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Review

Virtual humans in cultural heritage ICT applications: A review

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ABSTRACT

Virtual Reality (VR) is becoming an increasingly important tool for the research, the communication and the popularization of cultural heritage. A great deal of 3D interactive reconstructions of artefacts, monuments and entire sites have been realized which meet the consent of both specialist and public at large. However, until a few years ago most of these reconstructions were basically static and often missing an important factor: human presence. Thanks to the advancements in the technology, in latest years Virtual Humans (VHs) have started being used in a variety of cultural-related VR applications. From simple 2D characters to complex 3D avatars, technology continues to evolve and so is the adoption of virtual assistants in digital heritage. The acceptance of such tools deserves a greater attention from the scientific community. When designing such applications, researchers need to take into consideration not only motivations and constraints, but also the type of virtual human fitting in the scenario. In this paper we aim at providing a state-of-the-art on this subject, focusing specifically on the cultural heritage area, underlining the technological challenges and also analyzing the effects of avatar interaction on user engagement, sense of immersion and learning effectiveness. This review also presents the usage of VHs from user's perspective and from the design point of view. We finally discuss the strengths and weaknesses of current approaches and point out unsolved issues, identifying a set of recommendations and good practices to follow when designing VR-based cultural heritage applications including VHs.

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1. Research aims

This paper aims at providing a state-of-the-art on the use of virtual humans in virtual cultural heritage applications, underlining the technological challenges and also analyzing the effects that VHs interaction has on user engagement, sense of immersion and also learning effectiveness. The usage of virtual humans from the user's perspective and from the design point of view are two issues also discussed in this article. Additionally, this review aims at pointing out unsolved issues in this field, identifying a set of recommendations and good practices to follow when designing VR-based cultural heritage applications including virtual humans, based on the strengths and weaknesses of current approaches.

2. Introduction

Culture is traditionally linked to the environment, the materials and the objects used and created by a population. Culture also relates to knowledge and habits. Today, one of the most popular means used for re-enacting past cultures and linking them with their original environment is Virtual Reality. Creating 3D virtual worlds is being credited as the most affordable, dynamic and interactive option for integrating the environment, the artefacts and the knowledge associated with a culture [1].

Such virtual reconstructions have become very popular in the past years [2], offering visitors the possibility of being immersed in a digital world that re-creates buildings and artefacts of a certain historical time and place. However, virtual reconstructions presenting only static objects provide a limited user experience. Consequently, the current trend is to populate these worlds with virtual humans (VHs) showing appearance and behaviour very similar (hopefully identical) to that of the original inhabitant, basically virtual actors that may interact with the environment, among them, and with the user himself by human-like manifestations (moving, speaking, using tools, and so on).

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According to the particularities of their implementation, VHs used in cultural heritage applications may play a role that ranges from mere decoration to being an immersive knowledge carrier [1], or even a guide [3]. The ultimate goal of populating virtual cultural heritage environments with VHs behaving similarly to the original people of the reconstructed places is to provide to the users a more engaging and realistic experience-The trend to incorporate VHs is stimulated by emerging technologies, such as the field called "edutainment", which express a synergy between education, training and entertainment [4]. In this sector, VHs are often used as virtual teachers in order to create more user-friendly applications and to attract players' attention [5].

The aim of this paper is to study the use of VHs in virtual reality applications developed in the field of cultural heritage. In our survey, we have selected a number of relevant applications developed in the sector in the latest years and for each of them we have identified specific links between the chosen technology, the type of virtual human representation, the level of user interaction and the software platform. Our study underlines the involved technological challenges and also analyses the effects that VHs interaction has on user engagement, sense of immersion and learning effectiveness. The usage of VHs from the user's perspective and from the design point of view are two issues also discussed in this article.

Our intent, following an extensive review of the existing literature, is to point out the main issues in this field, identifying a set of recommendations and good practices to follow when designing VR-based cultural heritage applications which include VHs, based on the strengths and weaknesses of current approaches. Last but not least, the paper provides a classification of existing applications, considering various parameters (such as application type, year of development or technology used) and a critical analysis on this topic, discussing the following questions:

- can a link be established between the type of virtual human, technology used and user interaction?
- what kind of VHs implementation works best for each application type?
- what technological issues are open and need solutions to be overcome?

The paper is organized as follows: section 2 provides an overview of known usage of VHs in the cultural heritage field. Section 3 offers a background on the virtual human technologies used in VR applications. Section 4 presents these applications, underlining their specifics. In section 5, an extensive critical analysis of virtual human implementations, applications, technologies and user interaction and assessment is provided. Finally, section 6 presents the conclusions of this study, together with a roadmap for developing a cultural heritage VR application with VHs, general guidelines and recommendations.

3. Overview of known usage of virtual humans in cultural heritage

The most widely-accepted definition of virtual human is that of a computer-generated character with the appearance of a human being [6]. There are commonly two main types of VHs encountered in VR applications: avatars and virtual agents. An avatar is a graphical digital representation of the user, in either a two-dimensional (images, static or moving) or a three-dimensional form (i.e., characters from video games or virtual worlds). A virtual agent is a computer-guided digital, interactive character, with or without human appearance, but with several human-like abilities (like cognition or communication by speech or gestures) that enable it to participate in a dynamic social environment.

Current VR technologies offer users the possibility of experiencing 3D-reconstructed heritage sites as a visitor, a traveller or even as a resident. The categories and behaviours of VHs encountered in virtual historic scenarios vary according to the application type and more specifically, to the type of exploration metaphor. Thus, in first person control (where the user controls the view and navigation), the encountered VHs are commonly more interactive, being able to provide real-time feedback (verbal and behavioural) to the user's actions. On the other hand, in guided-tour type immersions (where the user is simply a passive observer), they usually show a predefined ("scripted") behaviour consisting of performing certain actions or talking, as part of the tour [7].

A new and promising direction of research is the use of intelligent agents, embedding human-like personality traits and abilities, as virtual guides for contemporary museums [8]. This has the potential not only to entertain and engage visitors but also to contribute to the learning process by offering personalized feedback, by answering questions and using storytelling elements. Implementing virtual museum guides is not an easy task. These avatars must be naturally embedded in the environment, transparent, flexible, and responsive to the needs of contemporary visitors [9] in order to be considered as a social partner by visitors and therefore provide a valid contribute to the experience.

Deploying intelligent agents as VHs in virtual cultural heritage environments is credited to enhance the interactivity and playability of the reconstructed scenario [10]. Achieving the desired realism level of these virtual characters is a challenging task as several issues are required (such as character autonomy, user interaction and realism [11]). In order for the VHs to act as autonomous agents in their residing virtual environment, they need to be programmed accordingly and their actions must be adapted to the context (historical time and place of the reconstructed site) and also to the co-existing artefacts, the other VHs and most importantly, to the users. These agents need to be "intelligent" enough to make proactive decisions while responding to events in the virtual world, and not simply act based on pre-defined scripts. A key aspect in such virtual applications involving agents is the interaction between virtual and real humans. The user needs to perceive the agent he/she is interacting with as close to reality as possible. Thus, VHs need to be able to communicate both verbally and non-verbally, through gestures and facial expressions [12]. Last but not least, virtual agents need to be designed as realistic as possible, not only in terms of visual appearance but also in terms of personality: the should present a human-like behaviour and consequently be able to manifest emotions and other specific traits and characteristics [13].

Given the above, the process of designing and integrating VHs in cultural heritage related VR applications is a complex and diverse endeavour. It needs a synergy of efforts targeting a variety of technologies and areas of research like computer graphics, 3D animation, human-computer interaction, artificial intelligence, social sciences and so on. This provides an excellent research opportunity, as we have the chance to investigate which is the most appropriate usage of VHs in cultural heritage applications and to draft recommendations and best practices based on this analysis.

4. Technologies behind VHs implementation

Implementing VHs is commonly a complex and challenging task that often requires a multitude of technologies, software and hardware devices. Developers usually aim at achieving desired results in terms of avatar consistency, realism and interactivity by making use of different methods. This section details the most important tasks involved in the implementation of VHs, detailing the underlying technological background and the existing issues, together with the solutions used to address them. Hence, the following major top-

ics are covered in this section: the generation, the modelling and the reshaping of VHs. We also discuss here adding verbal communication capabilities to an agent and present an overview of the challenges and techniques used for implementing crowds of virtual agents.

4.1. Virtual human modeling

The most common approach to generate VHs is manual modelling. This is done either by means of general purpose 3D modelling software or through the use of specialized tools (such as the Smith Micro's Poser [14]).

The common approach is to produce a 3D model consisting of an invisible skeleton, mimicking the structure of human bones, whose animation induces the corresponding deformation of an external mesh (skin) linked to the skeleton's bones through a binding process named rigging. Given the recent development in low-cost depth cameras (such as Kinect, RealSense, and so on), another accessible solution for creating 3D VHs is using these devices to perform shape acquisition by capturing the static or dynamic geometry of real human subjects. The implementation of such systems may vary depending on the number of 3D cameras used. In i.e., [15], the authors use three Kinect devices (for the upper, middle and lower parts of the human body) with the human subject standing still on a turntable. In [16], two Kinect devices are used (for the upper and lower parts of the body) while the subject is asked to rotate by himself in front of the system. There are other methods that use a single camera to capture 3D data, with the subject having to rotate and face the sensor in different positions. In all cases, the key for achieving a reasonable 3D reconstruction is applying super-resolution algorithms and multi-view non-grid registration [17,72]. However, despite being relatively low-cost, easy to use and with high availability, the above-mentioned solutions create only a static 3D reconstruction of a human subject which alone is not enough to create virtual characters. Hence, additional processing efforts are needed for converting this static geometry into an animated agent [18].

Recent research efforts [19] aim at capturing the dynamic shapes and attributes of a human subject in order to easily produce animations of the virtual reconstructed avatar. In [20], a method is illustrated enabling to acquire a 3D model of a human and to control the resulting 3D avatar within minutes. This process requires taking 4 static poses at 90 degrees angles relative to each other, which are then used to construct the 3D model. After being given a skeleton and the smooth binding information necessary for control and simulation, the 3D model is ready to be used in virtual applications.

Another similar approach in the field of rapid generation of 3D avatars brings on novel features like reshaping capability and improvement of the auto-rigging quality in the automatic avatar generation pipelines [18]. Automatic rigging is indeed one of the most important advances in this field, as rigging is traditionally a manual process performed by specialized animators and requiring a consistent amount of time and energy. In recent years, several solutions for automated rigging have been developed. In [21] the authors describe a solution using a set of rigs (one for each body part), which are afterwards assembled into a full skeleton (using a pre-rigged template). The same basic principle is applied in [18], but in this case, the process is less complex, since it requires a single rig to be defined.

4.2. Virtual human reshaping

Achieving an easy and flexible customization of VHs plays an important role in Virtual Reality applications, where such models may assume a variety of appearances. Achieving a high level of diversity of the VHs is an important factor in ensuring the realism of the scene, especially when dealing with large numbers of characters (i.e., crowds). In this case, creating individual models from scratch, each with its own body shape, size and appearance, is not the optimal approach. In this respect, a critical issue is to have a consistent topology of the body's shapes and parts, a major requirement for morphing a human model in a variety of shapes and sizes. Thus, producing a morphable human model from the 3D data is a key process in generating animated 3D avatars that can easily be scaled. The existing methods for accomplishing this task usually rely on pre-existing templates [18], sets of meshes [22] or databases of registered body scans in different shapes and positions [23]. In [24], is proposed a method of achieving a variety of virtual human body size models derived from a skinned template, which does not require additional design efforts and uses the existing skinning data already attached to the template model. The sizing model algorithm is based on anthropometric body measurement standards.

Another novel method to modify a generic 3D avatar based on standard human body measurements is described in [25]. This method, that basically modifies the 3D model by scaling the vertices globally and locally, claims to achieve a speed-up compared to other approaches [24] and provides a natural-looking result. A method for automatically rigging a human 3D scan by using a human figure database and morphable model is described in [18]. The 3D scan may be reshaped and resized, and rigging attributes can then be transferred to a re-shaped body scan to produce the desired virtual avatar.

4.3. Clothes modelling

Achieving a good human body model is important, but not sufficient. VHs involved in digital cultural heritage experiences need to also wear appropriate clothing. This is crucial, since most of us tend to pay attention to the clothes of the people we interact with in the real life. Clothing and jewellery pieces are viewed by historians as important clues which can clearly show the state of the society including its technological and cultural level. On the social level, clothes and accessories are important to define the gender, age and status of their owner.

Simulating clothes is an old endeavour [26]. Early studies were facing the limitation posed by intensive computation models. Recent technological advances have greatly improved this field [27]. Most recent studies tackle finer features, such as modelling wet clothing [28]. With respect to cultural heritage, the clothing of the VHs need to accurately reproduce the not only the look and feel, but also to have their animation properly implemented (by solving the mechanics between the body of the virtual human and the fabrics). One platform which deals with these problems is the Fashionizer, presented briefly in [13].

4.4. Talking agents

VHs able to engage verbally the user in an interactive dialogue are more likely to be viewed as social entities. People tend to react to such "talking" digital counterparts in much the same way that they react to real people [29]. However, developing such agents is a difficult task from the technical point of view, as it requires to integrate various technologies like speech recognition, natural language processing, voice synthesis, and so on.

The communication flow with a talking virtual human can be divided into two sections, corresponding to input data processing (speech coming from the human user) and output data generation (the response given by the virtual human). If the VH receives human speech (voice) as input, the audio sequence needs to undergo speech recognition in order to be transformed into text, which is further processed by means of natural language algorithms in

order to extract the relevant keywords/concepts that may produce a response. These items are used to build the most appropriate response, usually from a pre-defined set, which is then spoken back to the user by the virtual agent.

One major challenge in interacting with talking VHs is speech recognition, as several problems may arise due to noisy environments, different dialects, and so on. This is why authors in [30] have chosen to use the keyboard as the input device. This approach, while ensuring a clearer communication, limits the interaction of the virtual human with only one visitor at a time. However, in this case, the VH uses camera-based perception in order to detect the presence of multiple persons and discriminate between them. Both speech and visual inputs are processed by a perception module, which transforms it into events. Events are then used by the behaviour generation module, in charge of all of the VH's manifestations, including speech (by synthesis of prosodic speech, face animation, and so on). Basically, the verbal communication is performed by two sub-processes: interpretation (analyzing and parsing the input text to understand the underlying concepts and statements) and dialogue management (in charge of the virtual agent's conversational behaviour, based on a multi-layer plan-based approach with condition-action rules).

Another example of a speech communication engine for talking VHs is described in [31]. In this case, VHs accept direct human speech as input. The recorded audio is first processed by an automatic speech recognizer (ASR) module, the extracted text being further on served to the language understanding (LU) module. This module uses a statistical text classification algorithm for mapping and selecting a set of responses believed to be most appropriate from a domain-specific library of scripted responses (about 400), which is then passed on to the dialogue management (DM) module. Based on the set of responses and conversation history, the DM module selects one particular response sequence for the characters to perform.

4.5. Crowds of agents

An important part in cultural heritage application where VHs play a crucial role is the re-creation of old cities and communities together with their inhabitants. In this case, VHs are important not only for providing a more realistic perspective on the recreated site, but also for highlighting that particular population's behaviour, habits, occupations and interaction with the environment at that precise location and historical period.

There are specific 3D virtual heritage environments (like cities) that need to be populated with a large number of VHs – so called virtual crowds [32]. These basically consist of a large number of autonomous VHs integrated in the surroundings (looking and behaving like the original inhabitants of that particular site). A set of challenges arise when dealing with the generation of such a large number of entities and with their real-time rendering, but also with their control: solutions vary from the inefficient and expensive approach of having human experts controlling avatars to the more affordable but complex option of implementing Artificial Intelligence algorithms for the control and simulation of the virtual agents. Hence, generating and managing large crowds of VHs is no easy task, being an issue more complex than dealing with a single virtual human. There are several research papers that discuss the methods used and problems overcome for generating such crowds of VHs in different scenarios.

The first and major issue is collision avoidance, which has been dealt with initially by applying short distance avoidance algorithms in local ([33] and [34]) or global navigation ([35] and [36]). However these solutions are viable for a limited number of models, and cannot handle simulating a large number of VHs at the same time. The most recent attempts in this domain use fluid dynamics principles to implement motion planning ([37] and [38]). A framework covering the processes of developing 3D virtual worlds with embedded static models of scenes/buildings from 3D modelling package and addition of crowds is described in [39]. The authors propose a grid-based behaviour system which scales to large crowds (more than 1000 virtual humans) with automatic model placement in scenes where they can move and change their behaviour/trajectory near obstacles. The process is automated in order to increase efficiency so that there is no detraction from the real-time experience and no additional modelling requirements are needed. A similar behavioural model, coupled with pre-rendered images in order to speed-up rendering and allow to scale up to 10000 VHs, has been used in [40] where the dynamic simulation of large crowds was used for emergency planning in open spaces, in particular to plan different routes with specific functions: paths for evacuating visitors, and paths for evacuating important cultural assets.

The authors in [6] accomplished their goal of creating and animating interactive virtual crowds by developing a three-tier system. The first component deals with the creation of the VHs and configuring their physical appearance. Each virtual human is derived from a template selected from a set and is personalized by applying one of several appearance sets (textures and colors). The second component allows simulating the navigation of the VHs, while the third one executes the real-time computations needed for moving each virtual pedestrian. The effectiveness of this solution – shown by populating a virtual reenactment of the ancient city of Pompeii with crowds – comes from targeting computing resources in the area where the attention of the user is focused. However, the VHs in this example do not present advanced features: they do not manipulate the environment and they do not engage into historically authentic interactions [41]. Another approach tries to solve the issue of previous crowd simulation algorithms that are not suitable for modelling complex individual behaviours and role-based virtual interactions by treating 3D worlds as normative multi-agent systems [41]. Virtual Institutions Methodology [42] is applied for the design and deployment of virtual worlds requiring complex interactions between both humans and autonomous agents. This approach is based on the hypothesis that for an autonomous agent to be capable of showing complex behaviour similar to that of ancient humans, the complexity of the agent's environment must be reduced. As an example of their proposed methodology, the authors developed a 3D virtual reconstruction of the ancient city of Uruk and programmed the virtual human population.

5. Application types

VHs are being used in a variety of cultural-related applications, being credited as having a significant potential to enhance these applications, by making them more realistic, attractive and interesting. This section aims at grouping this multitude of applications in three main categories. We describe them and highlight the importance and role played by the VHs in each case. First, the cultural reconstruction-type applications are reviewed, as virtual humans increase the realism and authenticity of the simulation. Another category of VHs' applications in cultural heritage is that of conversational agents acting as interactive guides for museums, virtual exhibitions, historical or cultural sites, and so on. In this case, the avatar usually manifests human-like personality traits and communicates verbally to the users in order to achieve the social acceptance of a real human guide. Finally, the last category of applications are serious games with cultural heritage content. This is a very popular subject today, such games being developed for both fun and educational purposes. Virtual characters are of course

mandatory for achieving the desired experience and user acceptance in this category as well.

5.1. VHs in virtual cultural heritage reconstructions

A common application of VR to cultural heritage relates to the virtual reconstruction of ancient cultural and historical sites. In this case, VHs are tightly integrated in the virtual environment in order to increase the realism of the simulation and make the user's experience more authentic, being given the appearance and behaviour of the original inhabitants.

Fig. 1 depicts some of the most representative virtual cultural heritage reconstructions featuring virtual human agents.

In [43], authors present their efforts to integrate virtual humans in a virtual reconstruction of the ancient city of Pompeii by developing a real-time mobile mixed reality system. Their methodology aims at providing realistic simulations of human actors who augment real environments. They argue that their approach brings on significant benefits for the user, who is presented a mobile superposition of the real world with a virtual scene representing fully simulated living characters in real-time. This scenario is also credited for enhancing user engagement by generating authentic behaviours and interaction between real and virtual entities.

The virtual restitution of the church of Hagia Sophia [44] (located in Istanbul, Turkey) is another example of a virtual cultural heritage application where, besides the virtual reconstruction of buildings and historical sites, the experience includes VHs – representing the people of a certain era – in order to increase the realism of the simulation and make the user's experience more authentic. In this example, when representing the VHs the authors also took into consideration the historical particularities regarding the behaviour and appearance of the characters.

Other applications target the adoption of avatars as tour guides of virtual environment. In [45], the exploitation of an agent to accompany the user on a guided tour of a 3D virtual environment is proposed. The virtual human acts both as a navigation aid (helping the visitor to find places of interest) and as an information provider (offering facts about the artefacts and places visited), in other words making the 3D environment more lively, attractive and easier to navigate for the user.

A very important landmark in the research for populating cultural heritage environments with virtual agents is the EPOCH project, developed by a consortium of European universities with the goal of improving and releasing frameworks that support the development of interactive audio-visual real-time 3D VR systems and contributing with virtual human simulation technologies [46].

Amongst the results of this work is the vhdPLUS core platform, available as an open-source tool for the cultural heritage community, a flexible and extensible framework enabling the development of interactive audio-video simulation applications in the VR/AR field, with emphasis on virtual human simulation technologies [46]. Together with vhdPLUS, another instrument derived from the same project is the Avatar Research Platform (ARP) toolkit, which supports the design and animation of VHs capable of speech and sign language [46].

Another example of a virtual tour guide implementation is described in [47], where, using the ARP toolkit, an interactive female agent acts as a guide for the re-created 17th century German town of Wolfenbüttel. The agent can also respond to questions related to the town's buildings and other points of interest and is capable of gesture animation and natural language understanding.

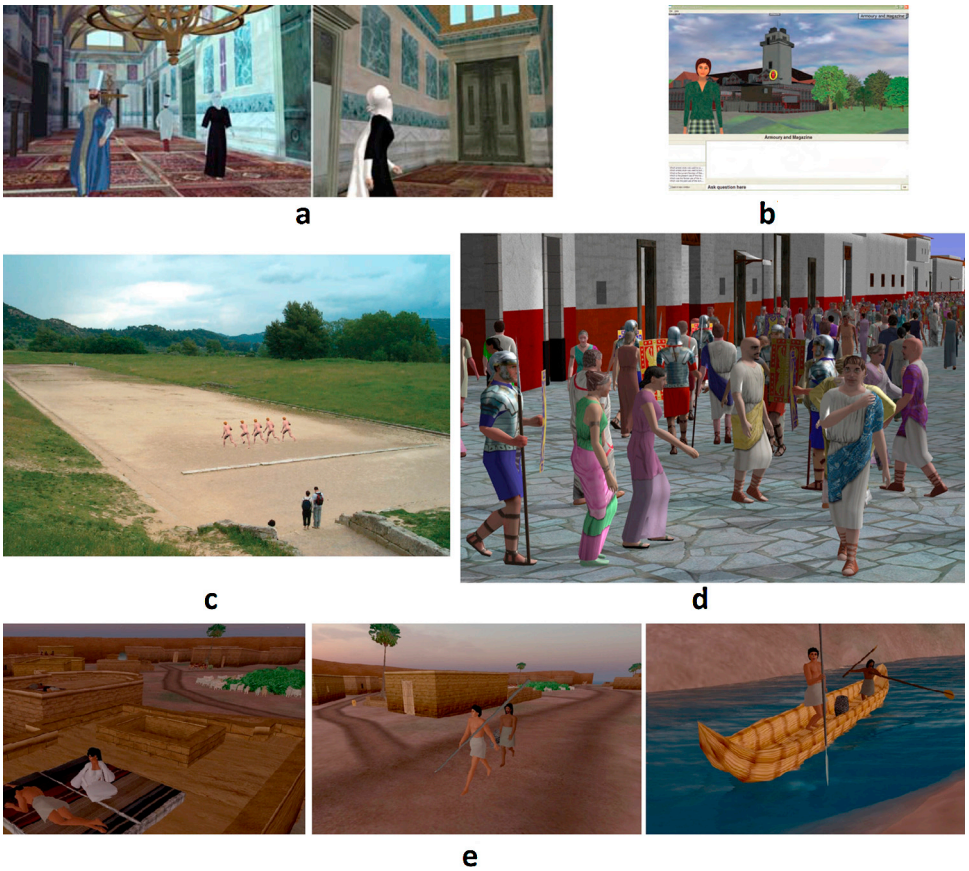


Fig. 1. Each image depicts representative virtual cultural heritage reconstructions of ancient sites populated with VHs: a: Hagia Sophia [44]; b: German town of Wolfenbüttel [47]; c: Stadium in ancient Olympia, Greece [48]; d: Ancient Pompeii [32]; e: The Sumerian city of Uruk [41].

Augmented Reality guides for cultural heritage sites may also integrate VHs in order to increase the realism and user engagement. For instance, in [48], the application implements augmented video frames where virtual athletes compete in a real stadium, thus providing a reconstruction of the ancient Olympic Games. The presence of VHs is a feature reported to have helped users to better understand the site's history.

Another application based on the research from the EPOCH project is the revival of the ancient city of Pompeii [32]. In this case, alongside the simulation of ancient buildings and landscapes, the city is populated with crowds of VHs. These avatars represent various social and occupational categories of people, and their appearance and behaviour has been modelled accordingly. For example, there are rich and poor districts in the city, and each virtual human knows where it belongs, some districts being restricted to certain categories of people. Seven basic templates have been designed to be able to represent such a large and diverse crowd, which are instantiated multiple times with variations in colour and texture.

In [41], the authors accomplished the 3D virtual reconstruction of the ancient city of Uruk from around 3000 B.C. in Second Life, one of the first virtual worlds to put a particular attention to VHs. Being a massive online multiplayer world, their presence was needed in order to provide credible characters. The reconstruction presents an accurate replica of the daily life of the Uruk's inhabitants and helps users to experience the culture of the ancients Sumerians. Visitors can become a part of that virtual society and interact with VHs in order to solve specific tasks. As an example, the daily life of two fisherman families can be experienced by visitors. Each family is composed of a husband and wife, and the "day" lasts approximately 15 minutes. During this interval, the virtual humans perform the entire range of daily activities: from waking up, collecting water, preparing breakfast, going fishing, returning home and finally going back to sleep. Last but not least, during the process of designing and implementing their virtual world, the authors have developed a novel methodology, called Virtual Institutions, which consists of a collection of tools for the design and development of such virtual environments.

In [49], a virtual human is the one and only protagonist, as the entire experience focuses on the virtual reconstruction of John Calvin in his familiar surroundings and activities in order to foster a better understanding of his life. A particular care was devoted into the development of a 3D character respecting the character as grounded in the collective memory at the same time relying only on (the few left) historical data and testimonies.

VHs are fundamental when dealing with intangible cultural heritage, as this type of heritage is often related to human actions or performances. In [50] is presented the virtual reconstruction of the Namaz Pray of a simulated Ottoman Imam in the 16th century. The project aims at demonstrating that abandoning traditional concepts of static cultural artefacts in favour of interactive, augmented, character-based narrative representations can make virtual reconstructions from historical sites a more exciting and engaging edutainment medium. The AMICA project [51] aims at the same objective, although with different technological means (3D video data of real actors instead of 3D modelled characters) and within a different context (the dissemination of the heritage of engraving handcraft).

The digital reconstitution of Le Boullongne [52], an 18th century merchant ship, aims at understanding on-board living conditions by means of a realistic interactive naval simulation, including interaction with some ship elements, spatialized sounds, dynamic weather conditions and realistic movements. Three animated sailors accompany users in their sailing experience, offering a limited interaction; for instance, when the user comes close to the helm, the captain walks backward on the deck to allow the user to interact with the helm.

A large crowd of VHs is portrayed in the reconstruction of George Town [53], a mobile application enabling an interactive virtual walkthrough of the town in two different flavours: present and past. The stress here is put on the simulation of the crowd dynamics which is managed in two different ways: 360° images of the present town are populated by 2D images of VHs that behave according to information retrieved from the video (for instance: obstacle recognition, avoidance, etc.), while the reconstruction of the ancient town, together with the crowd of its inhabitants, is fully virtual and therefore takes place in a 3D digital environment.

5.2. Conversational virtual humans–agents as interactive guides

An important issue regarding the use of VHs as conversational agents in cultural heritage applications (but also in other domains) is that of social acceptance. This issue is being widely recognized and analyzed by researchers in the field of human-computer interaction [54]; their studies and experiments show that by integrating emotions together with other human-like personality traits enhance the acceptance of the conversational agent, leading to the users treating the avatar as an equal social partner rather than a simple object.

In Fig. 2, three conversational agents acting as museum guides are depicted.

Max [30] is a conversational virtual human deployed at the Heinz Nixdorf Museums Forum (HNMF) in Germany as a museum guide, capable of engaging with visitors in natural, face-to-face communication, while providing information about the museum's exhibits and being able to conduct other small-talk conversations. This was one of the first implementations of virtual conversational guides at this level of complexity. Visitors visualize Max in human-like size on a static screen. Being equipped with camera-based visual perception of the passing visitors, Max is able to engage them in conversations, providing information about the museum and exhibits. Visitors are able to give natural language

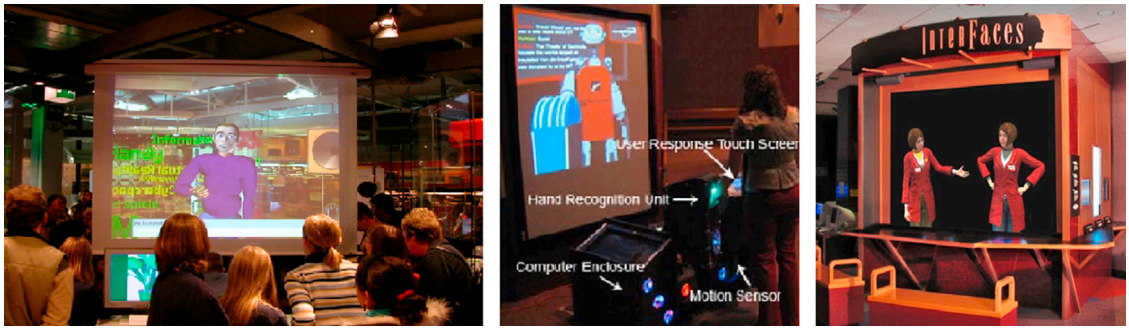


Fig. 2. Three conversational virtual human agents: Max [30] (left), Tinker [8] (middle), and the twins Ada & Grace [10] (right).

input to Max using a keyboard, while he answers back using a synthesized voice. Also, the virtual agent has been programmed to provide non-verbal actions (gestures, facial expressions), which, together with small talk, are meant to increase social interaction between visitors and the virtual guide. These features are enabled by an extended rule-based approach to dialogue modelling, taking account of semantic-pragmatic and context-dependent aspects of dialogue acts, and combining rule application with long-term plan-based behaviour, in order to drive the generation of output in the forms of both text and full multimodal behaviour [30]. Max's activity at the HNMF has been evaluated after a 7-year period, during which the researchers analyzed the log files and visitor feedback. The results have shown [55] that the key feature attracting the visitors and contributing to the sense of immersion and engagement was the emotional capabilities of the VH. In many situations (like after a completely inappropriate answer provided by Max) the visitors are believed to have dropped out of the dialog if it was not for the dynamics of the agent's emotional system to compensate and keep up their interest.

Another VH playing the role of a virtual museum guide is Tinker, deployed at the Computer Place exhibit at the Boston Museum of Science [8]. Tinker appears as a 3D cartoon robot projected in front of the visitors and is able to communicate with them using synthetic speech and synchronized non-verbal behaviour. This virtual agent's role is to provide visitors with information and directions regarding the museum's exhibits, while establishing social bonds with them using empathy, social dialogue, reciprocal self-disclosure and other relational behaviour. A novel feature in this case is the range of human relationship-building features integrated in this virtual agent and used to engage users, especially the ability to identify returning visitors based on biometric parameters, thus being able to continue the conversation/relationship with them. The authors in [8] also analyzed the outcomes of having an intelligent virtual agent with relational behaviour capabilities as a museum guide, and showed that this significantly impacts not only positive attitudes towards the agent but also improves engagement and learning.

In [10], the authors describe two (twin) virtual museum guides, Ada and Grace, encountered by the visitors of the ComputerPlace at the Boston Museum of Science. These VHs are life-sized, photo-realistic characters interacting with visitors in natural language and capable of gestures and other forms of non-verbal communication. They can answer general questions about that specific museum gallery and other questions pertaining to the topic of information sciences, being able, based on the interests manifested by visitors, to suggest exhibits to check out. The key features credited by the authors (based on their research and studies) to increase engagement and make the VHs more attractive to visitors are: their appealing appearance, the fact that they are two characters, natural language interaction and near photorealistic appearance. However, a particularity with this case is the fact that the VHs interact directly via natural language only with each other and a human handler (museum staff member), visitors not being allowed to talk directly to the agents.

The Recreation of St Andrews Cathedral [56] enable visitors to participate in historic scenes whilst hearing the stories of historic characters they meet such as Bishop William de Lamberton, King Robert I, the Cannons of the Cathedral and visiting pilgrims. These VHs each have a background and a story to tell and follow a timetable of events. In general, the show a scripted behaviour enabling them to react to events or to hold keyword-based conversations with users, responding by means of text or speech. Similar features are proposed in Virtual Agora [57], a virtual heritage aiming to replicate daily life in an ancient Greek agora using VHs possessing a set of basic attributes that relate to its biological and physical characteristics, as well as its personality and behaviour. Every VH also possesses an extra set of actions, based on its assignment of a role or profession. Users can observe daily activities performed by the characters and interact with them by asking questions.

5.3. Serious games and cultural heritage

Serious games have been targeted by recent research as a potential instrument for enhancing learning in cultural heritage VR applications. They are basically videogames designed for educational purposes, with the objective of supporting the user/player in learning through a fun and interactive experience. Serious games make use of virtual characters for a more engaging experience, since studies [58] have shown that empathy with a game character is very helpful in better understanding certain historical events, cultural issues and specific behaviours.

Fig. 3 depicts users playing such serious games with cultural heritage content.

In [59], the authors propose an innovative brain-computer interface (BCI) system for controlling a cultural heritage serious game – a virtual reconstruction of ancient Rome. In the game, using non-invasive BCI technology, the user navigates its avatar inside virtual Rome and interacts with other VHs (intelligent agents) while learning at the same time.



Fig. 3. Two users playing cultural heritage serious games: Muru in Wonderland [65] (left) and MediaEvo [60] (right).

Another similar approach [60] describes the MediaEvo didactic game dealing with the history of the Middle Ages, in which the user is immersed as an avatar in the virtual reconstruction of the Italian town of Otranto, and can navigate and explore the environment with or without a guide, interacting with the virtual artefacts. Imago Bononiae [61] is a 3D real-time serious game focusing on the interactive exploration of a large reconstruction of Bologna during the Roman age. Using natural interaction devices, the visitor is immersed into a large and rich 3D environment populated by a virtual crowd, which visually guide the user through the ancient town and providing also different visions of the future urban layer of Bologna, enabling the experience of its urban evolution.

Game engines are used also for developing virtual museums guides. In [62], the proposed system – based on a commercial game engine – enables the visitor to be immersed in either a third- or first-person view of the virtual museum. Also, a VH acting as a museum guide is available to lead the visitor throughout the site.

There are also mobile-based cultural heritage serious games (like [63] and [64]) that, using augmented reality and features like context- or location-awareness enhance the user's experience at a cultural site, also guiding him through the exhibits by the means of a virtual character and providing interactive puzzles and quests for the user to solve. A slightly different approach is adopted by Muru in Wonderland [65], an immersive experience where a 3D toon-like character augments 360 videos of the city of Gwangju, soliciting spatial exploration through a hide-and-seek game.

6. Discussion

Besides providing an overview of virtual human types and applications in the field of cultural heritage, the ultimate goal of this paper is also on the one hand to analyze the effects that the interaction with VHs has on user engagement, sense of immersion and learning effectiveness and, on the other, to offer a critical analysis on the existing virtual human applications in this field, from which guidelines and recommendations can be derived to be used in future projects. Consequently, this section provides an assessment of the impact that user engagement has on the success of an application and how is this engagement influenced by the features and implementation of the VH. Following this assessment, a critical analysis of the links and dependencies between application and virtual human type, user interaction methods and technologies used is then presented. This analysis is based on a classification of the application examples described throughout this paper using the above-mentioned criteria.

6.1. Evaluating user engagement

The sense of engagement perceived by the user in the virtual environments of cultural heritage applications is very important as it has an impact on learning [66], especially when mediated with motivation. This issue leads the designers of such applications to implement interactive and feedback mechanisms to enhance the user's feeling of engagement. In this context, a key feature that fosters the engagement is social presence [67]. Being able to offer an authentic sense of engagement to the user is the key element that makes the difference between a mere virtual repository of digitalized cultural artefacts and an authentic, immersive virtual experience. This means that the social agents existing in a virtual cultural heritage scenario need to properly interact with the environment – the cultural setting – according to its specifics and also with the artefacts existing at that cultural site. Thus, it is to expect that by being able to interact visually and verbally with VHs, talk to, obtain information, the user will feel a deeper sense of engagement in that particular virtual cultural setting.

A successful virtual heritage application should be the result of a well-balanced synergy between representation (enabling the visualization of cultural data), experience (integrating elements that can provide in a captivating way enhanced knowledge) and interaction (engaging the user actively in the virtual world) [9]. Consequently, the role of VHs in such applications becomes very important since they represent a mixture of all three characteristics: a representation of an individual from a particular historical era and location being able to provide real-time experiences linked with the way of life, environment and artefacts, and last but not least, an inter-active communication with the user, being able to talk, answering questions, providing additional information and responding to the user's actions.

VHs may also play an important role in increasing the attractiveness of the virtual heritage site, as shown in [68], where visitors where more fascinated by their actions and lifestyle than by the actual reconstructed historical buildings and artefacts. Hence, virtual worlds without virtual human agents and social interaction tend to be perceived by the users as boring and empty environments [7]. Moreover, the way in which users tend to relate to VHs is highly influenced by their perception of them. VHs which are able to engage in interaction with the user are more likely to be viewed as real social entities rather than as objects [69]. This issue is relevant from another perspective: the sense of social presence supports the acquisition of knowledge [7], making interactive heritage applications more likely to offer an increased cultural knowledge transfer.

A trend in the development of virtual environments tries to achieve the richness of association and the level of user engagement found in computer video games [70], a goal not reachable without the integration of interactive, intelligent agents [71]. This has led to user-driven navigation VR applications, changing the role of the user from that of a mere observer to being an active participant in the virtual environment, and changing the data and knowledge flow, from a linear, unidirectional one, to bidirectional – the user retrieving data following his interactions with the virtual environment and its inhabitants.

6.2. Critical analysis

As shown above, there is a variety of implementations for virtual humans in cultural heritage applications, each having its own shape and size, different interaction capabilities, various technologies behind its implementation, and ultimately each VH has been designed to be application-specific. However, as previously anticipated, identifying links and dependencies existing between application goals and main emerging features (VH type, user interaction, and implementation technology) will serve to elaborate some general guidelines and good practices regarding the use of virtual humans in cultural heritage applications. Consequently, in the following These criteria for performing the comparison have been selected in order for each of them to be measurable and operational, in the sense that it is possible to assess, in either qualitative or quantitative terms, how each particular application relates to each criterion. The proposed criteria help in providing a comparative view of the surveyed applications from several points of view: scope and type of application, usability, technology behind the implementation, and user engagement. We also added a perspective on how such apps evolved throughout the years, in order to have a better picture of the main trends in the sector.

Table 1, the applications described in this review have been classified based by the above mentioned features. These criteria for performing the comparison have been selected in order for each of them to be measurable and operational, in the sense that it is possible to assess, in either qualitative or quantitative terms, how each particular application relates to each criterion. The proposed criteria help in providing a comparative view of the surveyed

Table 1
Comparative assessment of virtual human applications in cultural heritage.

Application	Type	Virtual Human	User interaction	Key implementation features	Year
Church Of Hagia Sophia [44]	3D virtual environment	Crowd (people)	Not possible	3D model created using 3D Studio Max 4.2	2002
Namaz Pray [50]	3D virtual environment	Single (Ottoman Imam praying)	Not possible	VHD++ real-time framework	2003
Ancient Pompeii [32]	3D virtual environment	Crowd (roman citizens)	Not possible	3D model created based on CityEngine with a semantic data navigation graph	2007
Wolfenbüttel [47]	3D virtual environment	Single (guide)	Q&A chat-based interaction	ARP UEA Scene Assembly Toolkit	2007
St Andrews Cathedral [56]	3D virtual environment	Single (user's avatar shown in either first or third-person perspective) + multiple (non-playing characters populating the church)	User can interact with Non-player characters that populate the environment in both textual and audile conversations	Open Virtual Worlds; OpenSim; Oculus Rift	2013
John Calvin [49]	3D virtual environment	Single (John Calvin)	Not possible	Zbrush; Miralab's Fashionizer; VICON	2014
Georgetown [53]	3D virtual environment	Crowd (town inhabitants)	The virtual humans interact in advanced scenarios, but no user interaction is possible	Unity 3D	2016
Archeoguide [48]	Augmented reality	Crowd (athletes)	Not possible	GIS photos; VRML 3D reconstructed models	2002
ARmuseum [63]	Augmented Reality (Mobile)	Single (guide)	The virtual guide gives the user instructions on how to complete the tasks	Game engine middleware software	2013
Le Boullongne [52]	Immersive 3D virtual environment	single (user's avatar) + multiple (sailors)	The user can interact through his avatar with different items on the ship	3DsMax 2013; Unity 3D; MiddleVR	2015
AMICA [51]	Immersive 3D virtual environment	Single (user's hands avatar) and multiple (artisans shown as 3D videos)	The user can interact through his avatar with the environment and might see "through the artisan's eyes" how the artwork is created	XVR; Oculus Rift; Microsoft Kinect and Primesense Carmine for 3D capture	2015
Virtual agora [57]	Immersive 3D virtual environment	Single (user's avatar) + multiple (people walking around the square)	User's avatar can interact with NPCs through conversation, storytelling, quests and other activites	Open Virtual Worlds; OpenSim	2016
Muru in Wonderland [65]	Immersive interactive 3D video tour	Single (toon-like anthropomorphic virtual character as a guide)	Users interact with the VH through storytelling but also physical (haptic) contact	Oculus Rift; Unity 3D	2016
Max [30]	Screen projected VH	Single (museum guide)	Keyboard-based input, spoken natural language output and camera-based visual perception	VH modelled using the Behavior Expression Animation Toolkit (BEAT)	2005
Ada and Grace [31]	Screen projected VH	Single (museum guide	Spoken natural language based input and output	Smartbody (SBM) behavior realization system; Gamebryo animation engine: SONIC toolkit	2010
Tinker [8]	Screen projected VH	Single (museum guide)	Keyboard-based input, spoken natural language output.	VH modelled using the Behavior Expression Animation Toolkit (BEAT)	2011
"Gossip at palace" [64]	Serious game (Mobile)	Single (museum guide) + multiple (16 characters animating the game)	Chat-based conversation with dialogue branches	Android application	2015
Mediaevo Project [60]	Serious game 3D virtual environment	Multiple (city inhabitants)	User can play as the avatar	Nintendo Wiimote and Balance Board	2011
Imago Bononiae [61]	Serious game 3D virtual environment	Single (user's avatar) + crowd (inhabitants of the ancient Bologna)	The user's avatar can navigate the environment populated with non-player virtual characters (NPCs) but cannot interact with them	Microsoft Kinect	2015
The City Of Uruk [41]	Serious game 3D virtual environment	Multiple (city inhabitants)	Q&A chat-based interaction	3D design of the city using Unity	2009

applications from several points of view: scope and type of application, usability, technology behind the implementation, and user engagement. We also added a perspective on how such apps evolved throughout the years, in order to have a better picture of the main trends in the sector.

In this comparative, multi-criteria assessment, we see specific correlations emerging between the application, the virtual human's type and user interaction capabilities. Single VHs or avatars are usually encountered for very specific purposes: as virtual guides for museums or exhibits and, obviously, as the user's avatar in 3D virtual immersive environments and serious games. In the case of virtual guides, a single virtual human not only mimics a real guide (which in the real world is also usually a single person) but also significantly reduces the complexity of the implementation. Since

a virtual guide must be capable of verbally interacting with the audience while also manifesting a human-like personality, having multiple such guides in the same application means that each must be unique – with regard to looks, voice, and non-verbal manifestations – which would highly increase the implementation complexity. This is confirmed by the single application example of virtual guides with more than one character – the twins Ada and Grace which are basically one and the same virtual human.

In the case of 3D virtual immersive environments and serious games, portraying the user's avatar is the most natural solution since it contributes to increase the immersion effect and the user engagement. Crowds, or multiple virtual humans, are instead encountered mainly in the case of 3D reconstructions of historical and cultural sites, where they play the role of the original inhabitants of the particular location, thus increasing realism and authenticity of the environment. These crowds of virtual agents however are generally not capable of interacting with the user but, in some cases, they do interact with one another based on pre-defined action scenarios. In latest years the most recent applications are somewhat an exception to this rule, for example 3D reconstructions like Imago Bononiae, St Andrews or Wolfenbuttel, where large crowds not only play the role of enriching the environment but, at the same time, can be interactively addressed by users in order to provide information.

To summarize the correlations between the VH and the application type, we can conclude that single avatars with enhanced interaction capabilities work best as the user's avatar in 3D immersive environments or when the situation is best represented by a single counterpart (like in the case of virtual guides), in other words in applications where the VH and the user must interact closely. Multiple avatars (even crowds) are instead opportune to populate virtual reconstructions where the user navigates and explores wide environments and the VHs are simply actors playing their part for increased realism.

Additionally, another important emerging correlation is the very tight link between the avatar/application type on the one hand, and the type of interaction between the user and the virtual human(s) on the other. The user interacts as himself using real world actions (spoken natural language and/or keyboard input) generally in the case of virtual museum guides, which are usually implemented as screen projections (Max, Tinker, Ada and Grace). In other applications like serious games or immersive 3D virtual environments, the user is impersonated by an avatar and through it he/she can interact with elements of that environment, including other computer-controlled VHs. Such edutainment applications are becoming increasingly popular, focusing on educational goals achieved through forms of entertainment familiar especially for young people. Virtual guidance can also be provided through this approach, often proposing different puzzles or quests for the user to solve, pertinent to the environment (museum exhibits, town elements, etc.). Of course, there are also applications where there is no interaction whatsoever between the user and the VHs present in the environment. This is usually the case of older applications, which are mainly virtual reconstructions of various sites that the user can navigate passively through.

One can also observe how the application types have evolved throughout the years. For example, the first virtual reconstructions of ancient cities or historical sites (like the cities of Pompeii and Uruk, the Olympia stadium, Hagia Sophia church, George Town) are mostly 3D virtual environments, non-immersive (with the exception of Uruk), and populated with crowds of VHs that allow no or limited user interaction, their role being mainly to increase the authenticity, realism and user engagement. The recent 3D reconstructions however, benefiting from the latest technologies and design tools, are immersive environments that the user can navigate and explore exploiting a more advanced interaction (Le Boullongne, Virtual Agora). This is an understandable fact, and is based on the breakthroughs in 3D and virtual reality technologies.

From a technological point of view, it can be noticed that, as expected, the most recent applications are also the most immersive and interactive ones, offering improved graphics quality, performance and increased realism, fostered by the amazing technological developments that, in the latest years, have appeared on the scene. The spread of relatively cheap solutions like the Oculus Rift, the HTC Vive and the Playstation VR, enables unprecedented highly immersive experiences, which greatly improve the perception of the reconstructed environment, including its inhabitants. The wide availability of advanced interaction devices such as Kinect-like cameras or Wiimote, is instead pushing new forms of interaction with VHs, for instance enabling the use of gestures and body language. Finally, the appearance on the market of dedicated development tools such as Unity or Unreal Engine, to name a few, which offer powerful means and a faster learning curve with respect to the previous generation tools such as XVR, OpenSim and similar, has led to a significant increase in the number of VR/AR applications in the last few years. As far as the modelling of VHs is concerned, the high degree of realism today obtainable by CG-generated (i.e., 3D models) VHs makes this choice almost ubiquitous in the analyzed applications, with the partial exceptions of those where the accuracy of the reproduction of gestures (sometimes crucial when dealing with intangible heritage) favours the use of 3D video data, which however still lack a good resolution and, consequently, visual quality.

Today, any cultural heritage application involving VHs must not only provide a high quality visual interface, but also enhance the interaction between the user and the virtual agent, through natural and body language or other means of non-verbal communication. In the case of virtual guides, the VH must be designed with a high degree of realism and human-like verbal skills and personality traits, not only to maximize its social acceptance but also to achieve an increased level of user engagement for the application to be successful. At the same time 3D immersive environments like virtual reconstructions or serious games that also include virtual characters, either single or crowds of VHs, must offer complex interactions between one another and between the virtual agents and the user, as these aspects are able to enhance the realism of the reconstruction, in the first case, by adding life and important cultural information, and to improve and make more engaging the game dynamics in the latter case.

7. Conclusions

In this paper, we have presented a state-of-the-art of the use of VHs in cultural heritage VR applications, highlighting the technical efforts behind the generation, integration and simulation of VHs in 3D virtual environments, presenting also the application range where such virtual agents are deployed and analyzing the complex outcomes that VHs have on user engagement.

Analyzing the state-of-the-art from a technological perspective, we have underlined some of the most important challenges and issues that need to be addressed by researchers in order to achieve realistic interactive virtual human agents, capable of human-like behaviour and interaction so as to be perceived by humans as realistic social entities. The generation of 3D avatars from 3D scans of human subjects is a key research issue and the trend is to develop low-cost, fast and flexible solutions using 3D cameras for human shape 3D acquisition also having the ability to quickly generate the dynamics of the subject in order to seamlessly generate an animated virtual character. Also, considering that a large number of cultural heritage VR-based applications deal with walkthroughs in reconstructions of virtual cities, the need of tools enabling an easy

modelling of virtual crowds is becoming increasingly important. Thus, scalable methodologies for achieving variations of the VHs appearance are in the spotlight, with novel approaches like automatic rigging and skinning. Virtual crowds raise also simulation challenges, which need to be properly addressed by implementing efficient crowd-simulation algorithms. An important feature contributing to the realism of the virtual environment and increasing the user engagement is represented by verbal communication capabilities of VHs, since humans tend to react towards virtual characters interacting using natural language much in the way they react towards real people. To design a talking virtual agent requires a joint inter-disciplinary effort involving technologies like speech recognition, natural language processing, facial animation, lip sync, voice synthesis and so on.

Concerning the application range and variety in the field of cultural heritage VR applications where virtual agents are deployed, our analysis shows that VHs are currently mainly used for two main purposes: populating reconstructed 3D cities in order to breathe life in virtual environments otherwise bare and soulless, or being used as conversational agents acting as tour guides for virtual or real heritage sites. In the first case, a particular care is devoted in defining VHs' appearance and behaviour mimicking that of the original inhabitants in order to increase the accuracy of the reconstruction and make the user's experience more authentic. VHs acting as virtual guides basically fulfil two roles: navigation aide, by guiding the visitors towards specific points of interest, and information provider, by offering facts about the site and its artefacts, hence contributing to making the 3D environment a more lively, attractive and easier to navigate place, with a positive effect on the learning outcome.

It is also worth mentioning the impact that the synergy between serious games and virtual reality has on enhancing the learning process in the cultural heritage context. Serious games have the potential of supporting the player learning through a fun experience, making use of virtual characters for a more engaging experience. Indeed, VHs have been shown to have a huge impact on the sense of engagement perceived by the visitors of virtual cultural environments. VHs able to properly interact with the environment and cultural artefacts according to their specifics, and to visually and verbally interact with human visitors, are keen to actively engage the human users in the virtual world. Such a virtual environment is in fact a more pleasant and attractive place than the "classic" static collection of cultural sites or artefacts (which still constitutes the large majority of the available virtual reconstructions) and, moreover, enables a better understanding of historical facts through the simulation of social behaviour, thus improving and enriching the learning outcome.

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