different parts of the world [35-37]. Entire villages [38], cities [39-42] and even caves [43] were constructed as part of virtual conservation work. These digital reconstructions have, to date, contributed significant awareness and interest among the general public, providing educational benefits to concerned parties and new research opportunities to archaeologists and conservationists.

The world's cultural and natural heritage has stood the test of time. Today though, the pace of progress – from urban sprawl to pollution, neglect, conflict, looting and even tourism threatens these landmarks of our past at an ever-increasing pace [44]. While UNESCO World Heritage [45] strives to protect natural and cultural properties of outstanding universal value against the threat of damage in a rapidly developing world, a very promising organisation has emerged to support the preservation of heritage with the use of technology. The Virtual Heritage Network [46] was launched as an international organisation promoting the use of technology for the education, interpretation, and preservation of cultural and natural heritage. Technology is solving one of the largest problematic issues concerning cultural heritage – non-destructive public access. Never before has there been greater opportunities to discover, explore, and educate in great detail these marvels of earth and of humankind, without the fear of irreparable damage [47]. Rapid advances in digital technologies in recent years, from new media to Virtual Reality (VR) and high-speed networks, have offered heritage new hope [44]. Particularly, VR has enabled humankind to explore forbidden or inaccessible heritage, cultural or natural.

1.2. A Definition of Archaeology

There have been many debates about the definition of archaeology as it has witnessed all kinds of developments in the past [48]. In particular, two fundamental divisions exist – that of traditional archaeology and the new archaeology [49]. Traditional archaeology has been accused [50] of having "a humanist, liberal philosophy as a matter of course. It has no defined method of asking questions; one digs for the sake of digging, aimlessly and haphazardly… the main thing is to describe and then classify the material for purely chronological purposes, or almost just for the pleasure of classification." It has been condemned for venturing into "interpretations or generalisations which it doesn't bother to prove." and "No attention is paid to the scientific problems of confirmation and verification; no mention is made of the control of data quality, although it is needed in hypothesis testing." A comparison of the two shows that where traditional archaeology is based on the historical view of things, is qualitative and 'particularising', the new approach in archaeology is experimental, quantitative and generalising. Clearly, archaeology as a science in the modern times has, since 1968 very much developed towards the later 'processual' (scientific) approach [51] – an approach believing in objective science [52]. In recent times, archaeology has arrived at the virtual age, using digital technologies to restore, preserve, and recreate sites and artefacts for analysis, interpretation, and in Virtual Heritage, for educating concerned parties and for initiating new research opportunities.

Archaeology [48] began as a method of identifying places and objects already known to exist from historical records. In its developments, it has also become a means of discovering new facts about ages beyond the reach of written evidence. The investigative methods in archaeology capture the surviving traces of activities of past cultures and civilisations as evidence of discovery. The survival of prehistoric man is dependent on their exploitation of natural resources available on the landscapes. As such, traces of tools, shelters, food residual and human remains naturally become part of archaeology's evidence for piecing together past cultures. This information then becomes instrumental in the recovery of past societies and their way of life. Thus archaeology is defined as "a sub-discipline of anthropology involving the study of the human past through its material remains" [53] and as "A social science in the sense that it tries to explain what has happened to specific group of human beings in the past and to generalise about the processes of cultural change." [54]. The term is also used to refer to "a specific body of techniques used to recover evidence about the past." [55]

Having referred to the definitions of archaeology, the scope of the research presented here can now be positioned in the field of archaeology. The concern in this research contributes to the field by reconstructing the natural resources in submerged ancient landscapes, via the use of new models and technologies in Virtual Heritage, so that through the reconstructions, foundations for discovering evidence of human material remains may be laid.

1.2.1. Landscape Archaeology

A landscape is a backdrop against which archaeological remains are plotted and from an economic and political perspectives, landscapes provide resources, refuge and risks that both impel and impact on human actions and situations [56]. It is a material manifestation of the relation between humans and environments [57]. According to Barrett [58], it is "the entire surface in which people moved and within which they congregate. That surface was given meaning as people acted upon the world within the context of the various demands and obligations which acted upon them. Such actions took place within a certain top and at certain locales. Thus landscape, its form constructed from natural and artificial features, became a culturally meaningful resource through its routine occupancy." This particular study and focus on the impact of space and landscape upon cultures is often called settlement archaeology and the investigation of its prehistory is for tracing the evidence of settlement and subsistence.

The study of natural landscape [59, 60] is thus important in the realisation of subsistence and settlement patterns and has attracted several fields including archaeologists, geographers, and anthropologists [61] and to-date has involved geologists, seismologists, environmentalists [5] engineers and computer scientists [4] in which engineering and computer science plays a central role in modelling, simulation and visualisation as reported in this Thesis.

1.2.2. Archaeological Process and Interpretation

Interpretation in archaeology requires knowledge and expertise to complement the sometimes vast amount of facts and discoveries associated with a site. Interpretation in archaeology is "a process in which there is a fluid and non-dichotomous relationship between the archaeologist and archaeological data. Archaeological research involves a 'fitting' (not a testing) process which is both data and question (perspective) led so that subject and object are interrelated" [52]. Increasingly, archaeology is applying the sciences [62-64] in the process of interpretation. This application of scientific techniques and methodologies requiring mathematical models and computer modelling to archaeology is called Archaeometry. An illustrated flowchart of the general conceptual framework in which the archaeologist operates is obtainable [65].

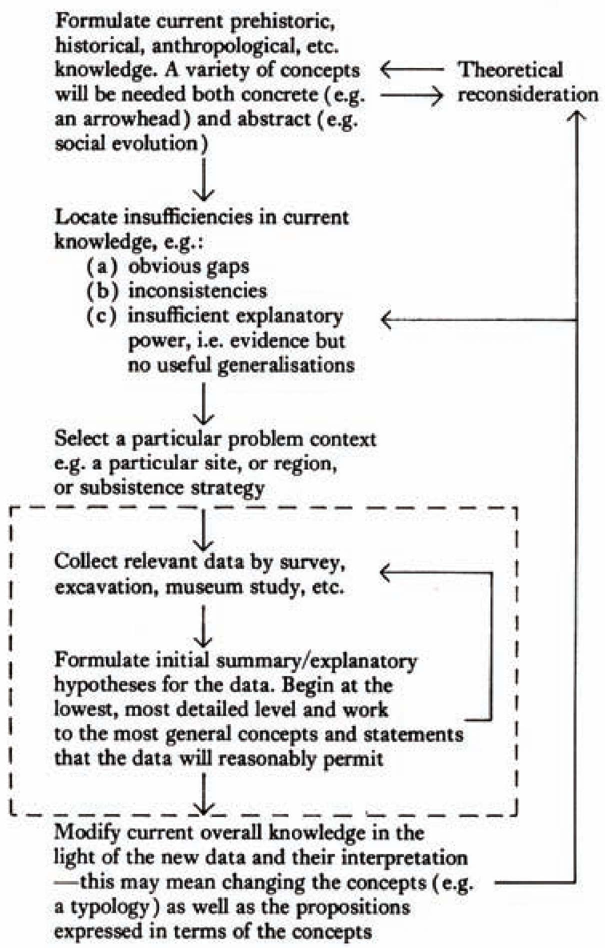

Figure 3. Flowchart illustrating the general conceptual framework in which the archaeologist operates. (From Doran, J.E. and Hodson, F.R. [65])

In a landscape thought to possess significant archaeological value for example, the formulation of a theory may be that at this location in a specific time, due to the geological formations, the terrain could act as a land bridge for the migration of the Mesolithic man. And, since the landscape at a relatively large scale with river beds and features habitable to edible plants, which in turn is favourable to land mammals, some prehistoric travellers may have decided to settle down due to the available land and water resources for immediate subsistence and settlement benefits. In order to know which kind of cultures the travellers belonged to, the question then is to locate a probable site on which they might have settled. At this point, if only the topology of the landscape is recovered, the missing step required to complete the picture could be to determine the sources for sustenance and protection. So, beginning from pollen analysis and botany and an understanding of the prehistoric landscape environment, a collective knowledge of vegetation types and their preferences are gathered which eventually leads to a theoretical reconstruction of the landscape. Nearby, excavation work discovers prehistoric houses containing charred remains of acorns, Hazel nuts, and shells of clams, providing a glimpse of prehistoric diets. Based on these facts, a logical answer for finding the probable location for hunter-gatherer settlements might be to look for river beds and places where clams and Hazel shrubs are in abundance.

In the scenario presented above, initial steps in the process require data recovery, others such as the pinpointing of the probable location of settlements belonging to a more interpretive nature requires expert opinions. Intermediate steps, such as the complexity of vegetation formations on landscapes require mathematical and computer modelling.

1.2.3. The Role of Computers in Archaeology

The role of computers in archaeology did not become important before 30 years ago. In 1968, Chenhall [66] formulated questions for assessing the benefits of applying a computer-based methodology to an archaeological problem. The questions were:

1. Why were computers used?
2. Should they have been used?
3. Was anything accomplished by the use of computers which could not have been done just as well by some other means?

Perhaps 20 years ago, these questions still needed justification. Today however, the importance of computing in archaeological research has surpassed and replaced many techniques and has even become an integrated procedure in the archaeological process, both in the laboratory and in field work. Hardware and software technologies for digital recording, data processing, word processing, techniques for communications, correspondence, and dissemination, GIS in site and landscape studies, visualisation in 2D & 3D, reconstructions in i3D and VE, Artificial Intelligence, and even wearable computers [67] have pervaded the archaeological process and have become an indispensable tool in the domain.

Since 1973, the proceedings of Computers and Applications in Archaeology [68] begin congregating researchers working on early computer applications in archaeology. During the 1990s, topical research areas such as 'GIS and Evaluation of Spatial Patterns', 'Visualisation of Archaeological Data', 'Image Processing', and 'Artificial Intelligence' appeared in the same proceedings [69]. In the mid 1990s, Internet applications for archaeology began to appear and became widely popular for archaeological research in 2000. At the same time in mid to late 1990s, advances in Interactive Computer Graphics (CG) made possible some of the first attempts in the 'virtual modelling' of heritage.

This advancement owes its successes to early attempts at 3D computer modelling. Realising that *in situ* analysis of the structure of an archaeological formation can be fraught with many difficulties from vegetation cover, sunlight, topography and inaccessibility of the site, not to mention the destructive techniques of earlier excavations, researchers in the 1980s begun exploring new approaches for archaeological analysis. In the early attempts, aside from aerial surveys [70, 71] and remote sensing techniques, researchers begun experimenting with archaeological systems encompassing not only database capabilities but also ventured into 3D graphics visualisation [63, 72-81]. However, the approach in 3D graphics methods in the 1980s was only capable of computing very limited portions from a site. Even so, it was discovered that 3D graphics with database capabilities has advantages over aerial surveys as obstructions such as vegetation canopies need not be rendered in 3D space, thus preventing site features from being obstructed from view. Developments towards the latter part of 1980s also saw the potentials of 3D graphics in archaeology, particularly on the medieval land divisions in the Isle of Man [81], and that advanced graphics techniques could have an impact on the analysis of survey data [80].

1.2.4. GIS in Landscape Archaeology

Geographical Information Systems (GIS) have become an indispensable tool for organising spatially referenced data in landscape archaeology. GIS is "a system to collect, store, manipulate, analyse & present spatially referenced data" [82]. GIS has been used extensively in landscape archaeology [83-88]. It has also been used for determining vegetation formations based on different layers of base maps of soils, topography, and the time of arrival of each tree type [10, 89], in combination with other models [22], and used for exploring the potentials of integrating scientific methods and data with the phenomenological approaches [90] for the understanding of an archaeological site [91]. GIS has become an important element in archaeology where representation, manipulation, and analysis of archaeological database and spatial information are concerned. However, GIS has its limitations.

One of the great limitations in GIS is the record of data in 3D space. Cross [67] noted that in physical space, two items could occupy the same 2D location but could be several metres apart in vertical location. Since GIS references a physical item in 2D data, it has limitations with regard to 3D information, that is, what lies above or below a plane.

Ebert and Singer [92] identified three main areas in which GIS can be considered lacking. The three limitations are cognitive representations, temporal analysis and three-dimensional analysis. These aspects are particularly important to the modelling and visualisation required for determining vegetation formations and for exploring a digitally reconstructed archaeological site. The lack in temporal analysis becomes evident when vegetation life cycle is a modelling factor. Furthermore, the migration of species and the competition between species requires time as an element. On the limitations of visualisation, the representations of objects as point, line or polygon may be useful in some instances, but more often, cognitive ideas becomes difficult. Additionally, the lack in 3D capabilities hinders the analysis of 3D topography and archaeological deposits.

Another drawback is the accuracy of the represented model. Fyfe [22] noted that since GIS requires a simplification of the landscape, and the spatial scale (pixel size) applied within the analysis will determine the likely precision of the models when vegetation communities are applied, the accuracy is compromised. This is due to the fact that the pixel size of the elevation models are determined by the minimum available patch size within the simulations. Hence also, in the visualisation of any GIS-based simulations, it is unlikely for researchers to realistically 'feel' or 'experience' the various aspects of the landscape modelled in the GIS environment.

1.3. Interactive Media in Archaeology

The advent of Interactive Media has revolutionised communications and has provided new ways of disseminating information in all possible fields where concepts and ideas requiring a higher level of expression are needed. Unlike the unidirectional media afforded by text, pictures, audio and video, their combination with new media types such as i3D and the research in human-computer interaction has reached new heights for effective interactive communications. Interactive media not only allow users to receive thoughts from the medium but also empower them to actively participate in the use of the media. The use of interaction techniques in interactive media although important, and have been well researched as far as Virtual Environment [93, 94] and Virtual Heritage [38, 95-98] is concerned, it is beyond the scope of this research. The levels of interactive participation covered below refer to a user's total experience of a Virtual Heritage application and not to their use of interaction techniques, even though it is part of the experience.

From observations, Interactive Media can be categorised into at least four main levels of participation:

1. Selective Interactivity
2. Participatory Interactivity
3. Contributory Interactivity
4. Causative Interactivity

In *Selective Interactivity*, users are allowed to choose a number of given options in the media but does not contribute to it. Information websites in the World-Wide-Web (WWW) and many educational media such as Encyclopaedia CDs belong to this category. 3D viewers allowing a visualisation-only capability of any object or scene can also be part of this category.

In *Participatory Interactivity*, users actively participate in a two-way communication. Interactive story-telling where the user participate in a conversation-style interaction with a virtual avatar for site information belong to this category. Other examples are Web forums and discussion boards. *Selective* and *Participatory Interactivity* may be grouped as one.

In *Contributory Interactivity*, users are allowed to contribute directly to the shaping of the media. Wikipedia [99], the online encyclopaedia that allows anyone visiting the site to contribute to the content is a good example. Another example is the World Interactive Painting Project [100]. The author receives feedback from a text-based form on the website and carries out the painting on a physical canvas. The interactivity is quite primitive in this case as direct painting and real-time update is not possible, nevertheless, it serves as a good example of *Contributory Interactivity*.

In *Causative Interactivity*, the passage of time and the actions of users can have direct impact on the evolution of the media. The more recent computer games and evolvable virtual worlds stand in this category. This type of interactive Virtual Environments usually contain some form of agents with intelligence or characteristics of life that response to user interaction. The user-actions performed in the world helps shape the community and environment of the virtual world.

These categories of interactive media have in the last decade penetrated archaeological documentation and knowledge dissemination. For example, Current Archaeology [28] and especially the website of National Geographic Society [101] provides *Selective* and *Participatory Interactivity* via hypertext, discussion forums, and media-rich interactive explorations. In the following sections, media types and interactive levels that harness the power of *Causative Interactivity* for more engaging user experience are explored.

1.3.1. Previous Examples of Virtual Heritage

Since the field of Virtual Heritage came together in 1998 in the Virtual Systems and Multimedia (VSMM) Society conference in Gifu, Japan [102], it has brought together disparate disciplines from architecture to archaeology, the arts to entertainment, and museology to conservation, with computer science and technology [103]. This section looks at previous examples of Virtual Heritage research and its use of interactive media since 1998. According to Stone [29], in Virtual Heritage there are really only three different yet overlapping types of work as revealed in the sentence below:

The use of computer-based technologies to *record*, *preserve*, or *recreate* artefacts, sites and actors of historic, artistic, religious and cultural significance.

During the early stages of this project, a survey of literature in VH showed that works being conducted are mainly to *record*, *preserve*, or *recreate* with overlapping categories in virtual works (Figure 4):

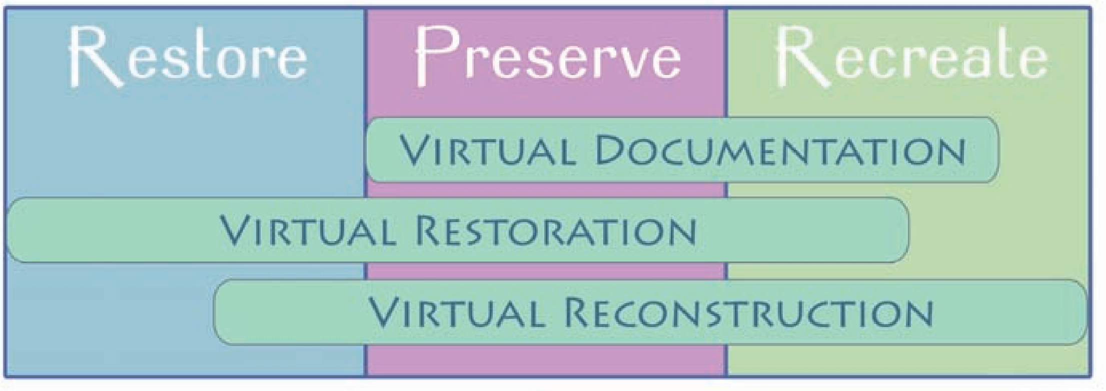

Figure 4. Overlap Categories of Virtual Heritage Work

The chart in Figure 4 shows that all research works carried out in VH are for preserving heritage (All labels overlapping the 'Preserve' segment). *Virtual Documentation* records physically and culturally based artefacts, sites, and actors with historical value and requires some form of artefact recreation (depicted with the overlapping label over the three-quarters of the 'Recreate' segment). *Virtual Restoration* attempts to restore historical artefacts that may be partially damaged due to the passage of time, natural calamities or vandalism. Occasionally restoration work may need some methods of reconstruction to recreate the missing parts of the artefacts or the environment where a monument once belonged. In *Virtual Reconstruction*, most of the work involve recreating existent or non-existent heritage and frequently requires certain techniques for restoration. From the survey of prominent works in Virtual Heritage, the majority of research is seen to belong to either *Selective* or *Participatory Interactivity* or an integration of the two.

Leavy's [104] vision of CyberDreaming using new technology to protect and digitally map indigenous Australia can be considered in the *Virtual Documentation* category. Other examples include the work of Mazar [105] on Ein Karem, a small bronze age village with approximately 2,200 residents. The project proposes a solution in the form of a CD-ROM multimedia documentation to act as a 'theatre of memory' for users requiring different interpretations of layered hegemony. Chausidis's CD-ROM project on Macedonian Antiquities uses a database and different media types for organising several levels of presentation on Macedonian history from the Neolitic Age until Turkish arrivals in the 15th century. Drennan *et al*. [106] use the Internet as a virtual museum, and Fujita *et al*. [107] present the conceptual scheme of a multimedia archaeological database and its system for managing and presenting Japanese ancient tombs over the WWW. All these examples belong in the *Virtual Documentation* category.

Examples of *Virtual Restoration* can be seen in the recovery of artworks and sculptures. Li, Lu, and Pan [108] integrated image processing techniques, information retrieval, knowledge representation, and intelligent reasoning to assist in the restoration of a Fresco in Dunhuang Mogao Cave, China. Barni, Bartolini, and Cappellini [109] uses image processing techniques to analyse, preserve, and restore paintings by Duccio da Boninsegna conserved in the Uffizi Gallery in Florence. Zheng [37] and Zhang's work [110] developed an imaging device to digitise damaged pieces of the Terracotta Warriors. They also built a VE interface for connecting broken fragments in virtual space so that the original model can be visually recovered and displayed in a presentable multimedia format, demonstrating the potentials of virtual recovery for preserving the artefacts from actual physical recovery. Others, such as Thalmann *et al*. [111], reconstructed a short film on the Xian Terracotta warriors using their integrated HUMANOID software.

The work of *Virtual Reconstruction* is highly popular in VH. This is due to the highly interactive and engaging experience that can be afforded by techniques in i3D. Harada *et al*. [112] developed a technique for photorealistic modelling based on pictures. Applied to the virtual modelling of Himeji Castle, the techniques include the improvement of texture quality, a top-down modelling approach, and Level Of Detail (LOD) modelling. Bharat [113] integrates a wide range of information and protocols such as text, 3D models, still images, audio and video for a 3D and multimedia documentation of a UNESCO world heritage site in India. In Bharat's research, VRML was used extensively for the exploratory walkthroughs. Endo *et al*. [114] employ an image-based walkthrough system for navigating large scale scenes such as Shirakawa-go with panorama-based and morphing method. The methods although not 3D, created an illusion of space characteristic of 3D systems. Kanaya and Chen [36] propose a method for accurate and efficient reconstruction of relic shards. Haval [115] reconstructed the Fatehpur Sikri based on architectural blueprints, site surveys, photographs and archaeological data and uses a custom engine for interactive walkthroughs with 3D surround sound, music and voice-recognition techniques for hands-free interaction. Daniel Pletinckx *et al*. [116] use different VR approaches to bring to life archaeological remains, standing monuments, and elements of historical landscapes. An approach superimposes a 3D model of the Abbey church over a real-time video of the exposed foundations for visitors to see the church as it appeared in its original state.

The Virtual Heritage research process (Figure 5) begins from data capture for recording relevant details of an artefact or a site. Information processing is where reconstruction, restoration, content generation and the design of interactive interfaces is accomplished. The assembly of information finally leads to the dissemination of knowledge for public access.

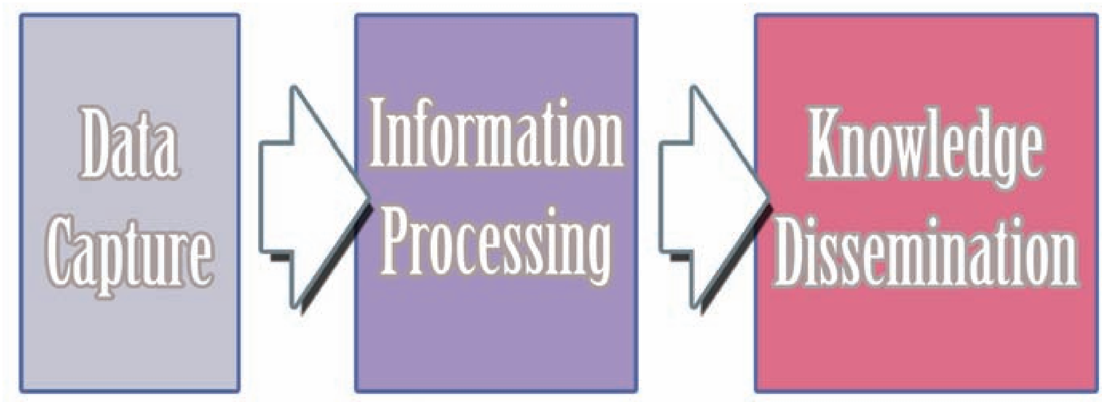

Figure 5. Processes in Virtual Heritage Research

The stage of *Knowledge Dissemination* is where the interactive media become useful. From previous examples, the virtual documentation, restoration, and reconstruction necessarily leads to an outcome in different types of media or the combination of media types into an interactive format. The survey revealed two categories of interactive media types used in Virtual Heritage Research – 2D and 3D. There could also be a third category in between, which could be termed 2½D or *Two-and-a-Half-Dimensional* media.

2D interactive media types are frequently a combination of non-interactive media types with some form of programmable base for integrating the text, graphics, images, audio, video and animation into an interactive format. Macromedia Corporation's Authorware™, Flash™, and Director™ are popular programmable bases. Microsoft Corporation's PowerPoint™ presentation tool can also be considered in the same category. Frequently, image-based web page design tools such as Macromedia's Fireworks™ and Dreamweaver™ and Adobe's Photoshop™ and

ImageReady™ provide a drag-and-drop interface for applying Dynamic Hyper-Text Markup Language (DHTML) capabilities to an otherwise static website in order to add an interactive layer to it.

2½D interactive media types are provided by software tools that can seamlessly ‘stitch’ 2D images in order to create an illusion of 3D depth and space but does not necessarily involve the mathematics or algorithms that describes vectors and polygons in a 3D world coordinate system. A good example is Apple’s QuickTimeVR™. Apple’s authoring tools allow creation of panoramic images captured from multiple camera angles for explorations of an object or a site. Early attempts for 2½D visualisation use stereoscopic imaging techniques. Stereoscopy was used in archaeology as early as the 1980s. For example, Spicer [117] uses stereoscopic imagery for representing archaeological data and Reilly [118] uses stereoscopy for assisting in the interpretation of an archaeological burial ground. This method of visualisation has evolved. Today, StereoGraphic’s SynthaGram™ autostereoscopic monitor allows viewing stereoscopic images without the use of special eyewear.

3D Interactive media types or i3D are interfaces that allow explorations of objects, actors and sites in 3D and typically provide navigation modes for ‘flythrough’, ‘walkthrough’, and ‘study’. Since i3D adds a third dimension to visualisation, properties of the physical world could be simulated, and this enhances interactivity. For example, i3D allows user-interaction with objects or environments programmed with properties of physics, and intelligent avatars or agents that mimics the biological life. This interaction between users, agents, and environments constitutes the category of *Causative Interactivity*. Simulations in 3D are typically hosted in a Virtual Environment, also known as Virtual Reality [1, 29, 119-123]. Applications for visualising and exploring VEs are abundant. Examples for web-enabled VR are VRML and Macromedia’s Shockwave 3D™. Programmable PC-based systems include Sjoland & Thyselius’s Blueberry3D™, World Viz’s Vizard™, and TGS’s Amira™ and Open Inventor™ products. Presently, the abundance of programming languages, software libraries and Application Programming Interfaces (APIs) have also empowered Virtual Heritage researchers to develop new algorithms and custom applications in order to meet new research demands.

VR can be extended today to include Serious Games (SG). Stone [124], in the invited keynote of VSMM 2005 stated that, *“Serious Games” is a global revolution in interactive 3D (i3D)* *technology that promises to develop intuitive, affordable, accessible and familiar training environments for a wide range of educational and training applications, from medicine and healthcare to defence training for urban and special operations combat; from national heritage to multicultural interaction.* In another paper, Stone *et al*. [125] defined SG as follows: *Serious Gaming focuses on the exploitation of computer games software tools such as those underpinning the "first person shooter" (FPS) or "role-playing" games currently being enjoyed by youngsters and adults alike, all around the world. These tools take the form of software development kits (SDKs), released by leading games developers shortly after the publication of a new product, such as FarCry or Half-Life 2, together with a growing number of supporting content generation packages. The tools enable games players to develop their own virtual humans ("avatars") or computer-generated forces, environments, weapons and adversaries, thereby prolonging the longevity of the game they have purchased.* Where yesterday's VR failed, SG is giving the i3D community a second chance. In fact, the most engaging implementations in the Virtual Heritage community uses games engines technology as a base for cost-effective, and highly usable and accessible visualisation and educational tool. Three examples are Virtual Florida Everglades [126], The Living Virtual Kinka Kuji Temple [127], and Virtual Reality Notre Dame (VRND) [128].

The role of interactive media for visualisation in Virtual Heritage has been shown. The popularity of using i3D in Virtual Heritage research is due to its usefulness in visualisation and its capability for *Causative Interactivity*. i3D adds value to the user's experience. In an archaeological site, there is more than meets the eye. The insights of users into the past, present and future of a site depends on how effective Virtual Heritage researchers are able to preserve, restore, reconstruct, and disseminate knowledge via the use of computer technology. Years of damage has scarred many heritage sites. An example is Stonehenge. Once opened to the public, it has become highly protected. Unaware to visitors, the acid in their hands could kill the flora that has thrived for thousands of years on the surfaces of each stone. The reconstruction of Virtual Stonehenge [34] helped to bridge this inaccessibility gap. Users were able to explore Stonehenge without causing damage to the actual site.

Since a heritage site is unique in space and time, and there will not be a likely recurrence of it, there is the need for ways in which the general public could *experience* and *learn* about the site. By introducing technological developments in Virtual Heritage, an otherwise inaccessible site can be investigated, and those that are bounded by time and space could be restored, reconstructed and explored so that through such an experience, users can be *educated* to respect a heritage site in order to preserve it for future generations.

1.4. The Need for Modelling and Simulation in Virtual Heritage

The goal of Virtual Heritage is to deliver the research results "openly to a global audience in such a way as to provide formative educational experience through electronic manipulations of time and space" [29]. Today Virtual Heritage is solving one of the largest problematic issues concerning cultural heritage – non-destructive public access. "Never before has there been greater opportunities to discover and explore in great detail these marvels of earth and of humankind, without the fear of irreparable damage" [47]. To achieve this goal, the process of research is important as the outcome and credibility of a heritage site depended upon it. Refsland *et al.* states that, "Virtual Heritage can be an invaluable tool, but if not used wisely, has the potential to do as much harm as good.", and that the "Historical accuracy, thorough documentation of sources, and care while at sites is perhaps more important than ever in the new digital landscape." Hence the need for protocols and methodologies in the process of a Virtual Heritage site production. Thwaites and Malik's article [129], provided the basics of Communication Analysis Protocol (CAP) as applied to the pre-production and design process of Virtual Heritage worlds and sites and, Boulanger *et al*. [130], examine methods for the accurate creation of models and systems for virtual visits targeting VR related creations.

An important feature considered lacking in today's Virtual Heritage sites is the addition of 'living' environment and 'responsive' avatars or agents rather than non-interactive media and simple walkthroughs. For example, Stone and Ojika [131] stated that VR users demand more and more in terms of interaction, participation and content, not just simple walkthroughs. Thwaites' [39] analysis of Ville de Quebec suggests that *Samuel de Champlain* be introduced as a virtual avatar in order that users could learn the history of the city from him, and that the potential of this aspect of Virtual World Heritage is currently a missing element in most, if not all Virtual Heritage projects. In fact, the VR community shared the same thought. Luck and Aylett's survey [132, 133] of the applications of VEs showed that the use of AI and alife techniques in Virtual Environments can provide a valuable and effective way for research within specific application areas and it is especially noted that some researchers in the field of VR and CGI seek to progress beyond visually compelling but essentially empty Virtual Environments to incorporate other aspects of physical reality that require intelligence or agents with characteristics of life.

A survey of prominent VH research in the previous section revealed the applications of media types and various levels of interactivity but what is disappointing is that the lack has not been sufficiently fulfilled. The literature review has shown that many of the virtual reconstructions although physically accurate and aesthetically pleasing, did not utilise to the full the level of interactivity that can be afforded with current computing technology. Most interactive media types used were linear, static, non-evolvable and at most, employed the level of interactivity that is as high as the term *Participatory*. Some projects utilises non-interactive digital images and animations for visualisation. Others combined various media types with a programmable base for more interactive explorations. Many research projects applied i3D techniques for restoration, reconstruction, and visualisation, yet for the most part provided a navigation-only feature for exploring the sites and for manipulating the artefacts.

Among the more elaborate and successful projects that can be classified as having *Causative Interactivity* are those that integrate some form of intelligent agents, Artificial Life, or living artificial ecosystem. Among the reviews at least two projects employed techniques for creating a living Virtual Environment whereas many others uses some form of artificial intelligence or agents with characteristics of life in combination with a partially 'living' environment. These will be covered briefly in this section and in detail in chapter two.

The projects using living environments are Virtual Snowshoe [134] and the use of real-time weather information and GIS terrain data for exhibiting natural ecosystem conditions, and the virtual villages of Shirakawa-go [38] and its environmental simulation of weather to see the long-term cause and effect of climatic conditions on built heritage.

Projects that incorporate some form of 'living' agents can be grouped into two. The first consisted of those that incorporate agents with characteristics of life. Examples are the fireflies in the Virtual Living Kinka Kuji Temple [127], the responsive egret in Virtual Florida Everglades [126], and the 'energetic' birds in Virtual Snowshoe [134]. The second group consisted of those that introduced virtual humans which could be divided again into two categories - limited avatars and crowds. Projects incorporating limited avatars are those with tour guides in cathedrals [96, 128, 135], worshippers in Mosques [136, 137], a King in his Palace [138], the Peranakan culture [98], and athletics in ancient Olympics [139]. Projects incorporating crowds in heritage settings are Ryder, Flack and Day's adaptive crowd behaviour system [140], Ulicny and Thalmann's virtual praying crowds [141], and Ciechomski *et al.*'s virtual audience [142].

The lack observed in the Virtual Heritage research plus the identification of successful Virtual Heritage implementations showed that in order to properly address the general issues that are deficient in the field and specific issues in landscape vegetation reconstruction related to this research, some form of modelling and simulation techniques are necessary. The remaining sections introduce potential techniques for investigation and applications in the work presented here.

1.4.1. The Role of Artificial Intelligence in Problem Solving

Artificial Intelligence (AI) focuses on using computer algorithms for providing solutions to real life problems. Russel and Norvig [143], based on eight recent textbooks, propose four main definitions of AI: Systems that think like humans, systems that act like humans, systems that think rationally, and systems that act rationally. Therefore, AI is a field that not only aims to model human intelligence, but also uses such models for solving real life problems such as automating tasks requiring intelligent behaviours.

According to Luger and Stubblefield [144], the two most fundamental concerns of AI researchers are *knowledge representation* and *search*. The former addresses the problem of capturing in a formal language the full range of knowledge required for intelligent behaviour. Search, is a problem-solving technique that systematically explores a space of problem states in the problem-solving process. These concerns has developed from a state space search in board games, and automated theorem proving in early AI research to the currently more useful domains such as expert systems, natural language understanding and semantic modelling, human performance modelling, planning and robotics, and machine learning.

A more recent endeavour, one very much different from the traditional AI approach seeks to build intelligence using models that parallel the structure of neurons in the human brain. This bottom-up approach is called Parallel Distributed Processing (PDP) and Emergent Computation, a technique explored extensively in the field of Complex Adaptive Systems (CAS) and alife. These techniques are covered in later sections.

Over the last decades, the development of the Internet and communications technologies have revolutionised human interactions and the process of business operations. This information super-highway has afforded a new environment for developments in AI. Agent-based AI or intelligent agents [145] have become a relatively popular technique suited to this new environment. Guilfoyle [146] predicted well in 1995 that in 10 years time most new IT development will be affected, and many consumer products will contain embedded agent-based systems. Today, agent-based models are not only being developed in open environments such as the Internet, but can also be very useful for solving problems in the confines of a personal computer, or within a software program. A good definition of a software agent is given by Russel and Norvig [143], "An agent is anything that can be viewed as perceiving its environment through sensors and acting upon that environment through actuators."

Have any of the AI techniques presented above been used for solving archaeological problems in the past? Gardin [147] presents six case studies of the use of expert systems [148] in the archaeological domains. However, each of the studies although relatively useful, uses expert systems for the reproduction of more of a reasoning nature in the archaeological process and is not suited for the type of research presented in this thesis. Others such as Barceló [149] applied AI for automated problem solving, and Gibson [150] explored the potentials of neural networks for archaeofaunal ageing and interpretation. An approach more suited to mimicking natural systems is the use of agent-based techniques, such as the distributed AI techniques implemented by Palmer and Doran [151].

1.4.2. AI Techniques Suitable for Vegetation Modelling

There are a wide range of techniques being developed in the field of AI. Some of the mainstream AI techniques have been described in the previous sections. Based on Russel and Norvig's definitions presented previously, AI can be defined as the study of the modelling of human intelligence. Since no trace of intelligence is found in vegetation, it is not immediately clear whether techniques in the field of AI can be used for modelling them. The aim of this section is to identify potential techniques for vegetation modelling.

Every living organism possesses states. In its lifetime, a plant transitions through various states (seed, seedling, young plant, mature plant, old plant, and death). Even within a seasonal year, a deciduous plant goes from an active growing state to a state in dormancy. It has some form of actions, for example, the seed of a plant germinates, grows, changes appearance, and reproduces. In other words, it has a lifecycle. A plant also senses the environment and reacts according to threats. It accesses nutrients, water and sunlight and competes against other plants for them. Although a plant may evolve over thousands of years by adapting to its environment, it does not 'learn' as humans do. Even so, the techniques experimented in the field of AI could be used in certain cases, especially those applied in computer games [152].

A behavioural model referred to as Finite State Machine (FSM) or finite automaton consisting of states, transitions, and actions apparently is an appropriate modelling technique since it corresponds to the phases of a plant's life cycle. A plant also stands as a separate entity, senses its environment and reacts according to it. In this case, techniques in agent-based models can be applied. Genetic Algorithms (GA) [153], a biologically inspired model that resembles the process of natural selection could also be used for the sexual reproduction and in large timescale spanning hundreds of thousands of years, for simulating the micro-evolution of plants. These techniques are suitable for modelling matter related to life, in fact, the emerging field of Artificial Life has very much adopted these methods.

In the preceding paragraphs, techniques appropriate for modelling vegetation have been narrowed specifically to three methods. However, it is important to note that in observations of natural systems, local interactions between individual entities necessarily generate global dynamics that cannot be reproduced by the mere study of an individual plant unit. This phenomenon can also be observed in the formation of vegetation communities on landscapes. Thus, in order to reconstruct a landscape with vegetation, the collective effects of entity interaction has to be taken into consideration. The following sections introduce specific fields such as Complex Adaptive Systems (CAS) and alife related to the study of natural phenomenon.

1.4.3. Complex Adaptive Systems (CAS)

Complexity Science aims to study phenomenon in physical, natural, and societal systems [154]. Science for three centuries has been essentially mechanical, characterised by linearity, repetition and predictability. Most of nature however, is nonlinear and is not easily predictable. A classic example is the weather. The outcome of weather is many components interacting in complex ways leading to difficulties in predictability. A feature of nonlinear systems is that “very slight differences in initial conditions produce very different outcomes”. Ecosystems, economic entities, developing embryos, and the brain are examples of “complex dynamics that defy mathematical analysis or simulation” [155]. In Kauffman’s search [156] for the “order of biological world”, one which “arises naturally and spontaneously because of the principles of self-organisation – the laws of complexity”, gave an insight into how the natural world was formed. He stated that “We live in a world of stunning biological complexity. Molecules of all varieties join in a metabolic dance to make cells. Cells interact with cells to form organisms; organisms interact with organisms to form ecosystems, economies, and societies.” This idea of the complex whole exhibiting properties that are not easily understood by studying the individual parts is called *emergence* [157, 158] and is widely researched and to this day has been applied for problem solving [154]. The concept of emergence is covered in more detail in Chapter Two.

1.4.4. What is Artificial Life (alife)?

The phrase Artificial Life or *alife* is coined by Christopher Langton in the Proceedings of the *Interdisciplinary Workshop on the Synthesis and Simulation of Living Systems* [159]. The field owes its deepest intellectual roots to John von Neumann and Norbert Wiener [160]. Von Neumann [161] was the first to design an Artificial Life model without referring to it as such. He attempted to understand the fundamental properties of living systems by creating his self-reproducing Cellular Automata (CA) that exhibited those properties. Wiener [162] at about the same time started applying information theory and the analysis of self-regulatory processes (homeostasis) to the study of living systems. According to Bedau [160], both the constructive and abstract methodology of cellular automata and the abstract and material-independent methodology of information theory still exemplify much of alife.

Artificial Life as defined by Langton [159], is "…the study of man-made systems that exhibit behaviours characteristic of natural living systems. It complements the traditional biological sciences concerned with the analysis of living organisms by attempting to synthesize life-like behaviours within computers and other artificial media. By extending the empirical foundation upon which biology is based beyond the carbon-chain life that has evolved on Earth, Artificial Life can contribute to theoretical biology by locating life-as-we-know-it within the larger picture of life-as-it-could-be." It is simply "life made by humans rather than by nature". However, in later years, Langton states that "Artificial Life is many things to many people" [163]; he also suggests that "It is probably safe to say that the field as a whole represents attempt to increase vastly the role of synthesis in the study of biological phenomena." Rietman [164], on 'Creating Artificial Life' gave a short list of biological life that might consist of reproduction, metabolism, evolution, growth, self-repair, and adaptability. A practical goal of alife is to find a mechanism for an evolutionary process to be used in the automatic design and creation of artefact [165].

The history of the formal studies in AI is significantly earlier than alife. As such some have attempted to classify alife research as being a subfield of AI. Even though studies in alife overlap with those in AI, both approach the subject rather differently. The studies in AI aim to model the human mind whereas alife attempts at modelling life. The former uses the top-down approach whereas the latter uses the bottom-up approach of emergent systems. In fact, research in CAS and alife are parallel.

1.5. The Fusion of Virtual Reality and Artificial Life for Heritage Reconstruction

The scope of work and motivation for the research presented here has been identified in this chapter. The project falls within the scope of Virtual Heritage with specific application of problem-solving in the field of landscape archaeology. An introductory analysis of the research requirements targeting the field revealed the need for the fusion of two elementary strategies for this project – visualisation and modelling. Subsequently, an early review of literatures specific to the scope of work has identified a number of techniques used for visualisation and modelling worthy of development. A look at the current use of the various levels of interactive media in Virtual Heritage has shown that advanced visualisation techniques could give users a more engaging experience which could benefit the educational aspects of a heritage site. It was also shown that a necessary element considered lacking in any Virtual Heritage implementation is the addition of environments that are 'living' and agents that are 'responsive'. The addition of these 'living' entities and environments could give Virtual Heritage applications a richer, more evolvable content, and a higher level of interactivity. On the other hand, modelling accuracy and scientific credibility in reconstructing heritage sites is important. An analysis of scientific methods for modelling individual vegetation life and their collective dynamic behaviour revealed suitable techniques within the field of AI, CAS, and alife.

The following presents the research questions, from which this research is based. This thesis attempts to answer these questions based on evidence gathered from literature reviews, implementations and experiments in favour of the argument that modelling using Artificial Life techniques could address issues related to current models of vegetation distribution pattern in archaeological landscapes.

1.5.1. The Virtual Heritage Question (Research Question)

The goal of Virtual Heritage research is to restore, preserve, and recreate artefacts in order to educate the general public regarding its values. One of the requirements for this task is the historical accuracy of the reconstruction, especially projects related to Virtual Heritage. The other is the publishing of the heritage artefacts or sites via interactive media. Therefore, what are the modelling and visualisation techniques that could both accurately reconstruct a site on the one hand, and allow users a high level of participation on the other? Which interactive media could simultaneously address the need of both modelling and visualisation? Should the 'processual' and the sensual/experiential aspects be a separate procedure as witnessed in archaeological reconstruction of landscapes?

1.5.2. Addressing Limitations in GIS-Based Systems (Research Question)

In section 1.2.4, it was shown that there are limitations in the use of GIS-based techniques, one that is heavily utilised for vegetation pattern modelling in archaeology. In particular, it was shown that GIS-based systems could not properly address issues related to temporal analysis, 3D analysis, and the accuracy of represented model. Since natural landscapes are continuous and three-dimensional, and the analysis of an archaeological site involves large timescales, the use of GIS-based techniques although convenient, will not properly address the issues. Therefore, the second question is how to identify new methodological requirements for modelling large temporal and spatial vegetation patterns. What other ways could vegetation patterns be modelled that can address the lack in GIS-based techniques? If so what are the techniques that could allow vegetation to be modelled to a level of accuracy sufficient for archaeological interpretations?

1.5.3. New Techniques for Vegetation Modelling (Research Question)

Vegetations are living entities. Collectively they manifest spatial emergence in the niches of their biotic and abiotic environment, clothing the landscape in time and space. Traditional methods in archaeology use the top-down approach in modelling vegetation patterns. This is like an automated system that speed up the process of manual placements of vegetation based on their ecological preferences without consideration for the vegetation life cycle. Is the bottom-up approach studied in CAS and the synthesis of life in alife a superior method? In this type of novel modelling approach, what are the necessary features that will allow an artificial vegetation to mimic its natural counterpart and thereby clothe a landscape in both space and time?

1.5.4. Computing Resources and Alife-based Vegetation (Research Question)

If vegetations are modelled as individual entities with all the necessary aspects of their life cycles, can computing resources cope with the large number of plants required on a large spatial and temporal scale? Are there any techniques for minimising resource bottlenecking expected in such systems?

1.5.5. Other Applications (Research Question)

The present study is concerned with applications of novel methods using the concept of emergence associated with Artificial Life. It is realised that the models, if well developed, could be potentially useful in other areas related to landscape reconstructions. If so, what other areas could make use of the models?

1.6. Thesis Structure

The remainder of the thesis is organised as follows:

Chapter 2 includes a literature review which looks at specific Virtual Heritage research in large landscape reconstructions and the application of 'living' entities in the Virtual Environments. A review of alife-based and GIS models related to vegetation modelling is conducted to determine its strength and limitations. The chapter continues with a survey of hardware and software technologies that are suitable for application in the work presented here. Finally it concludes with a summary of the findings.

Chapter 3 covers early technical investigations of seismic data conversion techniques, 3D reconstruction and visualisation of large landscapes and Mesolithic artifacts, and different implementations of interactive Virtual Environments. The chapter concludes with a summary of the work.

Chapter 4 covers the development of an alife framework for supporting experimentations with virtual vegetation. It also investigates how vegetation and its ecology can be modeled and incorporated with the alife framework. Notably the technical aspects of alife vegetation modeling are studied and its agent-based responses to environmental threats and benefits are implemented. A segmentation algorithm was also developed for optimising the speed and efficiency of interaction among alife entities.

Chapter 5 discusses the results of experimentations with the alife-based vegetation model and explores its potentials for determining vegetation pattern distribution in virtual terrains. This includes studies related to the fitness of different species of vegetation preferences in parameterised environments, studies in vegetation responses on environmental variations, competition, migration, and species concentration in ecotonal boundaries.

Chapter 6 introduces a compressed simulation concept for reconstructing the Shotton river valley. The same chapter explores the collective effects of the growth and distribution of alife vegetation and its Mesolithic ecological model on segments of the Shotton river valley before reproducing the vegetation distribution model on a games engine-based Virtual Environment.

Chapter 7 is an overview of the previous sections, presenting the potentials of alife-based vegetation modeling and Virtual Environments and its use in Virtual Heritage and possibly disciplines in which landscape vegetation pattern research is studied. A discussion of the limitations of the approach is given. Finally, it looks at areas in which this research can be extended.