Air Quality Monitoring Platform for Virtual Reality-Enabled Digital Twin: the Use Case of Cartagena (Spain)

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***Abstract*—Recent advances in the virtualization of the world we live in have enabled an increasing number of new functionalities that are generating increasing interest from governments, private organizations, and the general public. One of these functionalities is the real-time display of Internet of Things (IoT) data in different types of environments and at varying scales. From maps encompassing wide regions, to buildings, and objects, such as industrial machinery. Air quality monitoring is one of the most popular uses of IoT in Smart Cities due to the severe health effects that air pollution may cause in people. As such, there is a growing concern in creating new tools to enhance the accessibility of the data and increase the awareness regarding air quality. This paper addresses this specific matter, presenting a Virtual Reality-enabled Digital Twin for air quality monitoring platforms. The use case reported in this work applies to the city of Cartagena (Spain), where several of our air quality monitoring devices for polluting gases and suspended particulate matter are deployed. The digital twin was developed using Unity and Citigen for environment development coupled with the data stored in the servers localized at the Universidad Politécnica de Cartagena (UPCT) from our LoRaWAN air quality monitoring IoT network.**

Keywords-Digital Twin; air quality; Virtual Reality; Unity.

I. INTRODUCTION

In the recent years, IoT has been adopted for multiple purposes, accounting for more than 9 billion devices in the world [1]. Smart cities are one of the applications where a higher number of devices is needed, as it is necessary for characterizing each area of the city. Specifically, air quality monitoring devices are present in most smart cities due to the growing concern regarding the pollution generated by increasing amounts of traffic. These devices are often equipped with sensors that measure two main types of pollutants: gases and suspended particulate matter. The most relevant polluting gases include CO, SO_2, O_3. and NO_2 [2]. Conversely, suspended particulate matter is measured for three main particulate sizes, including PM_1, $PM_{2.5}$, and PM_{10}. Monitoring these pollutants in real-time leads to a a great amount of data that needs to be managed and presented to the users in an accessible manner. Dashboards allow data representation in graphical and table formats, but it is limited in functionality. For that reason, new forms of data representation leveraging virtual reality and augmented reality are being considered [3].

Digital Twins provide new possibilities for data representation enabling the creation of digital replicas of the physical world that can be used for real-time monitoring [4]. Other functionalities that can be included in digital twins are learning, predictions, and simulations [5]. Most Digital Twins currently in use have been developed for engineering applications that includes a series of objects or spaces that usually do not surpass the scale of a small number of buildings. But as this technology evolves, the interest of using it for more ambitious purposes has increased. Smart-cities are viewing digital twins as the next tool for providing smarter and more flexible services [6]. However, the creation of a city-level digital twin introduces new challenges as the functional boundaries of a city have higher complexity, not allowing a straightforward upscale.

The technology used to develop a digital twin depends on its intended use. Digital twins intended for buildings are often created based on technologies, such as Building Information Modelling (BIM) and Computer-Aided Design (CAD) that have evolved from its first stages as software to aid builders in the construction process [7]. However, these software tools are not intended for large scale city-like representations. Therefore, it is necessary to use alternative tools, such as video game engines, which have substantially evolved allowing the creation of meta-worlds that can be interacted with. In this paper, we present a digital twin of a smart city for air quality monitoring enabled by virtual-reality. It was developed using Unity and the Citigen tool for the creation of a 3D map of the city of Cartagena (Spain). Each air quality monitoring device deployed in the city had its corresponding object in Unity that could be selected to display a dashboard with the current air pollution readings gathered from the sensors. The solution is enabled by virtual reality, facilitating the navigation of the city.

The rest of the paper is organized as follows, Section 2 presents the related work. The methodology is presented in Section 3. The results are discussed in Section 4. Lastly, the conclusion and future work is presented in Section 5.

II. Related Work

Many of the currently existing digital twins focus on buildings and monitoring the physical factors that affect them or the people inhabiting them. One of them is the digital twin created by Khajavi *et al.* for the facade of an office building [8]. It was equipped with six sensor devices for real-time monitoring of temperature, relative humidity, and environmental lighting. More than 25,000 readings where stored, analyzed and represented in the limited digital twin that overlapped a 2D graphical representation of the lighting received by the sensors using different shades of color on top of an image of the building's facade. However, city-scale digital twins have begun to be developed as well. Mohammadi and Taylor presented a paradigm for a smart city digital twin [9]. Their use case for the city of Atlanta was developed in Unity and based on virtual reality. A plugin was developed to provide analytics according to the data. Furthermore, an augmented reality crowd-sourcing module was included as a tagging system, using a mobile application to run it. In addition, Wolf *et al.* presented a digital twin for emergency management in smart cities [10]. The digital twin includes information, such as weather and traffic data for improved service coordination. The digital twin was developed using the Microsoft Azure cloud for its analytical functionalities, and the maps were generated utilizing TomTom and the Microsoft Azure Maps Web Software Development Kit.

As air quality monitoring has been gaining more relevance, the prospect of creating digital twins that feature air quality data has been increasing. Some of the proposals focused on indoor environments. Qian *et al.* presented an indoor air quality intelligent management approach based on digital twin platforms [4]. Data from different sources was collected, integrated, analyzed, and displayed through a web-based interface. The system was tested in a traditional home in china. The results showed that winter morning presented the most air quality problems. The definition of healthy quality thresholds allowed identifying air quality concerns that could be acted on, solving these problems within 30 minutes since their detection. Furthermore, Ariswala *et al.* used BIM to create a digital twin for monitoring and control of equivalent carbon dioxide in indoor spaces [11]. The solution used IoT devices equipped with low cost sensors, the Microsoft Azure Cloud Platform, Azure Digital Twins, Azure Machine Learning, Power Bi, and the Polycam application to scan the desired building. The resulting digital twin with the 3D implementation of the building included a dashboard to display real-time data and forecasts.

Smart cities have a great interest in air quality monitoring as well. As such, city-scale digital twins are also including these features. Ariansyah *et al.* presented a digital twin for air quality monitoring in smart cities using mix reality technology [12]. The proposal integrated air quality, meteorological, urban infrastructure, and traffic pattern data that could be displayed through a mixed reality headset that represented the map and information as an object placed in the real world. Lastly, Siddaraju *et al.* proposed a digital twin for PM2.5 estimation [14]. This version of digital twin was focused on the simulation of the environment to determine PM2.5 levels and did not include a 3D digital representation of the location where the meteorology stations were deployed. The authors used machine-learning techniques to implement PM2.5 prediction models.

Instead of focusing on building-scale digital twins or 2D, visually limited representations, this paper presents the implementation of a city-scale 3D digital twin for outdoor air quality monitoring enabled by virtual reality.

III. Methodology

In this section, the methodology followed to create the Air Quality monitoring system using virtual reality is presented.

A. Architecture

The architecture of the proposed integral solution for an air quality monitoring platform enabled by a virtual reality-based digital twin is presented in Figure 1. IoT monitoring devices for polluting gases and suspended particulate matter with different sizes are deployed in the city of Cartagena (Spain). These devices take measures periodically and send them to the LoRaWAN Gateway. The Gateway communicates to the LoRaWAN server through MQTT protocol. Telegraf is subscribed to the MQTT topics belonging to the IoT devices to capture the data, provide context and store it at the Influx database. The 3D environment of the Digital Twin for air quality monitoring is created using Citygen3D, a tool for map creations in Unity. The panels that display the device's data are created as objects, and the data from the database is accessed by Unity to display it. Lastly, the users can experience the Digital Twin with a VR headset or in an ordinary monitor.

The following subsections will detail the implementation of each of the elements of the architecture.

B. Air quality monitoring sensor devices

Our air pollution monitoring devices were developed independently, one encompassing the polluting gas sensors (SO_2,

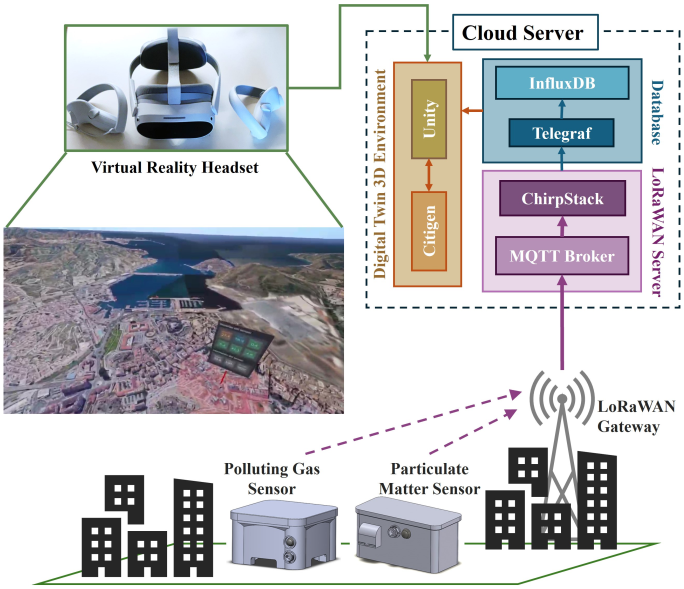

Figure 1. Architecture of the proposed VR-enabled Digital Twin for air quality monitoring.

NO_2, O_3 and CO), and one including the suspended particulate matter sensor (PM_1, $PM_{2.5}$, and PM_{10}) [2]. Both devices include a Pycom embedded system that manages data collection, message formatting, and data transmission. The three devices deployed in Cartagena were equipped with a LoRaWAN transceiver for long range communications. Figures 2, 3, and 4 present the data gathered by the suspended particulate matter for a common weekday. As it can be seen, the concentration of suspended particulate matter increases with rush hour, particularly PM10. The polluting gas data is presented in Figures 5, 6, 7, and 8, respectively. It can be seen that the gases present a different behaviour compared to each other and the suspended particles. Newly deployed devices are easily integrated in the solution, only requiring their activation in the LoRaWAN network. If necessary, other sensors intended for different air quality metrics could be similarly embedded to be adapted to different environments and purposes.

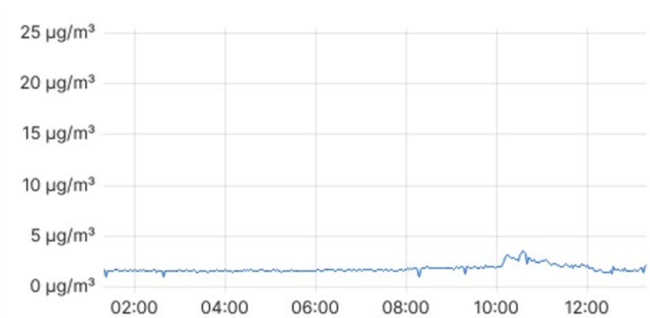

Figure 2. PM_1 data from suspended particulate matter device.

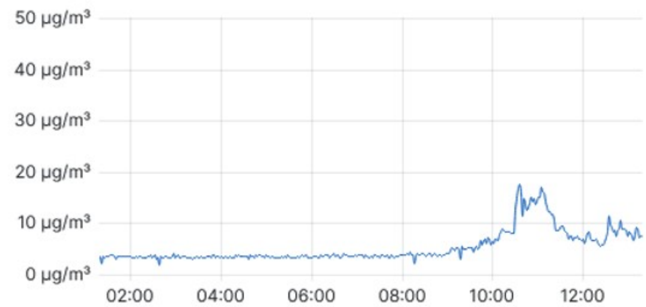

Figure 3. $PM_{2.5}$data from suspended particulate matter device.

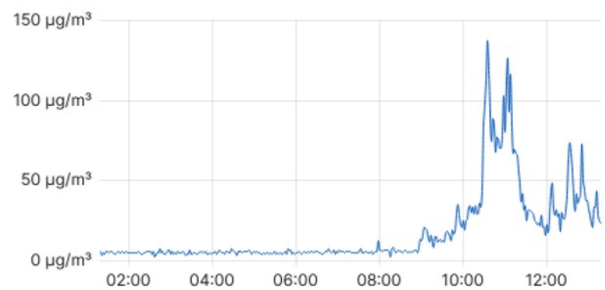

Figure 4. PM_{10}data from suspended particulate matter device.

C. *Virtual Reality Headset*

Virtual Reality Headsets are devices that show images generated by a computer, usually in 3D, through screens located very close to the eyes. The headsets occupy all the user's vision field, providing an immersive experience. In this project, two types of VR Headsets were used to assess user experience. No significant differences were found in their use. The characteristics of the headsets are the following:

1) PicoBlaze: The Pico 4 VR Headset [14] includes a Snapdragon XR2 processor which can reach speeds of up to 2.84 GHz. It offers 8 GB of RAM, ensuring smooth performance in applications and games. The employed model offers 128 GB of storage. Regarding connectivity, it supports WiFi 6 (802.11 a/b/g/n/ac/ax) and 2x2 MIMO dual-band (2.4 GHz/5 GHz). It also has Bluetooth 5.1 for pairing with other devices. The display is high quality, with two 2.56-inch LCD panels and a resolution of 2,160 x 2,160 pixels per eye. It offers a high pixel density (PPI: 1200), a refresh rate of 72/90 Hz and a wide 105° field of view. In addition, the interpupillary distance adjustment is electric and varies between 62-72 mm, adjusting it correctly allows you to view images without distortion. It features dual stereo speakers and a dual microphone for an immersive experience. Echo cancellation technology with 50 dB reduction ensures clear communication. This device runs on the Pico OS 5.0 operating system.

2) Quest 2: The Quest 2 VR headset [15] also includes a Snapdragon XR2 processor. Regarding storage, our headset is equipped with 256 GB. The connectivity of this device has support for WiFi 6 (802.11 a/b/g/n/ac/ax) and 2x2 MIMO dual-band (2.4 GHz/5 GHz). It also has Oculus Link, to connect to

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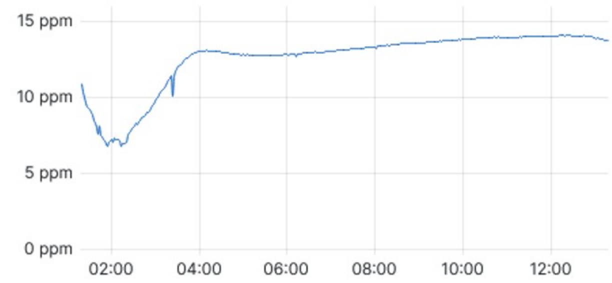

Figure 5. COdata from pollutant gas monitoring device.

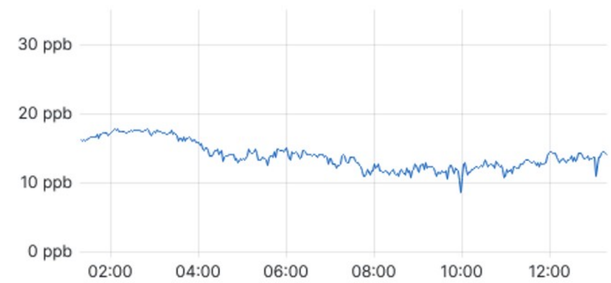

Figure 6. SO_2data from pollutant gas monitoring device.

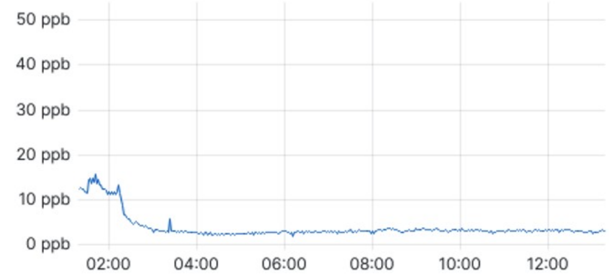

Figure 7. O_3data from pollutant gas monitoring device.

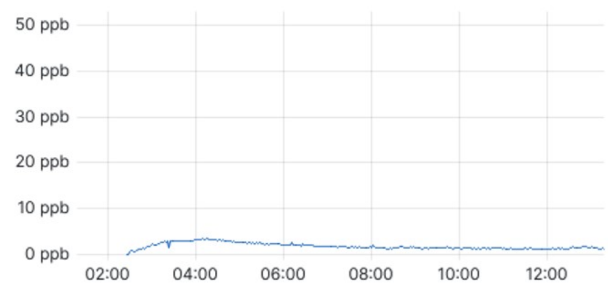

Figure 8. NO_2data from pollutant gas monitoring device.

a PC via USB cable. The display has two LCD panels with a resolution of 3664 x 1920 pixels per eye. It offers a high pixel density (PPI: 1100), a refresh rate of 72/90 Hz and a wide field of view of 105°. The electric interpupillary distance adjustment varies between 63-72 mm. It features dual stereo speakers and a 3.5mm audio port for external headphones. The echo cancellation provides a 45 dB reduction. This device runs on the Oculus OS operating system, which includes a stable and efficient Android-based platform.

D. Unity

The digital twin needs to be supported by a powerful software that enables smooth visualization of 3D environments and assets. Furthermore, it is necessary to ensure its compatibility with popular VR headsets to provide accessibility. Unity [16] is the most popular game development engine and 3D application creation platform, and thus, it has an extensive community and substantial development tools and support. It is used by developers to create games, interactive simulations, virtual reality (VR) and augmented reality experiences, and 2D and 3D applications. Unity is known for its versatility and ease of use, making it perfect for the development of this project. It allows importing and managing 3D models, textures, sounds and animations in order to speed up the development process. It can also be programmed in languages, such as C# and JavaScript to create custom behaviors. The physics system that allows simulating realistic movements and collisions in the virtual world.

Some of the main aspects to be considered when creating the 3D map of the city of Cartagena included the need of changing between predetermined levels of detail depending on the distance of the object, to increase or reduce the number of polygons to optimize the scene. The textures are also critical. A height map was used instead of a normal map to take into account the angle of the viewer with the surface. Its downside is the longer processing times. Texture compression improved these times, selecting ASTC for our project. For lighting, the use of lights was reduced as mush as possible, utilizing baked lights whenever possible. These type of lights reduce the computational cost of rendering the scene, but using many of them increase the number of objects and thus the processing time. All options for improved visual quality could not be included and objects had to be configured as static to avoid increases in execution time.

Other configurations include animations, physics, object loading, and geometry. Animation changes are not problematic, but they have a significant performance cost, so the blend nodes were kept below 6 to reduce this cost. Each object needs to be linked to an animator object, but interpolators are recommended instead of animators. They can be implemented using custom scripts, especially for the user interface. Regarding physics, the reuse of collision callbacks was enabled. Combined primitive colliders were employed to mimic the object they are attached to. Moreover, the layer-based collision detection was used to detect collisions of an object of a predetermined layer with the rest of the objects. By default, Unity loads objects on top of other objects which causes overlapping pixels and longer execution time. Using Occlusion Culling prevents Unity from loading objects outside the camera view. However, it must be done with each object, which is time consuming for an entire city plan. Lastly, the wireframe mode is used to optimize the geometry. It makes the level of detail of the objects depend on the distance to the view. The models must be created manually, adding the LOD Group component, and placing them in the renderers section.

In order to display the information received from the sensors, a series of objects are included to display the individual information of each sensor. To do this, an object is added at the position where the sensor we want to display is located. This object has an associated script that opens a screen to view the information when clicking on it. Other objects where added inside, since the first object only serves to open the screen. The next object is where the information is printed. It displays the sensor measurements and is placed on the previous object. The object is comprised of several sections including temperature, humidity, CO, NO2, O3 and SO2 (See Figure 9).

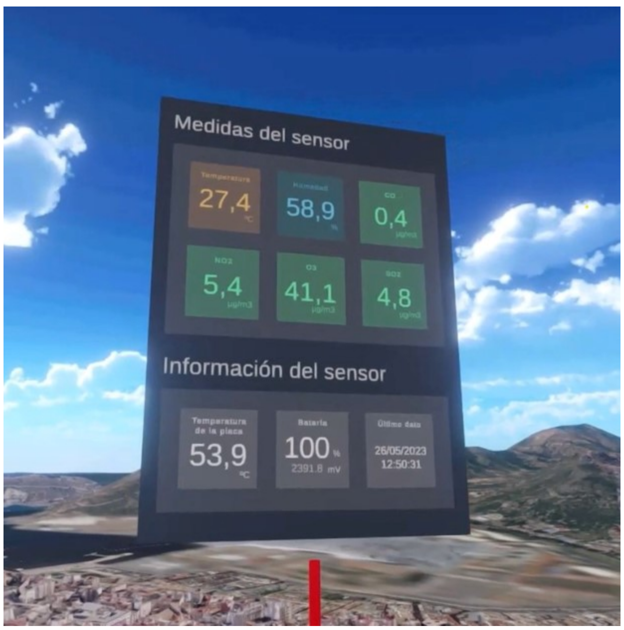

Figure 9. Unity object displaying air quality data from sensor devices.

E. Citygen3D

CityGen3D [17] is an extension for the Unity editor designed to simplify the automated creation of three-dimensional scenarios based on real-world map data from OpenStreetMap. CityGen3D does not require additional coding. A specific location, by means of latitude and longitude coordinates, can be provided and it will download and analyze the real data of the world map inside Unity to generate the scene. To make it a more realistic experience, CityGen3D adds heightmaps in order to be able to appreciate the height differences (mountains, ports, etc). This presented some problems because the height difference in the relief generated too many triangles to represent it correctly. Therefore, modifications were necessary to prevent the application from excessive loading times. Splat textures could be selected from different types of terrain (grass, asphalt and earth among others) to make the world more realistic. The road network could also be generated automatically using the combination of Unity and Citygen3D. Most trees were eliminated since they occupied a great part of the rendering memory and were unnecessary information for our purpose.

F. InfluxDB

The database used in our project is InfluxDB [18]. It is a time series database that can receive and process a large amount of data thanks to the TSM engine, which guarantees data availability, integrity and retrieval.

IV. Results

This section presents the results of our implementation of complete virtual reality-enabled digital twin of the city of Cartagena, that displays the data gathered by all the air quality monitoring devices deployed in the city.

The result for the creation of a virtual world representing Cartagena using the Citygen3D tool is shown in Figure 10. This specialized software has demonstrated its ability to generate detailed three-dimensional environments with high levels of realism.

Figure 10. Empty map of Cartagena using Citigen3D.

The final visual presentation inside the virtual reality glasses can be seen in Figure 11. The differences in height are clearly appreciable and the object with the dashboard for air quality data representation is easily detectable.

Figure 11. Complete visualization of the digital twin using the VR headset.

The users can interact with the panels using the controllers associated with the virtual reality glasses, as shown in Figure 12.

We have therefore succeeded in the implementation of the digital twin of Cartagena. It can be navigated seamlessly with the CR headset and the panels can be activated and removed at will. Other existing works on digital twins for air quality monitoring use 2D representations [8], [14], are intended for

Figure 12. Interaction of VR controllers with dashboard objects.

other parts of the Reality–virtuality spectrum [9], [12], or target only one building [4], [11]. The digital twin presented in this paper encompasses the city of Cartagena (Spain) and provides its 3D representation enabled by virtual reality.

V. Conclusion and future work

Digital twin technology is currently evolving, adding more functionalities and scaling to bigger environments. Smart cities are viewing this technology as a tool to provide accessible information to its citizens. One of the main aspects to transfer into digital twins is air quality monitoring IoT solutions. In this paper, we describe the implementation of our digital twin for air quality monitoring in the city of Cartagena (Spain), which can display the data gathered from polluting gas and suspended particulate matter sensors at different locations of the digital twin map. It is enhanced by virtual reality, providing an immersive experience for the user. There is however ongoing challenges to be addressed. The main one being the optimization of polygons that comprise the city 3D mesh and the trade-off between visualization quality and performance. Nevertheless, the growing interest in this technologies has led to conversations with several institutions, where the identified applications of the digital twin were not limited to data visualization, but also allows for helping policy-makers in performing informed decisions on redirecting traffic flows and urban planning.

For future work, we will implement Artificial Intelligence-based solutions that evaluate air quality form the sensors deployed in the city and present the predictions as heat-maps over the city, allowing the user to quickly determine the areas of the city with more expected air pollution. This also implies spatial predictions to obtain detailed information even in areas without air quality monitoring devices.

Acknowledgment

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