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RESEARCH TRENDS OF VIRTUAL HUMAN APPLICATIONS IN ARCHITECTURE, ENGINEERING AND CONSTRUCTION

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SUMMARY: *Human tasks that require interaction with the physical world are often constrained by time, location, and safety factors, precluding their feasibility of execution. Virtual reality has provided an opportunity for humans to experience similar interaction but with a virtual representation of the real world. In such virtual environment, virtual humans have been used as computer-generated entities that replicate or emulate the human physique and provide a vehicle to interact with other real or virtual objects, humans, or systems. Virtual humans offer a platform which escapes the physical, spatial, and temporal limitations tied to human corporeal interactions. This study discusses the current trends in virtual human applications in AEC, specifically focusing on avatar and virtual agent utilization as the two major types of virtual humans. An avatar is a virtual human controlled by a live user that allows the translation of real world actions, intentions, and thoughts into the virtual world. And a virtual agent is a virtual human created and controlled by computer programs, operating to support the interactions of the real users with the virtual environment. This research follows a systematic literature assessment methodology to summarize the results of 54 research articles over the last ten years, and outlines the research trends for applying virtual humans in AEC.*

KEYWORDS: *Virtual Human, Avatar, Agent, AEC Industry, Literature Review.*

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1. INTRODUCTION

The increasing amounts of information required to address complex and dynamic projects of the architecture, engineering, and construction (AEC) industries demand the employment of state-of-the-art technologies. Virtual reality provides a framework for visualization and interaction in a computer-generated environment. Several studies have discussed the benefits of using virtual environments in different areas in the AEC industry like simulation (Rekapalli and Martinez 2010, ElNimr and Mohamed 2011), education (Messer et al. 2003, Sampaio and Martins 2014), training (Dawood et al. 2014), and visualization (Shen and Marks 2015, Yang et al. 2016).

The virtual reality environments have also been expanded to not only host objects and systems, such as buildings, bridges and highways, but human physique virtual representations. With the necessity of simulating human tasks in the virtual world, user controlled and computer controlled embodiments of human have appeared in the current AEC applications. Virtual humans have been used as computer-generated entities that replicate or emulate the humans and provide a conduit to interact with other real or virtual objects, humans, or systems. Virtual humans offer a platform that escapes the spatiotemporal limitations tied to human corporeal interactions in two different forms: avatars and agents. Badler (1997) defined an avatar as a virtual human operated by a live participant and an agent to be a virtual human figure depiction that is generated and operated by computer software. This interaction is illustrated on Figure 1, where depending on the operator that controls the virtual human, a real human or a computer, the denomination of the virtual human becomes either an avatar (human controlled) or an agent (computer software controlled).

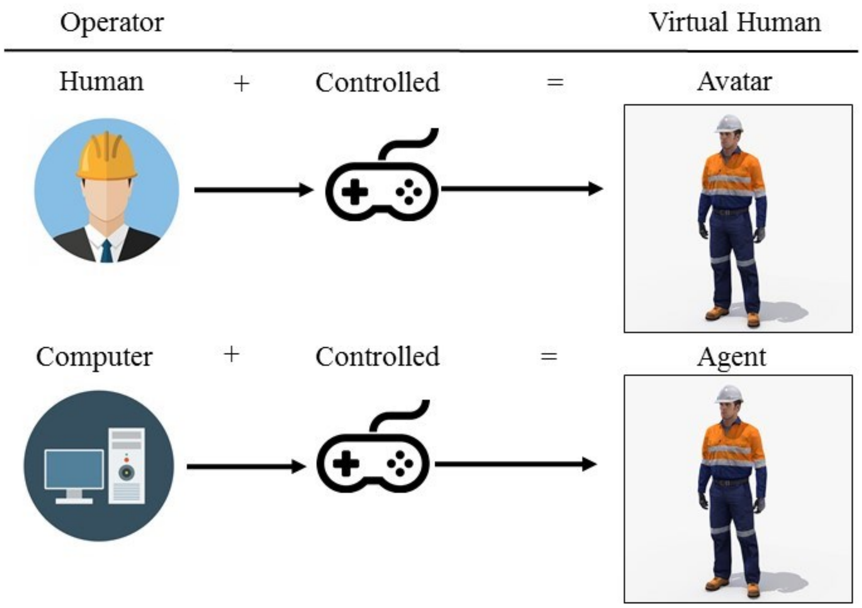

FIG 1: Virtual Humans: Avatars and Agents

Although there are several examples of using avatars or agents in the AEC literature, the word "virtual human" has not been employed to describe either avatars or agents. These virtual humans have not been presented as the focus of the studies but as a by-product of investigation topics that require human interactions. Since the implementation of virtual human is still new in the AEC, there is little information on this topic. This study explores the existing literature over the last decade to identify the recent employment areas of virtual human, the trends in using avatars and agents as two common examples of virtual humans, the reality-virtuality interaction types that required employment of virtual humans, and the hardware and software technology use to implement such virtual humans.

2. RESEARCH METHODOLOGY

To comprehensively and meticulously perform a literature exploration and draw conclusions based on the previous research, a review of the general trends in virtual humans in AEC was performed. The objective was to find the research trends of virtual human applications on AEC. The following research questions where formulated to address this objective:

- Research Question 1: What is the status of virtual humans in AEC?
- Research Question 2: What are the current applications of virtual humans in AEC?
- Research Question 3: What type of virtual humans have been used in AEC?
- Research Question 4: What type of interactions methods have been used for virtual humans in AEC?
- Research Question 5: What are the hardware and software tools implemented on virtual human studies in AEC?

To address these questions, peer-reviewed bibliographic databases were searched using strings of keywords in a two-phase process (Figure 2). First, the literature was searched based on unconstrained and unstructured iterative query to explore the topic of virtual humans and collect preliminary data. The objective from these initial searches was to establish a set of constraint keywords or classifiers for the topic. The second phase, consisted of a systematic constrained web search approach using iterations to perform a criteria-based literature selection within the boundaries identified on initial search phase of the investigation. To concentrate the study exclusively on the trends of virtual human in AEC, the articles resulting the literature selection were arranged and categorized. Finally, all the information was analyzed and discussed with the intent of illustrating state-of-the-art data on virtual human trends in AEC.

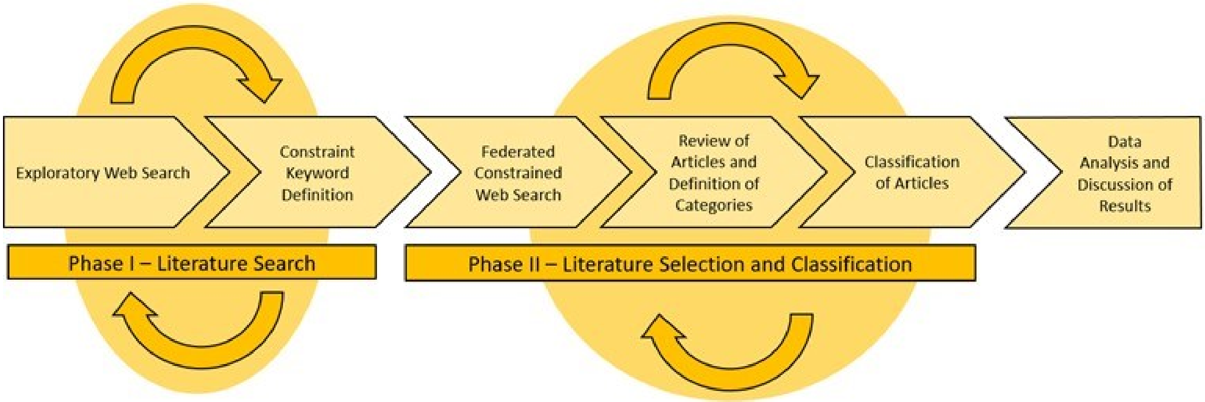

FIG 2: Research Methodology

2.1 Literature Search:

This study aimed to locate the publications that contained virtual humans as computer-generated entities replicating or emulating humans in the form of avatars or agents. These virtual human representations were required to have a visual corpus contained within the virtual environment that allows for interaction, or in other words, the users of the systems could directly observe the virtual human as it interacted with the digital settings. To accomplish this endeavor, a set of keywords were selected from the exploratory web search to evaluate and filter the content obtained, eliminating any possible articles that did not aligned with the criteria of the topic. Four filters (Table 1) were used to systematically assess the literature searches according to elements presents on the articles' structure. These filters, specifically designed for the Title, Abstract, Body, Year of the publication, were employed in a combinatory fashion to assess the literary space available.

The first filter evaluated the field of study of the publication. The exploration was comprised within the Construction, Architecture, and Engineering domains. As a result, these three classifiers ("Construction", "Architecture", and "Engineering") we include to be contained within the title or abstract of the publication. The second filter reviewed the content of the study. This is a pivotal filter that defined the characteristics present on the abstract or body of the document to be examined. After performing the initial unstructured web search, the terms "Virtual Human", "Avatar", "Agent", "Virtual User", "Educational Games", "Serious Games", and "Virtual Agent" were defined as the classifiers commonly observed. These were selected to accurately reflect this research's scope. The third filter evaluated the specific context in which virtual humans were applied in the abstract or body of the article. It was determined that "Simulation", "Education", "Training", and "Visualization" were the preliminary contexts where virtual humans were applied in the AEC. Finally, the fourth filter was concerned with the time of publication of the documents. Only articles over the last decade (January 2006 to September 2016) were considered to assure that the information contained in the publications were recent.

TABLE 1: Research Literature Filtering by Keyword or Classifier

Filter	Keyword or Classifier			
1. Title/Abstract	Construction	Architecture	Engineering	
2. Abstract/Body	Virtual Human Educational Games	Avatar Serious Games	Agent Virtual Agent	Virtual Users
3. Abstract/Body	Simulation	Education	Training	Visualization
4. Year	Jan. 2006	through	Sept. 2016	

2.2 Literature Selection and Classification:

Following the literature search, the constrained search was done by selecting publications from peer-reviewed databases. The search was done only to include journal publications and proceedings from conferences in the following research databases: American Society of Civil Engineers (ASCE), American Society for Engineering Education (ASEE), Elsevier, Emerald, Taylor and Francis (T&F), Sage, Springer, Hindawi, Institute of Electrical and Electronics Engineers (IEEE), Association for Computing Machinery (ASM), Canadian Science Publishing, World Academy of Science, Engineering and Technology (WASET), and Cumulative Index in Computer Aided Architectural Design (CumInCAD). Additionally, Information Technology in Construction (ITcon), Associate Schools of Construction (ASC), International Council for Research and Innovation in Building (CIB), and Digital Games Research Association (DiGRA), were included in the search as these are excellent outlets for technical papers publications regarding technology research in AEC.

To evaluate the significance and relevance of each study regarding the topic of virtual humans, a set criteria was established to include or exclude publications based their contents. Initially, the articles that did not directly report research on virtual humans, were identified and excluded. Additionally, the type of publication was assessed to evaluate that the findings were either peer-reviewed journal publication or conference proceedings, excluding other types of manuscripts (e.g. editorial notes, book reviews). Second, the manuscripts that complied with the first criteria were reviewed to establish if the content of the article discussed at least one of the research questions (RQ) regarding: (RQ2) application of virtual humans, (RQ3) types of virtual human used, (RQ4) type of interaction methods between virtual humans and system users, and (RQ5) implementation of hard/soft-ware tools for virtual humans. As incremental evaluation of the papers was performed, the documents that fitted the criteria from the different data sources were added to the analysis.

The data obtained from the collection was of qualitative nature, which indicated that a saturation point could be found when no new information of significance (trend or patterns) were obtained for ongoing thematic development and theorizing of the topic (Patton 1990; Lincoln and Guba 1985; Higginbotham et al. 2001). The final decision about sample number of the study was based on evidence that the data saturation or redundancy occurred. This saturation point was observed when constant comparison of data assessed and new emerging data indicated that there was little need for additional sampling, as it would only have confirmed the perspectives, categories, and conclusions in the reviewed literature present in the sample (Suter 2011). This was achieved by moving back and forth between the data in an iterative process, identifying and interpreting the data constantly. The saturation point was reached as enough information was gathered to provide insight on trends and patterns for the previously discussed research questions within the spectrum of virtual humans. A total number of 54 relevant publications were obtained from this literature selection and classification.

2.3 Data Analysis and Discussion of Results:

The 54 studies obtained from the literature selection were categorized to segregate the content of the articles and facilitate interpretation of the data. The analysis was performed for each individual publication based on questions and criteria formulated in Table 2. The analysis criteria presented was defined with the objective of answering the corresponding research questions, by collecting the data for each of the presented variables. This process enabled the synthetization of the findings of individual studies to unveil the framework of virtual human trends in AEC. Finally, a summary of the findings was presented with it corresponding conclusion.

TABLE 2: Analysis Criteria for each proposed Research Question

	RQ1	RQ2	RQ3	RQ4	RQ5
Analysis Criteria	Publications Number	Virtual human application	Utilization of avatars and agents	Human-Avatar Interactions	Type of output device
	Publication year			Human-Agent Interactions	Type of input device
	Publication source			Other type of interactions	Game engine software utilized
	Publication authors				Other type of software utilized

3. VIRTUAL HUMAN IN THE AEC

The number of publications on virtual humans per year are illustrated on Figure 3. The first five years (2006 to 2010) present a low number of articles with an average of 2.4 per year. On the year 2011 the number of publications almost quadrupled previous years' averages increasing to 9 publications. For these three following years (2011-2014), there is sharp change in publications displayed on the fitted curve rapidly growing. A significant drop in publications has been present in the last two years (2015-2016) which could indicate a local minimum in the overall trend.

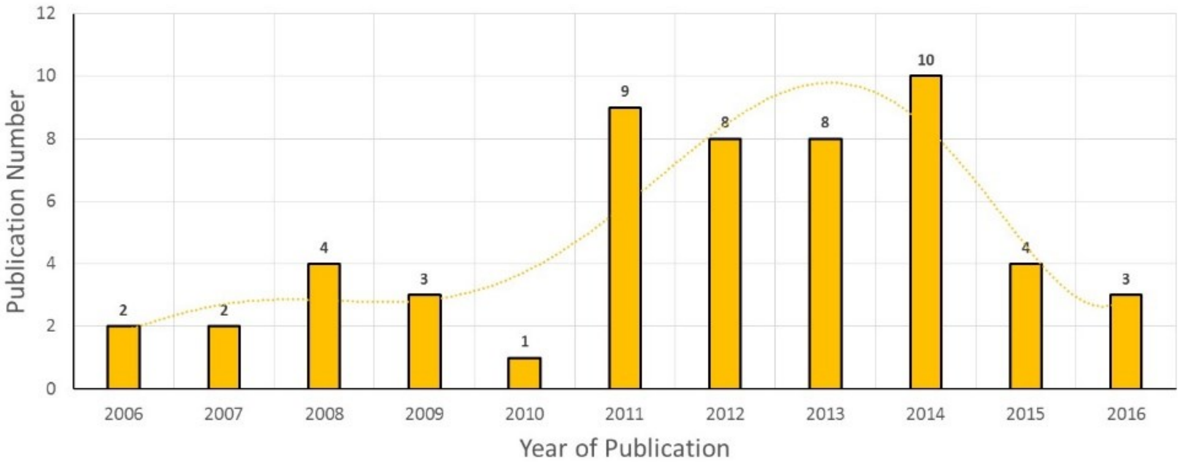

FIG 3: Number of virtual human publications 2006-2016

Additionally, the number of publications obtained from the search methodology were categorized by journal and conference within its corresponding year range. Table 3 displays the journals and conferences with more than 1 publication on virtual humans over the last 10 years. For the journal publications, the highest number is displayed by the *Journal of Information Technology in Construction* (26.66%), followed by a tie in the *Journals of Automation in Construction* (20%) and *Computing in Civil Engineering* (20%). These three journals encompass the 66.67% of all the total journal publications found and continuously published virtual human topics for 8 years since 2006. For the conference manuscripts, the highest number of publications falls on the *Construction Research Congress* (20.8%), followed by the *Conference of Education and Research in Computer Aided Architectural Design in Europe* (12.5%), and the *International Conference of on Computer Aided Architectural Design* (8.3%) tied with the *American Society for Engineering Education Conference and Exposition* (8.3%). This allocation shows that most of the virtual human publications were in construction and design with proceedings in technology related journals and education-computing related conferences in AEC. The remaining publications that are distributed across the other journals and conferences demonstrates multidisciplinary and multifaceted research efforts that are applicable to virtual human applications in other fields within AEC.

TABLE 3: Number of publications by Journal or Conference on Year Ranges

Journals and Conferences	Year Range	Number of Papers
Journal of Information Technology in Construction (ITcon)	2006-2011	8
Journal of Automation in Construction (ELSEVIER)	2010-2013	6
Journal of Computing in Civil Engineering (ASCE)	2012-2014	6
Construction Research Congress (ASCE CRC)	2009-2016	5
Conference of Education and Research in Computer Aided Architectural Design in Europe (eCAADe)	2007-2008	3
International Conference on Computer Aided Architectural Design (CAADFutures)	2009-2011	2
American Society for Engineering Education Annual Conference and Exposition (ASEE)	2013-2015	2
Others	2007-2014	22
Total		54

Finally, the publications obtained were analysed employing word clouds. This type of analysis provides a graphical representation of word frequency, visually weighting the words according to their incidence of occurrence. The authors last names and the titles of the publications were assessed using this approach to provide an overview of author publication frequency and title words. In Figure 5 (a), it is observed that the top authors published were: *Li, H.* (Hong Kong Polytechnic University), *Lin, K.* (University of Washington), *Goedert, J. D.* (University of Nebraska), and *Teizer, J.* (Ruhr University). The author with the biggest number of publications, Li, H., has 5 articles relating to virtual humans between 2012 and 2015 and his publication focuses on construction informatics, construction management, and construction health and safety. In Figure 5 (b), it is observed that the most common words contained in the studies titles are "*Construction*", "*Virtual*", "*Safety*", "*Education*", "*Design*", and "*Game*". This verifies the assessment done on Table 3, were both in journal and conferences related to the AEC industry, the "*Construction*" and "*Design*" sectors were the topics frequently affiliated with virtual humans. "*Safety*" and "*Education*" were the recurrent applications used and "*Virtual*" and "*Game*" exhibit the computing-technological components on the overall titles from the publications found.

(a) Author *(b) Article Title*

FIG 5: Word Clouds

4. VIRTUAL HUMAN APPLICATIONS IN AEC

Throughout the literature review, tendencies were observed that lead to the classification of virtual human applications into seven overlapping categories: (1) Cost Estimation: Assessment of expenses associated to tasks and activities within a project; (2) Site Management: Simulation of project field operation and processes; (3) Scheduling: Evaluation of project task planning and management; (4) System Evaluation and Analysis: Design evaluation and simulation analysis; (5) Collaboration and Communication: Multidisciplinary information exchange within or between AEC trades; (6) Safety: Hazard identification and management; and (7) Education: Training or coaching of individuals . These categories employ virtual humans as their core dynamic through interaction and conversation. Figure 6 displays the percentage distribution of per application and the number of studies catalogued under that category.

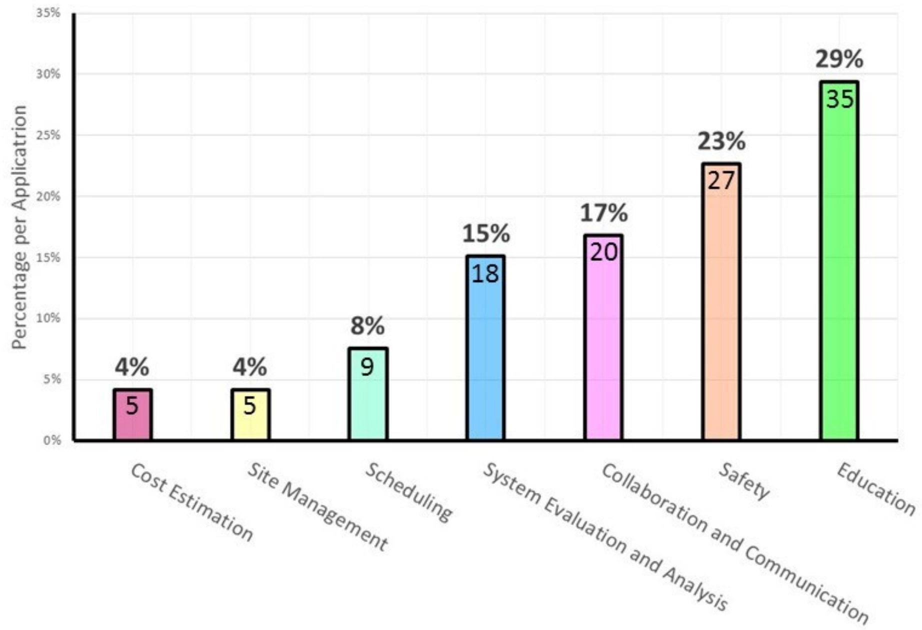

FIG 6: Virtual Human Application on AEC.

The cost estimation category was found in 4% with 5 publications of the reviewed articles. Virtual humans were used to interact with the user as part of a game system that educates about estimating cost for tasks within a work breakdown structure (Shiratuddin and Thabet 2011, Goedert et al. 2011, Goedert et al. 2013, Rokooei and Goedert 2015, and Goedert and Rokooei 2016). Analogously, site management was found in 4% with 5 publications. Field operations and processes were simulated by virtual humans for safety education of field operations (Ku et al. 2009, Li et al. 2012 (b), Lee et al. 2014), visualization of field operations (Goedert et al. 2011), or performance of field manoeuvre analysis (Cheng and Teizer 2013) as their objective.

Scheduling was found in 8% of the publications with 9 studies. The sequence or steps required to construct an element of the project were emphasized in these investigation through the utilization of virtual humans to explore and interact with an environment (Dickinson et al 2009, Ku and Mahabaleshwarkar 2011, Miller et al. 2012) or to visualize the spatiotemporal changes in a project (Goedert et al. 2011, Park and Kim 2013, Goedert et al. 2013, Sacks et al. 2014, Rokooei and Goedert 2015, Goedert and Rokooei 2016). The category for System Evaluation and Analysis was found in 18 publication or 15% of the articles. Virtual humans have been used as part of the design to improve end-user experience (Wokseep and Olofsson 2006, Chrstiansson et al. 2011, Boeykens 2011, Oerter et al. 2014), to review fire evacuation plan (Mòl et al. 2008, Aizhu et al. 2008, Wang et al. 2014), or to perform analysis over a simulated design (Yan and Liu 2007, Indraprastha and Shinozaki 2008, Dickinson et al. 2009, Yan et al. 2010, Shiratuddin and Thabet 2011, Teizer et al. 2013, Cheng and Teizer 2013, Fang and Teizer 2014, Fang et al. 2014, Sacks et al. 2014, Edwards et al. 2015)

The collaboration and communication category was found in 17% of the reviewed investigations with 20 articles. Virtual humans appeared as a collaborative design and construction tool (Rosenman et al. 2006, Nederveen 2007, Chase et al. 2008, Gu et al. 2009, and Merrick et al 2011, Arain and Burkle 2011, Ku and Mahabaleshwarkar 2011, Le and Park 2012, Le et al. 2014) implemented in the virtual environment created by the computer game "*Second Life*" (Linden Lab 2003). The game platform provided a space for multidisciplinary collaboration across the design and the construction trades, allowing avatars to communicate using voice chat and instant text messages. These characteristics allowed the platform to explore other similar applications, implementing channels for users to contribute in the design review process of a facility by expressing their ideas and needs into the virtual space (Christiansson et al. 2011, and Shiratuddin and Thabet 2011). The concept to use virtual environments to facilitate the communication between trades migrated outside the "*Second Life*" game platform into other game platforms (Guo et al. 2012, Li et al. 2012, Miller et al. 2012, Fang and Teizer 2014, Fang et al 2014, Edwards et al. 2015, Fallahi et al 2015, Du et al. 2016). Anderson and Dossick (2014) employed a similar game framework to explore problems in Building Information Models (BIM) while collaborating in a 3D virtual world. This communication medium replicates the physical world to some extent, but has the added benefit to allow participants to maximize the use of BIM models by the interaction provided by the use of avatars (Anderson et al. 2014).

The two categories with the most publications were safety with 23% (27 papers) and education with 29% (35 papers) of reviewed manuscripts. All the safety publications overlap directly with education manuscripts as illustrated on Table 4. This overlap is due to the inherent benefits of the virtual human technology, where the user can escape the physical safety constrains. The reviewed publications were performed as part of an educational framework to teach concepts related to safety without potentially exposing the individuals to hazards.

TABLE 4: Education and Safety Category Overlap

Educational Topic	Number of Publications	Area of Application
Safety-related	27	Hazard Recognition, and Hands-On Safety Training
Non-Safety Related	8	Design Education, Collaborative Education, and Project Planning

Virtual humans as educational tools have been widely adopted in the construction safety industry. Hazard recognition (Ku et al. 2009, Lin et al. 2011, Ku and Mahabaleshwarkar 2011, Le and Park 2012, Tepe et al. 2012, Zhao et al. 2012, Liaw et al. 2012, Miller et al. 2012, Park and Kim 2013, Chen et al. 2013, Tixier et al. 2013, Greuter et al. 2013, Greuter and Tepe 2013, Albert et al. 2014, Lee et al 2014, Le et al. 2014, Bhide et al. 2015, and Kiral et al. 2015) and hands-on safety training (Dickinson, et al. 2011, Guo et al. 2012, Li et al. 2012 (a), Li et al. 2012 (b), Teizer et al. 2013, Cheng and Teizer 2013, Fang and Teizer 2014, Fang et al. 2014, and Fallahi et al. 2016) are the most prominent applications of virtual humans in safety education Hazard recognition and hands-on safety training allow the user to be exposed to high-risk scenarios in a virtual environment without any type of physical jeopardy, creating a secure consequence-free platform to educate the student through interaction.

Other non-safety related educational applications of virtual humans are also present in the literature. Design education (Yan and Liu 2007, Yan et al. 2010), collaborative education (Gu et al. 2009, Arain and Burkley 2011), and project planning (Goedert et al. 2011, Goedert et al 2013, Rokooei and Goedert 2014, and Goedert and Rokooei 2016) are the three non-safety related areas identified on the literature. The education of design is done through the system evaluation and analysis of simulations, stimulating interaction with the systems existing in a location. Analogously, collaborative education uses the interaction with other virtual humans along with other objects and systems to communicate ideas about a temporal and spatial context. Finally, project planning is taught by integrating these interactions between virtual humans, objects, and systems by simulating a project where the student must evaluate several aspects of the project (such as costs, constructability, and schedule) in time and space.

5. VIRTUAL HUMAN IN THE VIRTUAL CONTINUUM

Due to the recent implementation of virtual human in the AEC literature, several ways of categorization have arisen. The naming conventions of avatars and agents in AEC, the types of human-avatar-agent interactions, and the existing software and hardware implementation tools in the AEC literature are explored in this investigation.

5.1 Avatars and Agents Nomenclature

In the AEC literature, the naming conventions for virtual humans are fragmented and occasionally transposed. The concept of virtual human and its taxonomy comes from the computer science field, where it has been employed since the 1990's. Furthermore, the avatars and agents definitions have been switched or renamed by several authors in the studied publications. Often, the term "*avatar*" has been properly employed due to its origins in the gaming industry and its close association with computer science. The early popular implementation of virtual humans in AEC employed the "*Second Life*" platform (Rosenman et al. 2006 and Nederveen 2007) that expressly utilized avatars as the channel to interact with the virtual world. This trend has remained until today with the use of diverse platforms that allow the user to interact with the virtual environment, as is its shown on Du et al. (2016).

The main irregularities appear on the naming convention for agents. In the reviewed literature, the agent term has been replaced by other keywords as illustrated in Table 5. However, the essence of the agent entity remains in all the publications that deviate in the naming convention. The most used term is "*avatar*" which alters the keyword definition to refer to an agent, and the second most used is "*worker*" which refers to the generic entity that the agent represents.

TABLE 5: Agent naming convention found in the literature.

Keyword	Frequency
Avatar	6
Workers	5
Animated Game Character	3
Consultant	3
Virtual Humans	1
Virtual Users	1

5.2 Interactions

In this study, interactions are the mechanisms through which virtual humans might be used to transfer information or communicate between the virtual environment and real humans. The way these messages can be conveyed include speech, body language, text, audio, or any combination of them. AEC is a project-based industry where group networks are temporary, unique and discontinuous. The interrelation between people in these projects are continually changing due to the nature of the dynamic workplace. Every project has unique characteristics and involves a plethora of interrelated individuals, with a specific and finite involvement (Dainty et al 2006). Virtual humans have been used to facilitate this interaction and communication process between real and virtual environments. Therefore, it is of relevance to investigate the current information transfer techniques for VHs. These characteristics and mechanisms have been tested by researcher to replicated the complexity of group networks and human virtuality interaction.

Milgram et al. (1994) explored the concept of the Virtual Continuum that describes the interactions between the real environment and the virtual environment. This notion can be extrapolated into the interactions virtual humans present in either avatar or agent forms. The interaction between human, avatar and agent (Figure 7) in the virtual continuum has been somewhat explored in AEC. Overall, all interaction types, have been used in AEC except for direct interaction between avatars and agents.

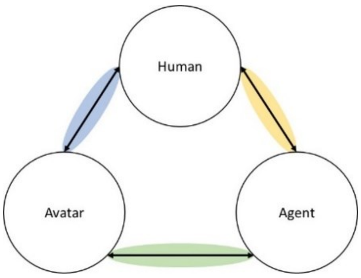

FIG 7: Virtual Human Interactions

Avatars possess a set of three possible interactions with humans depending on the direction in which the information is transferred within the virtual continuum (Figure 8). First, continuous information could be transferred from human to avatar (human→avatar) to direct the actions of the entity on the virtual environment. This type of interaction can be observed on Woksepp and Olofsson (2006) where an avatar is controlled by a human to direct every action of the avatar to explore and interact with a virtual environment. Seven human→avatar interactions were identified in the reviewed papers. Second, continuous information could be transferred from human to avatar to human (human→avatar→human) to obtain information from the virtual environment for decision-making. This type can be observed on Park and Kim (2013), where a safety manager used an avatar to provide workers with safety hazard information in real-time. Only 2 publications were found to contain human→avatar→human interactions due to the implementation difficulties of the method.

And third, continuous information could be transferred from human to human through the use of avatars (human↔avatar↔avatar↔human). As an example, Anderson and Dossick (2014) used CyberGRID® platform for communication and interaction of human users through avatars. Human↔avatar↔avatar↔human is the most common type of human avatar interaction (27 papers) in AEC literature through which users who could be geographically dispersed were able to collaborate on a project.

FIG 8: Human Avatar Interaction Classification (Adapted from Woksepp and Olofsson 2006, Park and Kim 2013, and Anderson and Dossick 2014).

In the reviewed AEC literature, agents have also been used in a set of three possible interactions with humans depending on the direction in which the information is transferred within the virtual continuum (See Figure 9). First, discrete or continuous information could be transferred from human to agent (human→agent) by inputting data into a system to indirectly command the actions of the entity on the virtual environment. Human→agent type of interaction can be observed on Sacks et al. (2014) where a user loads information into a discrete event simulation system to set in motion a virtual construction crew that perform actions such as installation of studs for a partition wall. Human→agent interaction was used in 5 of the reviewed AEC literature and used mainly in applications where information transfer facilitates the simulation of human tasks in the virtual environment. Second, discrete or continuous information is transferred from agent to human (agent→human) to acquire information from the virtual environment for decision-making. This type of interaction can be found on Tepe et al. (2012), where agent perform action on a game environment so that the user can identify potential hazards. Agent→human is the most common type of human agent interaction for AEC applications (10 papers) and displays transfer of information from a preloaded AEC agent to a human user.

And third, discrete or continuous information could be transferred both ways between human and agent (human↔agent). This last type of interaction can be observed on Goedert et al. (2013) where a human provides information to an agent-based system and information is returned after analysis from the agent to the human to provide solution for an activity sequencing simulation. It is computationally challenging and very data intensive to create and implement a human↔agent system that can process user input and only 3 papers used this type of human agent interaction

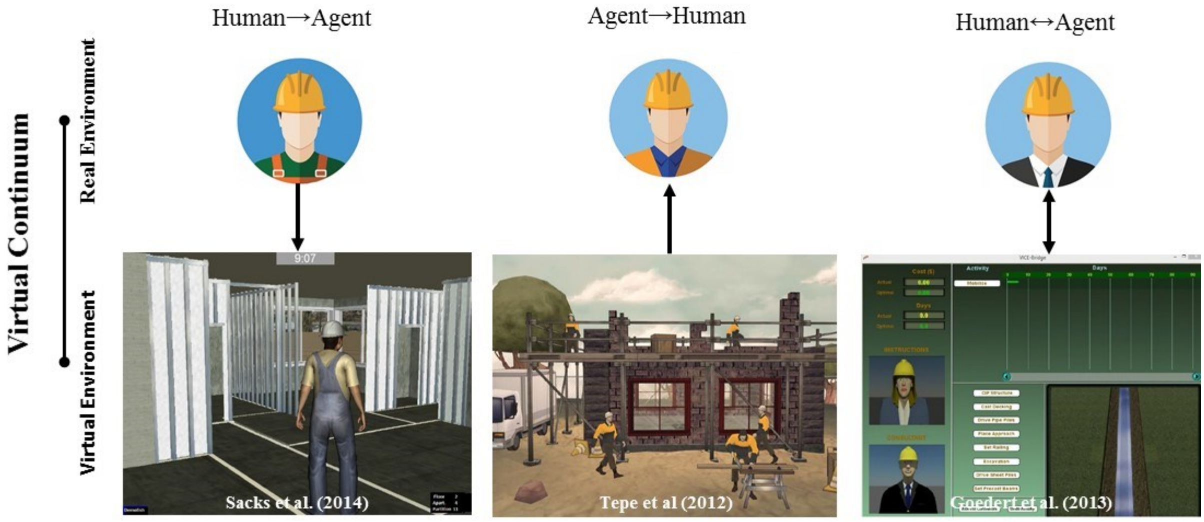

FIG 9: Human Agent Interaction Classification (Adapted from Sacks et al. 2014, Tepe et al. 2012, and Goedert et al. 2013).

6. DISPLAY AND INPUT HARDWARE

For this study, virtual human applications were classified depending on their type of displays and inputs (See Table 6). Frequently, studies made use of traditional arrangement of the computer setting, employing a monitor, a keyboard and a mouse to provide a gateway to interact with the virtual environment. This type of display and input was used in 40 (26 avatar and 14 agent) of the reviewed papers. This trend might relate to the ease of accessibility, development, implementation, and cost associated with providing display and input for the traditional computer platforms. Additionally, 4 of the reviewed publications have used the same computer set arrangement but extended with a gamepad (e.g. an Xbox® controller or a Wii® controller) to facilitate the navigation and interaction of avatars in the virtual world, but it has not been used for agents.

TABLE 6: Virtual Human Display and Input Types

Type of Display / Input	**Number of Publications**		
	Avatar	**Agent**	**Total**
Computer / Keyboard - Mouse	26	14	40
Computer / Keyboard - Mouse - Gamepad	4	0	4
Tablet Computer or Smartphone / Finger Touch	3	3	6
HMD / Keyboard - Mouse - Gamepad - Motion Tracking	2	0	2
CAVE / Keyboard - Mouse - Gamepad - Motion Tracking	1	1	2

Other hardware technologies have been used to increase the user immersion into the virtual environment. Portable devices, such as tablets and smart phones, have been used to offer an alternative to traditional computer, assisting in field operations. This type of display/input has been used in 6 reviewed papers (3 avatars and 3 agent application). Ultimately, to achieve the highest amount of immersion, head-mounted displays (HMD) and cave automatic virtual environment (CAVE) have been used along with gamepads and motion tracking devices. The HMD's state-of-the-art technology has a very high economical cost associated with it. The CAVE type of display and input is very recent and has only been used in one avatar and one agent applications.

7. SOFTWARE TRENDS AND UTILIZATION

Virtual human software technology is adapted from virtual reality software development kits available in the market known as game engines. Game engines are software packages that allow a designer to create games that include the rendering, objects, and input-output data though a simplified interface (Bhoir and Esmaeili 2015). Several game engines are available in the market that require different expertise levels of programming skills to model the game dynamics. In this study, the game engines that were used in the publications were compiled to investigate their usage in AEC through time. Table 7 displays the game engine employed, along with it utilization frequency and the year range in which has been used.

Unity® was found to be the most employed game engine used because of its popularity, flexibility, and freedom in game design (Li et al., 2012). This game engine was used in 24% of the total publications and found in applications from 2008 to 2016. Havok® followed with 20% of usage and is the game engine employed to develop the "*Second Life*" platform in AEC-related papers published between 2006 and 2014. Microsoft XNA® (Percentage: 9%, Year Range: 2007-2013) and Torque 3D® (6%, 2011-2012) are the other popular game engines that are completely free and Unreal Engine® (9%, 2008-2015) provides its software free of charge for academic purposes, with full access to the complete source code and tools. The other games engines have not been as popular as the discussed ones in the AEC literature with one or two applications. There were also 9 papers that used game engines but did not disclose any details on them. Game engine software was not the exclusive type of software found to develop the applications for AEC. Software tools such as Autodesk Revit, Autodesk Navisworks, Autodesk 3D Studio Max, Google SketchUp, Trimble 3D, among others that have been used together with game engines to model, render, and piece together the virtual environments.

TABLE 7: Game Engines Used on Year Ranges

Game Engine	Year Range	Frequency
Unity	2008 - 2016	13
Havok	2006 - 2014	11
Unreal	2008 - 2015	5
Microsoft XNA	2007 - 2013	5
Torque 3D	2011 - 2012	3
3DVIA Virtools	2012	2
CyberGRID	2014	2
EON Studio	2014	1
MicroStation	2006	1
OpenSimulator	2012	1
Multigen Creator	2008	1
Not Specified	2009 - 2016	9

8. SUMMARY AND CONCLUSION

Virtual humans have been used as computer-generated entities that replicate or emulate the human physique and provide a vehicle to interact with other real or virtual objects, humans, or systems. Virtual humans offer a platform that escapes the spatiotemporal limitations tied to human corporeal interactions. This research established the current trends of virtual human applications in AEC over the last ten years (January 2006 to September 2016). The main limitation in this research, similarly to many other systematic reviews, is the specific scheme keywords and criteria selected to evaluate the findings and the bibliographic databases chosen (Denyer and Tranfield, 2009). It is likely other papers in other publication venues are available, and that by using a distinct set of search strings (e.g. 'safety', 'design', and 'collaboration') other insights on this topic may be found. As this paper found its saturation, 54 conference and journal articles were found within the scope of this study. Through the publications assessed, it was found that virtual human application corresponds to seven overlapping categories related to AEC areas: cost estimation, site management, scheduling, system evaluation and analysis, collaboration and communication, safety, and education.

Within that categorization, the virtual human naming conventions observed in the publications showed that avatars were correctly named in the literature, but agents presented irregular and unstandardized nomenclature. This indicates that there is a need for unification over the terms employed for virtual humans in the publications, and there are motivations to propose a cohesive framework for the AEC literature. The recognized interactions between human, avatar, and agent suggest that the majority of the human-avatar interactions were classified as human↔avatar↔avatar↔human and over half of the human-agent interaction were classified as agent→human. Other types of interactions such as human→avatar, and human→agent appear in a minor degree, but further exploration is required to establish the overall spectrum of interactions possible between virtual humans and real humans for AEC applications. Interactions where humans, avatars, and agents simultaneously appear were not detected in the AEC literature, providing a clear opportunity for additional research.

The hardware used in most of the virtual human applications was a monitor, keyboard and mouse (traditional computer configuration) due to simplicity of adaptation, its reduced cost and its widespread availability. The most used game engine software technology was Unity®, along with Unreal Engine® and Havok®. Other supporting software have been used to model, render, and assemble the surrounding virtual environment where virtual humans are hosted. A variety of other platforms, from a smartphone screen to virtual reality head-mounted displays (HTC Vive, DAQRI Smart Helmet, HoloLens, or Google Cardboard), and CAVE platforms (EON Icube, Diice by Immersion, or VisCube) remain largely unexplored, as well as the implementation of other immersive motion tracking technologies (Oculus Touch, Leap Motion, or Kinect).

The integration of new emerging technologies in hardware and software to interact and display virtual humans, along with innovative ways of interaction between humans, avatars, and agents will lead future research in AEC. Immersive devices that employ virtual reality and augmented reality are heading towards the implementation of virtual humans for a plethora of applications, ranging from personnel training for construction, to complex design simulations in architecture and engineering. There is great hope for the future, as AEC continues to evolve and absorb new technologies that are crucial to converge with the increasing demand for the unconstrained replication of human tasks. While there is still work to be done, this research establishes the current trends of virtual humans for AEC applications.

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