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INCLUSION VR. A NEW VIRTUAL REALITY DEVICE FOR INCLUSIVE EXPERIENCES

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INTRODUCTION

There are many public and private spaces and environments where design characteristics are a severe impediment to accessibility for people with reduced mobility. Traditional measurements of accessibility are flawed, as they fail to account for people's mobility and physical differences. Structural barriers and individual mobility limitations that affect travel time, effort, and even successful completion are ignored. An accessibility measurement framework including measures of absolute, gross, closest assignment, single and multiple activity, probabilistic choice, and relative access has been proposed to address this problem [1].

Unfortunately, in most cases, people with reduced mobility are forced to renounce access to public and private spaces. Although the best solution would obviously be to make these places universally accessible, there are some sites where it is very difficult to make architectural changes without altering their identity. Cultural heritage sites are a good example of places where architectural changes are not feasible. This is especially problematic in the case of monuments and archaeological sites, as many of them are not prepared to receive these types of visitors.

The European Union considers cultural heritage as a means of achieving social integration [2]. Among its current challenges, the EU is promoting multidisciplinary initiatives that combine expertise in cultural heritage with the resources provided by technology. From another perspective, the use of virtual reality to evaluate and train inexperienced wheelchair users has been proposed [3].

People with motor disabilities can benefit from these types of actions. In situations where the value of a site must be preserved, and the needs of people with limited mobility must be taken into

account, building a digital twin of the space can be a way to experience/visit the site through virtual reality.
However, to achieve a satisfactory immersive virtual experience, the user must be sensorily involved. There is no point in creating a twin if the visitor is not as involved as those experiencing the real space.
The technical solutions for creating simulators for wheelchairs are very sophisticated and are usually expensive, cumbersome, and with an unattractive accessibility mode for wheelchair users [5]. For this reason, the UPCT's Industrial Design and Scientific Calculation Service has developed a low-cost virtual reality device based on their experience developing devices for virtual reality scenarios [5]. It consists of a platform allowing a person with a mobility disability to visit a cultural heritage site using a wheelchair while another person physically visits the site. Both can have similar, simultaneous experiences and can even communicate in a mixed reality environment.
This new platform emphasizes the user's ability to make their own decisions in a purely immersive environment. The objective of the work is to achieve a sensory and physical experience identical to that experienced by a person visiting the real physical space. People with motor disabilities would be able to visit the site without the assistance of third parties.
Commitment to the university community. People are the institution's most valuable resource. We must therefore respect their rights and support their duties and capabilities. To achieve these objectives, it is essential to improve employees' working conditions, take care of their health and safety, and offer them the possibility to expand their social and economic objectives. The Equality Committee also aims to ensure effective equality between women and men to create a more democratic, balanced, egalitarian, and tolerant university. University integration is one of the fundamental pillars of our commitment to our students. Their personal and professional training helps guarantee our future, and we must support those with special needs. It is necessary to guide students, facilitating their full integration and developing their training under the principle of social responsibility.
Commitment to inclusion. The university must develop instruments and action plans to satisfy the economic, social, and environmental needs of the present without compromising the fulfillment of these needs for future generations.

MATERIALS AND METHODS

Wheelchair driving simulator

Virtual wheelchair design

The wheelchair model selected for the driving simulation was a manual wheelchair instead of an electric one because most people with motor disabilities use manual wheelchairs. When designing the platform, we considered the technical characteristics of the wheelchairs available on the market. Anyone who wants to use the platform should be able to do so using their own wheelchair. The main characteristics determining the platform design were the weight and dimensions of the wheelchair. Steel wheelchairs weigh more than 15 kg, while those made of aluminum or steel alloys weigh around 13-16 kg. Ultralight wheelchairs weigh between 6 and 14 kg. Since we wanted the platform to be universally usable, we made it compatible with wheelchair weights of between 5 and 20 kg. Although wheelchair dimensions vary from one model to another, the measurements of a standard wheelchair are the following: Total height: between 89 and 105 cm. Total length: between 100 and 120 cm. Total width: between 50 and 70 cm (depending on the size of the user). Table 1 shows the ranges of these wheelchair characteristics.

Table 1. Ranges of wheelchair characteristics

Variable	Minimum	Maximum
Weight (kg)	6	14
Height (cm)	89	105
Length (cm)	100	120
Width (cm)	50	70

A three-dimensional wheelchair design was executed with Solidworks2014 (Waltham, Massachusetts, USA). The key components of the wheelchair were modeled, assembled, and parameterized according to the established technical specifications (Table 1). Finally, texture and rendering were applied for a more realistic appearance. The next step was to calculate the physical properties (mass, center of gravity, and moment of inertia) to ensure the model's realistic behavior. This process was carried out for the key wheelchair components, such as tires, axes, or chair. Special attention was paid to the wheelchair's capacity to turn each wheel in the opposite direction for faster and more effective turns.

Virtual scenario design

The stage was created from the site of the Punic Wall in Cartagena (Spain), which was turned into a museum 20 years ago. The strata of the site's different chronological stages, from the 3rd century B.C., when the Punic Wall was built, to the 18th century, when the funerary buildings were added, are on display. An oval-shaped funerary crypt housing several dozen tombs is a featured in this 18th century addition [6]. Figures 1 to 5 show images of the museum's most relevant spaces.

They have been chosen either for their historical importance or because they present barriers to people with motor disabilities.

Figure 1. Ticket sales and shop area of the Punic Wall

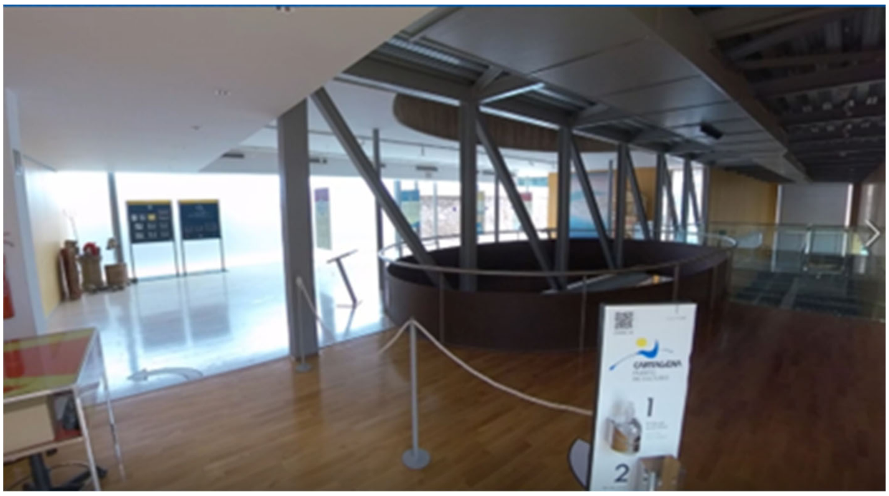

Figure 2. Hall

Figure 3. Crypt seen from above

Figure 4. Punic Wall

Figure 5. Detail of the stairs to the crypt

Figure 6. Detail of the tombs inside the crypt

The scenario was created using images taken with a high-resolution reflex camera using Agisoft photogrammetry software, combined with 3D scanning using a new generation 3D scanner with structured light technology (Artec EVA) capable of capturing points at high speed while maintaining good resolution. The information from the scanning and photogrammetry was combined to make the digital twin of the visitable space.

The software package used to create the virtual reality system was Unity 5 (Unity Technologies, San Francisco, CA, USA). The version of Unity used to develop the scene design included basic features, a powerful physics engine by NVIDIA PhysX, 3D audio, and the possibility of more than one user interacting with the scenario.

For a person with motor disabilities, accessing this site is very frustrating since the museum layout prevents access from the start.

RESULTS AND DISCUSSION

Wheelchair driving simulator

We had to create a virtual reality device capable of accommodating a wide variety of wheelchairs. It was necessary to develop a virtual reality wheelchair platform that allowed freedom of movement on its surface. The platform we designed can turn nx360°, turn using only one wheel, turn quickly using both wheels in opposite directions, and move forward or backward using both wheels simultaneously in the same direction, as well as provide resistance to simulate the virtual slope of the terrain. Movement can be controlled in two ways: (a) by the platform users themselves or (b) using a previously configured program in the computer system.

The user accesses and drives the wheelchair connected to the simulator autonomously by fixing the wheelchair to the platform, which is supported on rollers. These are the interface with the software. If the user moves the wheels, the rollers also move and transmit this movement to the computer. If the user is in an area with a slope, it is the computer that sends the order to the rollers to move, and the user feels that movement as in real life. Figure 7 shows the designed solution, consisting of a virtual reality platform for wheelchairs powered by electric motors and three encoders.

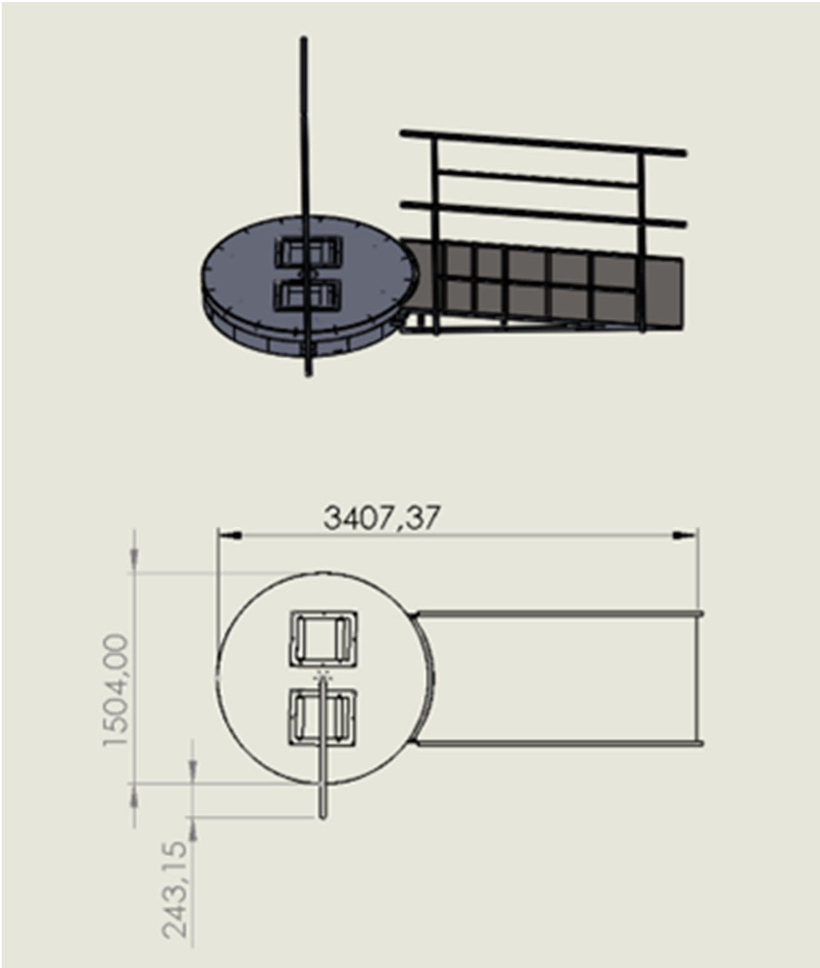

Figure 7. Diagram of the wheelchair driving simulator. Dimensions in mm

On the platform, each wheel of the wheelchair is placed between two rollers. Figure 8 shows the roller box where the wheelchair is fixed in place. The communication of the actions carried out by the user or by the scenario are received by encoders connected to the rollers that transfer the order to Unity and are translated into movement in the virtual environment (Figure 9). The height of the platform was determined by the mechanical elements needed to transmit movement housed inside it. An access ramp permits wheelchair access to the platform (Figure 10). Two of the three encoders are associated with the movement constituting the core of communication between the user's actions and the platform. An additional encoder is used to read the relative position of the chair on the platform. There is also a collector system through which the data from the encoders are sent to the motor and a plate to attach the encoders to the upper base of the platform.

In summary, the platform has a rotating circular base with four rollers (two for each wheel) on which the two driving wheels of the wheelchair rest. This permits rotation and movement to be transmitted so the user can feel realistic simulated movement.

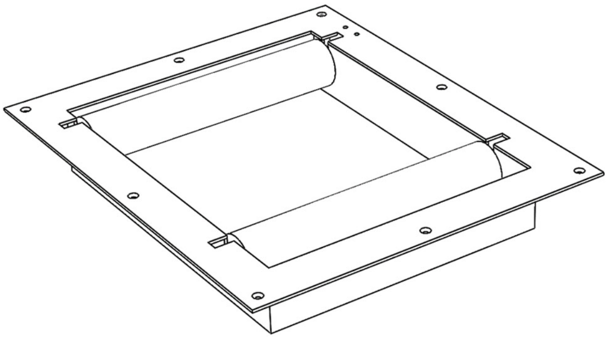

Figure 8. Perspective view of the roller box on which the wheelchair will be placed.

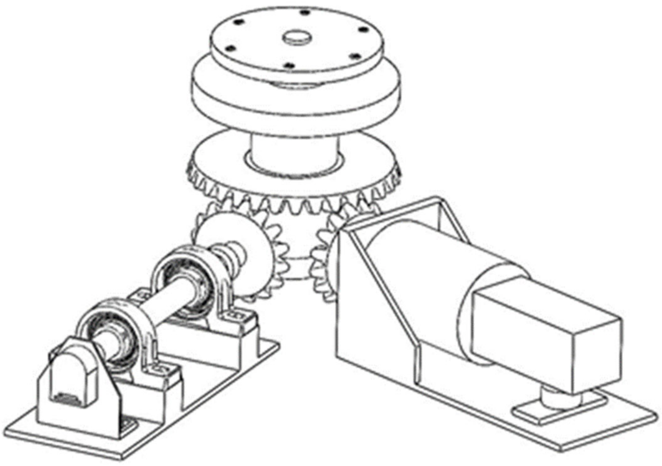

Figure 9.- Details of the gear and motor used to rotate the platform and the encoder that reads its position, the collector system through which the data from the encoders are sent to the motor, and the plate fixing it to the upper base of the platform.

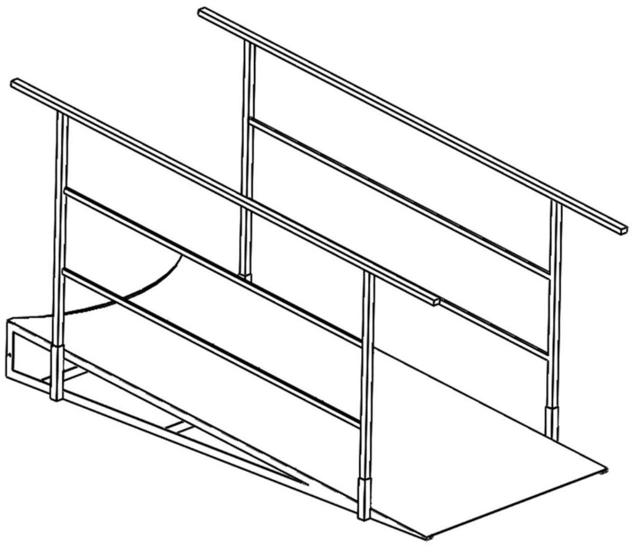

Figure 10.- Platform access ramp with safety rails.

The platform can handle up to 200 kg and provides turning and forward and backward scrolling. The simulation motion platform consists of a 3-DoF motion platform with a sensory real-speed wheelchair on it. The motion platform, connected to virtual-reality glasses for a single user, can incorporate a rear projector on the front of the platform, allowing the user and others to see the scene.

HTCview glasses with a 110º horizontal field of vision are used. The simulator also has a built-in 5.1 surround sound system, and a safety anchoring system for the wheelchair is incorporated into the platform to prevent falls since sudden movements could cause the wheels to disengage from the roller drawers.

The visual system, the motion platform, the operator console, and the sensory interface are controlled by a Workstation PC with an Intel C612 processor, 2.1 GHz CPU, 16 MB of RAM, 8Gb of DDR3 memory, and an NVIDIA M4000 graphics card with PhysX support.

Assembly example and functional description.

As mentioned in the description above, the platform has been designed in parts. First, the lower base with the motor and encoders are put in place and, using the central axis of rotation, the upper base is placed on top. Once fixed, the drawers containing the rollers are inserted into their respective positions and attached to the base.

Next, the cable-carrying structure of the Virtual Reality glasses is installed, and the access ramp is assembled. Finally, the railings are mounted on the ramp.
The platform is equipped with mechanical and electronic systems developed and optimized to meet all operational requirements.
One of each pair of rollers can rotate freely, and the other is linked to the motor. The movements of the two reels associated with the software, one for each wheel, are interpreted independently. The drive rollers have position-sensing devices on their shafts to transmit the electrical signal of their rotation to the computer, which reproduces the movements on the virtual model.
Movement and rotation transmission is achieved as follows: when the two drive rollers rotate in the same direction, the computer system measures the speed of each roller. If the speed of both rollers is the same or almost the same, the computer interprets that the user is moving forward or backward in a straight line and does not activate the platform's turning motor. The motor is only activated if a turn is required. When one of the roller's rotation speeds is faster than the other, the chair will rotate in the established direction. When the user wants to turn the wheelchair quickly, they must turn the wheels in opposite directions. If the left wheel is turned forward and the right wheel backward, the rotation is clockwise, and vice versa. The platform includes a computer system connected to position detectors that allow the two possible modes described above: active mode, in which the user directs the movement in the virtual environment, and autopilot mode, in which the computer system passively directs the user's movement in the virtual environment. In active mode, the platform creates rotational resistance to emulate the resistance of the simulated terrain.
Ramp access is an element that differentiates this platform from other more sophisticated and cumbersome solutions using elevators [7]. Elevator systems increase weight, reduce portability, and raise manufacturing costs, as well as adding to the user's feeling of dependency. With our system, the user backs onto and up the ramp to the platform. Exiting the platform is also done backward. The handrail on the ramp provides safety and added support.
The platform has a cable-carrying structure that connects the mobile base to the computer support and virtual reality glasses. This structure prevents the cable from getting snagged during use.
The platform has safety systems to limit the motor rotation speed, preventing it from going too fast, which could cause uncomfortable or risky situations for the user. It also has an emergency stop button that stops the activity immediately. Finally, the distance between the front and rear rollers has been established to prevent the wheels of the chair from disengaging, providing extra safety.

The platform was built in four easy-to-assemble parts (swivel base, access ramp, safety handrail, and spectacle hanger) to make it portable.

Virtual scenario

A tour has been created within a virtual environment identical to the one a visitor takes during a conventional visit. All the information panels and all the interactive elements of the site are represented in the digital twin.

The virtual path was built using Unity simulation software, which contained a large amount of information about the virtual paths. We increased the precision of the objects to make the scene look more authentic and thus improve the immersive experience. All the photogrammetry and scanned elements were processed and added to the environment to create a more realistic and informative digital scenario. Finally, the virtual wheelchair design with the physical properties described in section 2.1 was added to the scene design.

The tour starts through the entrance door to the museum, located on a higher level than the site's main elements. The next stage moves through a hall where information is displayed on panels and ends at a staircase leading down to the crypt. Visitors can contemplate the crypt's geometry, the arrangement of the tombs, and the paintings on the walls.

Then, visitors leave the crypt by going up another set of stairs. From these stairs, it is possible to see the other main element of this site, the remains of the Punic Wall. Various perspectives of the wall become visible as the upper level is reached. Advancing about thirty meters from the end of the stairs, visitors return to the entrance, and the route is completed. Figures 11 to 18 detail how realistic the digital scenario is. Figures 11 to 16 show the 3D digital twin on the left and the real site on the right.

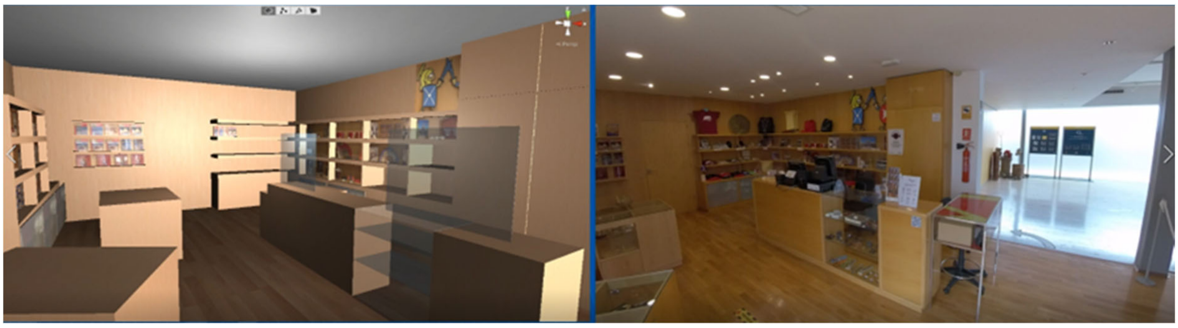

Figure 11. Ticket sales and shop area of the Punic Wall

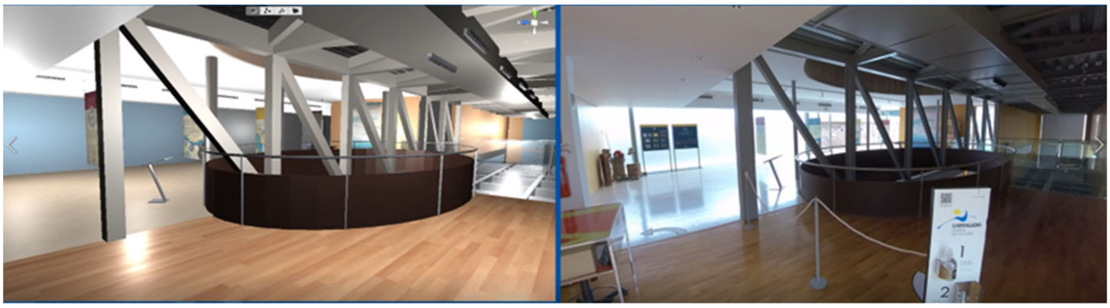

Figure 12. Hall

Figure 13. Crypt seen from above

Figure 14. Punic wall

Figure 15. Detail of the stairs to the crypt

Figure 16. Detail of the tombs inside the crypt

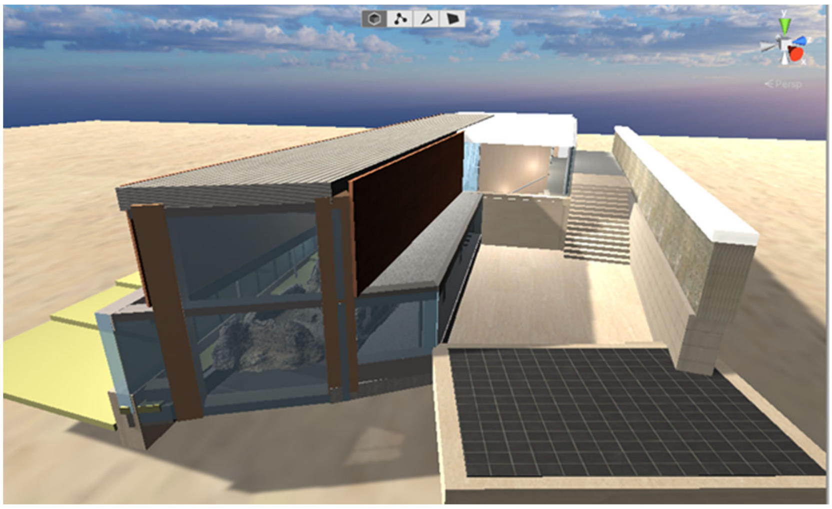

Figure 17. General view of the digital twin of the Punic Wall site (a)

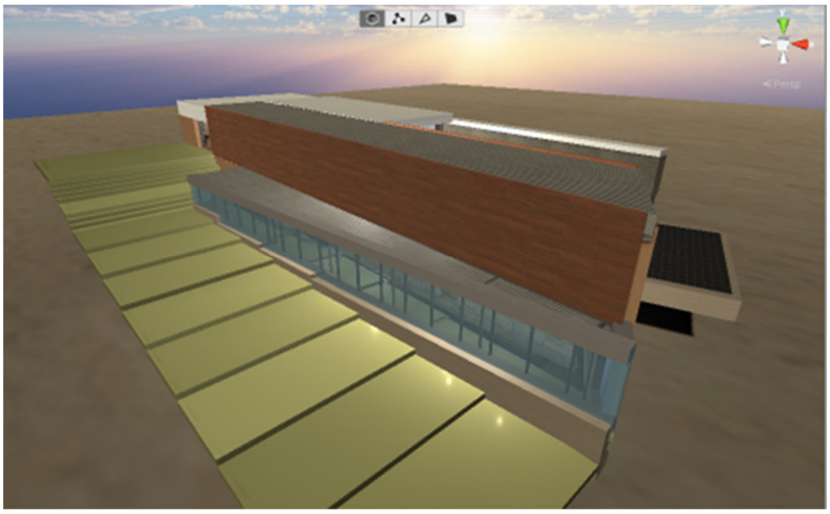

Figure 18. General view of the digital twin of the Punic Wall site (b)

Conclusions

The first prototype of INCLUSION VR, developed by the Industrial Design and Scientific Calculation Service of the SAIT at the UPCT, has been installed in the Museum of the Punic Wall in Cartagena. People with motor disabilities have already enjoyed this immersive experience from the platform in their own wheelchairs or with one available on the platform. They have been able to 'walk' and see both the remains of the defense of the Carthaginian colony from the 3rd century BC and the funerary crypt from the 17th and 18th centuries located in this enclosure. Visiting this site was previously impossible for people with motor disabilities and sometimes even difficult for people who do not have mobility limitations. Figure 19 shows a real experience using INCLUSION VR.

Figure 19. An immersive, inclusive experience

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