Digital Innovations in Architecture, Engineering and Construction

Andrea Giordano
Michele Russo
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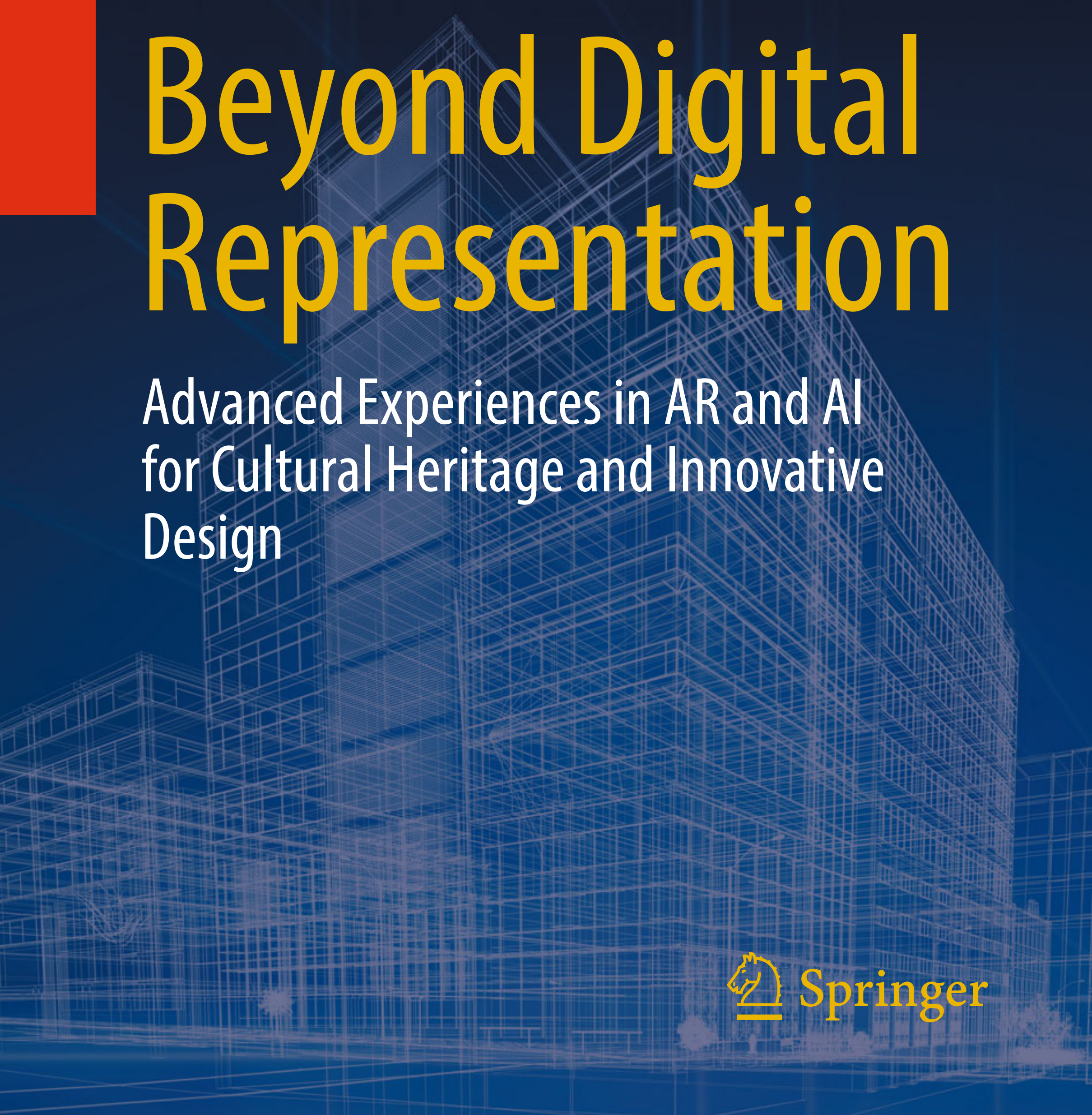
Beyond Digital Representation

Advanced Experiences in AR and AI for Cultural Heritage and Innovative Design



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Digital Innovations in Architecture, Engineering and Construction

The Architecture, Engineering and Construction (AEC) industry is experiencing an unprecedented transformation from conventional labor-intensive activities to automation using innovative digital technologies and processes. This new paradigm also requires systemic changes focused on social, economic and sustainability aspects. Within the scope of Industry 4.0, digital technologies are a key factor in interconnecting information between the physical built environment and the digital virtual ecosystem. The most advanced virtual ecosystems allow to simulate the built to enable a real-time data-driven decision-making. This Book Series promotes and expedites the dissemination of recent research, advances, and applications in the field of digital innovations in the AEC industry. Topics of interest include but are not limited to:

- Industrialization: digital fabrication, modularization, cobotics, lean.
- Material innovations: bio-inspired, nano and recycled materials.
- Reality capture: computer vision, photogrammetry, laser scanning, drones.
- Extended reality: augmented, virtual and mixed reality.
- Sustainability and circular building economy.
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- Big data: GIS, IoT, sensors, cloud computing.
- Smart transactions, cybersecurity, gamification, blockchain.
- Quality and project management, business models, legal prospective.
- Risk and disaster management.

Andrea Giordano · Michele Russo ·
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Editors

Beyond Digital Representation

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ISSN 2731-7269 ISSN 2731-7277 (electronic)
Digital Innovations in Architecture, Engineering and Construction
ISBN 978-3-031-36154-8 ISBN 978-3-031-36155-5 (eBook)
https://doi.org/10.1007/978-3-031-36155-5

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Foreword

This book testifies to the joint effort of a group of professors in the Disciplinary Sector of “Drawing” who were able to make clear already three years ago a channel of research particularly interesting for the topics covered. The Digital first, the Virtual then and again Artificial Intelligence and the complex intermingling of computer science and visual communication show a liveliness of speculation and research all directed to new ways of fruition, understanding and enjoyment of our Cultural Heritage, often suspended between material and immaterial.

While information technology and technological innovation might at first have created inhibitions for those trained in the social sciences, between documentary analysis, surveying and the design of architectural spaces, the REAACH-ID Symposia have been able to demonstrate how much the themes of Drawing, Representation, geometry and visual communication can be research opportunities that are always current and innovative.

It can be inferred from the pages of this volume how much the purpose of REAACH-ID meetings is to solicit and expand human intelligence through new inputs from new technologies; these are occasions that tend to bring together contiguous cognitive universes, not only between different disciplinary fields but also within the same discipline.

From the editors’ introductory essay and the authors’ contributions, an epistemological framework has significantly changed since the 20th century. The scheme of the two cultures seems outdated because of the complexity and cultural hybridity that marks today’s knowledge society. We are far from the pattern of fifty years ago when the scientific and humanistic cultures were separated by “an abyss of mutual incomprehension” (Charles P. Snow 2005. Le due culture, Marsilio, Venice, p. 20).

However, the confrontation between the two cultures is far from exhausted since the field of Cultural Heritage, until yesterday the prerogative of the humanities and social sciences, today has also become one of the main targets of technological research; it is a common pivotal theme that protects collective memory and contributes overwhelmingly to the definition of community identity and awareness (see Horizon 2020, 8th Framework Program).

Given the above, the symposium chairs thought it appropriate to promote a national and international network of researchers (REAACH Association) interested in Heritage Science to propose an increasingly organic and conscious way line of research in the field of Cultural Heritage by exploiting IT skills and applying them to Cultural Heritage. All of this was with a view to multidisciplinary exchanges of knowledge and the enhancement of advanced transversal skills.

It is a volume that brings together valuable evidence ranging from different ways of accessibility to Cultural Heritage to the use of Artificial Intelligence and Augmented Reality to applications of Extended Reality and Gamification to enjoy the fantastic universe of Cultural Heritage in a diversified way.

May 2023

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Preface: Introducing the Relationships Between Digital Representation and AR/AI Advanced Experiences

We are witnessing a rapid technological innovation, which in the space of two decades has completely subverted the panorama of the discipline of Representation: a panorama that now sees the involvement of interdisciplinary issues with findings, repercussions, and feedback in both theoretical and applicative fields. Furthermore, if the concept of Virtual Reality was already inherent in Representation also for artistic purposes—see in this regard the Renaissance pictorial works, precisely *ante litteram* attempts at Virtual Reality—today Artificial Intelligence (AI), fueled by Deep Learning, has made it possible to arrive at an Extended Reality (XR), which incorporates the adjectives of Virtual, Augmented and Mixed.

For this reason, Artificial Intelligence has proved to be a truly transformative technology, exploited daily in more and more areas, continuing to surprise us with its evolutions. Evolutions, however, must consider awareness. Awareness in both theoretical and practical terms is where training plays a significant role in engaging with a critical and constructive attitude. For this reason, it is unquestionably that an aware conceptual apparatus is at the basis of Artificial Intelligence and its relationship with Extended Reality, being able to relate to and describe entities directly suggested by the real and ideal world through more advanced conceptualizations. The definition of these concepts, with the awareness that interesting and ingenious considerations could be applied to them, is the first demonstration of the acute use of Artificial Intelligence for Extended Reality. Moreover, for this, we must consider the depth of thought that goes into the formulation of XR through the concepts of Representation and, subsequently, the skill with which these concepts are used.

Thus, the domain of reasoning becomes lawful and indispensable. It remains fundamental, for example, to be able to recognize an architectural surface in geometric and configurational terms to then have important effects in structural and constructive terms. Once these concepts have been acquired, implementing them through AI-XR increases the evolutionary scenarios, with enormous repercussions on the heritage (architectural/engineering/urban/landscape), whether existing or in progress.

This process, therefore, takes on a prodigious characterization, adapting the Representation to extensive/plural/multiple areas from a disciplinary point of view, with repercussions on the scientific aspect of the adequacy of the codes and expressions of knowledge to broad branches of culture. In this way, the "frontiers" of Representation are widened. Thus, the relationship between Representation Space and the Representation of Space further expands and explains the relationship between Science and Art, between concept and creativity and between elaboration and realization.

The digital world and the Representation domain are strongly interconnected. Their long-established relationship has seen a major step forward in the past two decades. The ability to survey in space any kind of artifact, draw and visualize it with digital models at different levels of detail and reliability is now considered an established practice. At the same time, the sudden growth in the last five years of Artificial Intelligence (AI) and Augmented Reality (AR) research, especially, but not exclusively, applied in the field of Cultural Heritage, has required a deep analysis of the role of these technologies in the Representation domain. Specifically, "if and how" these tools, strongly leaning by expertise to the world of computer science, can find a declination in the research of Drawing.

The answer to such a complex question requires extensive and in-depth discussion among those who have had the opportunity to critically experiment with AI and AR in different scientific domains. This is the main motivation that led us to promote in 2020 (REAACH-ID 2020), and for the first time, a symposium dedicated to these issues. The articulated framework of research that such an event brought to light allowed us to begin a journey of maturation from which two different needs emerged: on the one hand, the repetition of the event, promoting annually and consolidating a place for discussion and updating on emerging technologies. From this point descended, the organization of the symposiums in 2021 (REAACH-ID 2021) and 2022 (REAACH-ID 2022). On the other, the definition of a new entity that could support from a scientific and organizational point of view the promotion of these issues on a national and international scale, encouraging the increase of networks among different scholars. From this choice came the founding in 2022 of the REAACH Association (www.reaach.eu), which stands as a "bridge" between experts in different disciplines and some European research streams such as Heritage Science. The association promotes the symposium annually, nurturing interest in the issues and, at the same time, fostering that path of maturation toward an increasingly conscious use of emerging technologies.

The annual event presents an online format to maximize participation by both speakers and attendees. To encourage useful discussion, the authors present in-progress experimentation highlighting the pros and cons of the specific application. The definition of the paper occurs later, downstream of the meeting, reaching a more critical development of the contents. The articles, therefore, follow an autonomous path in which the symposium represents only a moment of critical feedback and comparison with similar research to understand the topic's relevance, arriving at a more informed synthesis in the research domain. The book presented here promotes the results of research that were presented as a first idea during the 2022 symposium and then developed independently following the event.

The book is divided into parts that collect contributions that weave together the two main topics, i.e., the discipline of Artificial Intelligence and the technology of

Augmented Reality, with specific objects of interest from the discipline of Representation. The definition of these parts is partly driven by the topics proposed in the call for papers and partly guided by the authors' responses, who have brought to attention new and interesting theoretical developments and application possibilities. According to this logic, the book is divided into six main parts.

The part "AR&AI and Historical Sources" deals with the accessibility and communication of archival historical heritage mediated by virtual reconstruction using 3D models and the experimentation of the heuristic potential of digital modeling for the 3D visualization of consistencies represented in archival drawings. The opportunities offered by the digital revolution and specific technologies and simulations are explored in the part dedicated to "AR&AI and Museum", with the aim of increasing the community's knowledge and awareness of heritage, also in terms of inclusion. In the "AR&AI and Heritage Routes" part, experiences in archeological sites are presented through virtual reconstructions and "augmented" tours of existing architecture and landscapes acquired through digitally surveyed. The part "AR&AI and Classification/3D Analysis" is largely devoted to papers presenting general considerations with extensive references to the most interesting and richly developed Artificial Intelligence methodologies. "AR&AI and Education/Shape Representation" is the part that contains Artificial Intelligence and Augmented Reality methodologies and technologies for shape representation and innovative teaching, as well as Extended Reality and Gamification applications for the presentation of curriculum work. The monitoring of the built environment, both historical and contemporary, characterizes the "AR&AI and Building Monitoring" part. The state-of-the-art digital methodologies and technologies enable the development of effective and efficient monitoring systems.

Each part is organized starting with the papers that set out general theoretical considerations or that refer to broad application areas and is followed by the papers that develop specific case studies. The parts are preceded by a keynote lecture dealing with a recent digital initiative at the Montreal Museum of Fine Arts that strives to mimic the lost pleasure of tactility, as well as to address the physical limitations surrounding the display of miniature objects in a museum, in an attempt to subvert canonical museum hierarchies by rendering visible the often-invisible, including the artworks' tactility, materiality and craftsmanship, which would otherwise be left obscured by a traditional museum display.

More than 150 scholars have participated in the realization of this volume, consisting of 53 chapters, contributing to the establishment of the scientifically up-to-date state-of-the-art of international studies linking the discipline of Representation with Artificial Intelligence and Augmented Reality.

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Artificial Intelligence and Virtual Reality in the Simulation of Human Behavior During Evacuations

Giorgio Buratti and Michela Rossi

1 Introduction

A widespread belief assumes that reality coincides with tangible, material objects. Since Plato's cave myth, the issue has been debated in philosophical and scientific circles, often leading to reductive theories that relegate virtual entities to non-existent. Instead, the etymon of the term virtual, from the Latin *virtus*, with the meaning of force but also capacity or faculty, leads back to the concept of possibility, that is, of unexpressed potential far from opposing the real, representing a diverse mode of existing [1]. Such a meaning nowadays seems more suited to the interpretation of those phenomena related to the technological and social evolution that is leading to the advent of the Metaverse, an advancement of the Internet that transcends the concepts of hypertextual and multimedia using simulated three-dimensional environments in which the fruition of meanings and interaction with objects and other users is mediated by virtual, augmented or mixed reality technologies.

Of all media, drawing is the one that has stood out most as a mediator between the potential level and the physical world, helping humans materialize their ideas or reproduce, dematerializing what exists in the real world. The digitization of the process has over the years redefined the question of the greater or lesser verisimilitude of a representation by arriving at the modelling of parallel virtual worlds, which not only constantly interact with and orient material reality, but are capable of such precise simulations that they become predictive. Simulation, from *simĭlis* (similar, make like), introduces the temporal dimension into the representation, thus

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A. Giordano et al. (eds.), *Beyond Digital Representation*, Digital Innovations in Architecture, Engineering and Construction,
https://doi.org/10.1007/978-3-031-36155-5_48

foreshadowing the dynamic evolution of a system or process from given initial conditions. Whether it is a virtual space of the Metaverse based on VR/AR technology or an application dedicated to a specific context, simulations require processing an abnormal amount of heterogeneous data to function effectively. Thus, various forms of AI capable of detecting, classifying and describing the data needed to make the comportment of entities and objects in virtual spaces verisimilar have evolved in parallel with the constitution of digital worlds. Video game development was the first field of managing such an articulated process through dedicated work platforms known as game engines, software capable of integrating heterogeneous data and optimizing the workflow. Originating in the creation of video games, these tools are also finding wide use in research and/or design, fields united by the need to visualize phenomena in real time with the support of robust computational simulation processes.

2 AI and Videogames

Traditionally, the relationship between artificial intelligence and video games has always been very close and used to make plausible elements that must respond to the rules of a particular digital context. At the dawn of the computer science discipline, Turing himself theorized for his celebrated test a game aimed at establishing the intelligence of an artificial application. The development of AIs capable of interacting by play with human beings dates back to the early 1970s, with programs capable of interpreting the rules of checkers, chess or go. In 1996, news of IBM's challenge to then-world chess champion Garry Kasparov to confront the AI created for the occasion, Deep Blue, was widely circulated. Deep Blue was the first computer to win a chess match against a reigning World Champion, Garry Kasparov, with a tournament time cadence. Deep Blue's strength came mainly from its extraordinary computational power, capable of calculating 200 million positions per second. Its evaluation functions were initially written in a general form, with many parameters to be defined (e.g., how important a safe position for the king is compared to a spatial advantage in the center of the chessboard, etc.). The system then determined the optimal values for these parameters by analyzing thousands of sample games. Today, high-level AIs based on neural networks in a few hours learning to play chess at grandmaster levels, although made for entirely different purposes. These experiments, based more on computer computing power than anything else, laid the groundwork for Automated Game Understanding, a field of study that applies AI tools to video games, developing systems that can perform specific actions without them being preprogrammed. Creatures, realized by Grand S. in 1997, a video game that turned out to be a commercial success, is an excellent example of the potential of an intelligent virtual environment. In Creatures, the player hides small, furry creatures called Norns in the virtual world of Albia (Fig. 1), teaching them how to talk, feed and protect themselves against predatory Grendels. Lively and curious Norn move autonomously in a two-dimensional world, interacting with it, evolving their behavior according to rewards and punishments set by the player.

Fig. 1 Some evolved Norns and the virtual world of Albia where they are born, interact and die. *Source* English Wikipedia

Each Norn then develops its behavioral range that characterizes how it approaches the virtual world. This astonishing learning ability is due to a network of 1,000 neurons and 5000 synapses that characterizes the Norns as Artificial intelligent life, enabling each agent to grossly recognize sounds, objects and environments and transmit characteristics and knowledge to successive generations, resulting in increasingly unpredictable behaviors. Creatures is today recognized as an essential experience in advancing research on intelligent virtual spaces, systems in which specific actions occur without being explicitly programmed. Although research has made considerable progress since the day it was commercialized, this videogame was among the first applications to highlight fundamental dynamics in any artificial agent's relationship with the virtual environment in which it acts. The relationship between VR and user, depending on the technology used [2], is usually visual and involves those perceptual aspects related to shapes, textures, brightness, and level of detail that contribute to the creation of signification. The other entities in the virtual environment interact only in terms of occlusion concerning the user's view. If, however, we introduce more complex entities, such as an intelligent agent, the interaction between objects, characters, and the virtual environment increases significantly. Agents must see and identify each other for any exchange to occur, as well as detect state changes occurring in the simulated virtual space, avoiding unwanted collisions with other objects, whether they are stationary, such as trees, buildings and furniture, or moving. For this recognition to occur, it is necessary for the algorithm that describes the behavior, analyze the inputs and decides on the outputs after examining them and based on what is happening on the screen at that instant. This difference distinguishes an AI from an ordinary program [3]. The problem is that to be applied to the analysis of any phenomenon, an AI requires the training time necessary to implement on a statistical basis the prediction of a datum from those it has, a process that, depending on the complexity of the application system, can take several months. The advantage of many game engines is that they have special libraries for AI, with effective tools, especially in finding the most efficient paths for agents. In fact, the protagonists of the games, characters, animals or vehicles, must move according to specific objectives and be able to identify the optimal routes from start to finish while also taking into account virtual geography. The agent must be able to understand the difference inherent in walking in tall grass rather than in a driveway or if they are in the presence of water rather than on the ground.

These computer applications free programmers from redesigning recurring features each time, allowing them to focus on game dynamics and the characterization of environments and characters. Years of development, supported by the substantial funding that has marked the evolution of the market, have enabled the creation of advanced models that robustly reproduce dynamic systems [4]. Considering, for example, a human body as a set of rigid structures joined by a system of constraints that define its degree of freedom, the motion in the virtual world will be the result of a continuous system of thousands of animations that these constraints admit while avoiding those that not correctly describe the action of a human body (e.g., a skull rotating 360°). These tools will be used in the next chapter to describe the behavior of virtual agents in fire situations.

3 Simulating Evacuation

The term simulation refers to creating a real word model that allows for evaluating and predicting the dynamic unfolding of a series of events consequential to the imposition of predetermined boundary conditions word. Typically, the designer defines the project's purpose, specifies the safety objectives he intends to ensure and translates them into quantitative performance thresholds. After that, using analytical or numerical modelling tools, it describes or calculates the effects of the design hazard scenarios on the assumed design solution for the activity. If the impact thus calculated preserve an adequate margin of safety concerning the previously established performance thresholds, then the analyzed design solution is considered acceptable. The use of simulation models has steadily increased over the years because of the constant attention paid by the countries' legislative bodies [5] that require building, plant and management measures to ensure the highest possible level of safety. Narrating the historical evolution of different evacuation models transcends the scope of this paper, which will only report how there has been a tendency to move from a simplified type of analysis to more advanced models over the years. Simplified evacuation analysis is based, fundamentally, on a so-called macroscopic type of behavior modelling, which predicts how a flow of people can be roughly described by approaches borrowed from fluid dynamics. Instead, advanced evacuation analysis uses so-called agent-based models (in a mesoscopic or microscopic framework). Agent-based approaches model the dynamics of each pedestrian (an agent) and allow control of each agent in terms of properties and behavior. Consequently, agent-based methods allow consideration of population heterogeneity and obtain information about the state of each pedestrian person at each instant of the simulation. It is evident that the creation of virtual reality agents for human behavior in the event of fire poses several challenges from the standpoint of model development and requires a multidisciplinary approach to the topic that considers physics, applied psychology, sociology, and computer science [6, 7]. Be that as it may, to represent the decision-making process employed in evacuation, the model must incorporate an appropriate method of simulating the behavior of exposed people. The theory adopted in this experiment finds its roots in the studies of behavioral dynamics conducted in the early 1950s by Von Neumann and Morgenstern [8] to those of Coleman [9] and Bartholomew [10]. According to these studies, agent motion can be obtained as an emergent property based on a set of global/local rules or differential equations (usually based on Newtonian forces) defined by the model developers. The experimentation conducted here is based on the more recent Helbing and Molnár [11] social force model, derived from the previous ones, which considers how an individual's behavior is triggered by external stimuli, which can change trajectory, speed and acceleration. Basically, the reference social force modelling describes the dynamics of each agent as that of a rigid body with three degrees of freedom, i.e. two planar translations and one rotation. The following rigid body dynamics laws govern the dynamics of each agent:

$$\begin{cases} m_i \cdot \ddot{\mathbf{x}}_i(t) = \mathbf{F}_i^g(t) \\ I_{z,i} \cdot \ddot{\phi}_i(t) = T_i^g(t) \end{cases}$$

where m_i (kg) is the mass of the ith agent, $\mathbf{x}_i$(t) (m) is its instantaneous two-dimensional position vector, $\mathbf{F}^g{}_i$ (t) (N) is the global immediate force vector acting on the ith agent, $I_{z,i}$ (kg · m^2) is the agent moment of inertia, $\varphi_i\ (t)$ (rad) is the instantaneous orientation angle, $T^g{}_i$ (t) (N · m) is the instantaneous torque acting on the agent, and dots indicate differentiation with respect to time. The way each agent interacts with the environment to achieve its goal is governed by its properties and parameters. Most of these parameters are fixed and the same for all agents. Other parameters, however, such as walking speeds (flat, uphill, and downhill), response time, and choice of an escape route, are specified as random variables with associated distributions in a move to reproduce the heterogeneity of the population according to physical type [12]. The simulation presented here was implemented through the Unreal 4 game engine, which, like all game engines, is not designed for exhaustive tridimensional modelling.

Therefore, the optimal workflow involved:

(1) Optimal modelling of the building or space to be studied using dedicated three-dimensional modelling software, in this case, Rhinoceros, and then importing the model into the UNREAL environment. The correctness of the geometric description of the model must be verified after conversion to interchange format (FBX) or following a dedicated Datasmith conversion algorithm.
(2) Use available virtual models to which the motion-related settings have been applied. UE4 already provides some functions related to collision physics among the available tools. Capsulecomponent, for example, determines an area within which specific behaviors are triggered depending on interaction with elements in the scene. However, many settings, such as the speed of movement, have been modified depending on the purpose of the simulation (Fig. 2).
(3) For other objects, such as furniture, which is part of the scene, a basic physics must also be set up that defines their nature and prevents moving elements from interpenetrating them. The Nav Mesh Bounds Volume algorithm allows the AI to read the obstacles along the path based on the objects to which Collision physics has been applicated, and that reside within this volume. The generated wall surface will be parallel to the normal of the staged characters at an angle less than the established angle, always less than 90°. Therefore, all elements perpendicular to the horizontal plane will be interpreted as obstacles. This process will determine the space within which the AI can move and on which it will calculate the path to the desired direction.

4 Conclusion

The experimental model obtained is very simplified, considering that the agents can only recognize the nearest exit and choose the optimal path while avoiding obstacles. These determinants need to be more comprehensive to fully describe how information is conveyed and align individuals with mass behavior in an emergency, even though behaviors in an emergency still need to be fully understood and quantified by modern research. Nevertheless, it is already possible to note how, as variables change, such as the fire's ignition position, the agents' behavior changes, allowing specific considerations to be drawn on the evacuation route. Having used the Unreal 4 game engine as a development environment has brought some unprecedented advantages:

- Integration of rigid body motion equations and contact addressing can leverage the PhysX-integrated physics engine [13]. The physics engine offers numerous possibilities to define agents' behavior with precise formulations, greatly simplifying the work.
- The environment allows the direct import and rendering of geometries described by generic 3D meshes. Once the agent behavior has been implemented, it is possible to test different architectural types quickly.

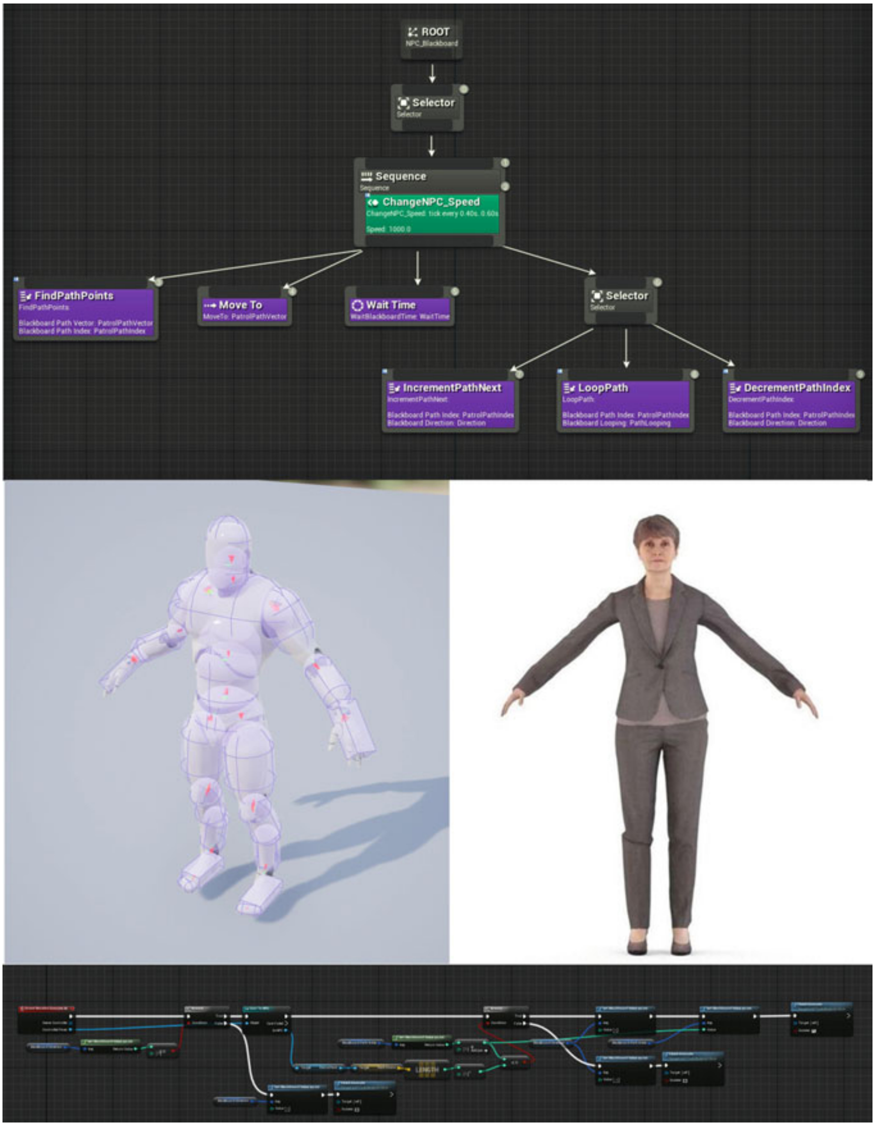

Fig. 2 Construction of the physical-anthropometric and AI characteristics of one of the virtual agents used in the test. Note the visual interface (a graph whose elements are interconnected according to a node logic) based on the Object Oriented Programming paradigm. *Editing* G. Buratti

- Most simulation systems available today require a calculation time and subsequently propose a movie showing the agents' behavior. Therefore, every time a change is made, a recalculation is necessary. Within Unreal 4, the simulation in progress can be viewed in real-time, with the immediate possibility of visualizing the result of any changes (Fig. 3).
- Many tools are available to develop the interactivity of virtual reality, offering the possibility to add sound and light effects, increasing the simulation's prediction. Furthermore, taking first-person control of an agent is possible, thus immersing oneself in the simulation to experience the virtual space and interact with other agents. This possibility is extremely promising for supporting decision-making processes and for training purposes [14].

Future development will improve the robustness and performance of simulation to achieve as realistic a description of human behavior as possible. In particular, the complex organizational capabilities of people under evacuation conditions must be investigated. The social force models used in this study are based on relatively

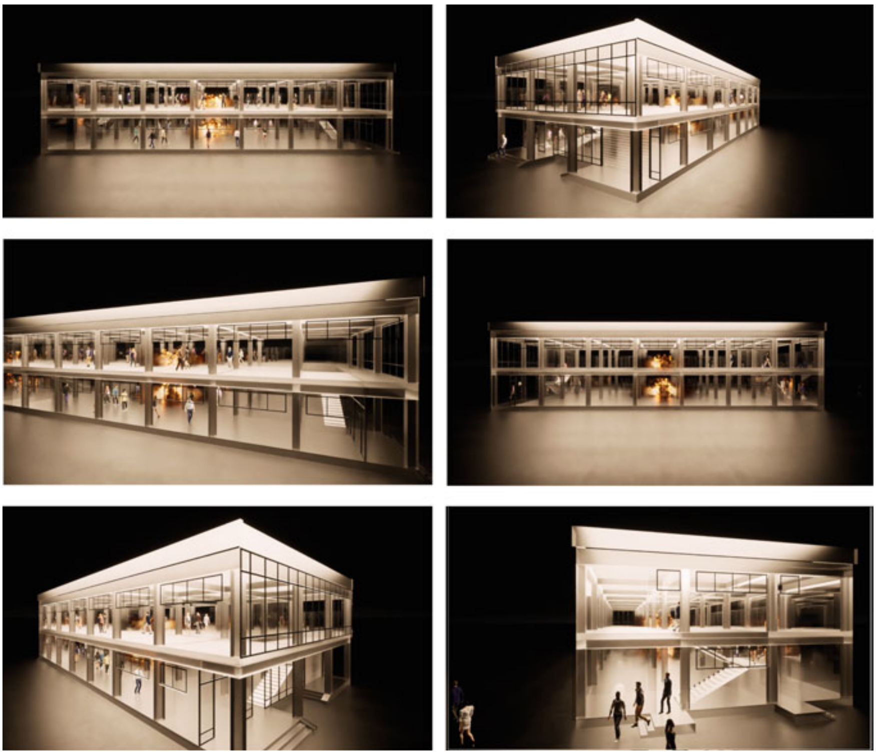

Fig. 3 Simulation at work: the different agents leave the burning building. Depending on their characteristics, they will follow various trajectories with dissimilar speeds, taking different times to reach safety. *Editing* G. Buratti

simple short-range interactions between agents that do not reflect the fact that, during an evacuation, human behavior can also be influenced by the evacuees' level of knowledge of the situation about spatial topology, density conditions, or that both immediate and estimated future needs can be considered.

These estimates can not only be based on a short-term assessment but can also be made in the long term and used to adjust the speed or choose the route to be followed. In particular, possible experiments with human interaction may pave the way for evacuation models' calibration and validation through virtual reality [15]. Consider that, due to the nature of the subject, it is hardly possible to test what happens in an emergency evacuation. The data available are mainly a posteriori, resulting from the analysis following the emergency event. Virtual reality is the most applicable and economical method that could enable studying catastrophic events [16]. Real-time human participation could be crucial for training in simulated hazard situations and have important design implications due to an improved perception of processes and the possibility for the planner to participate virtually and actively in the evacuation.

Acknowledgements Although the paper was conceived jointly, Michela Rossi is the author of Introduction, Gorgio Buratti is the author of AI and Videogames, Simulating evacuation and all the graphics. The Conclusions are drafted jointly.

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