Dynamic Exposure Visualization of Air Quality Data with Augmented Reality

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Keywords: Augmented Reality, Air Quality Data, Environmental Data, Visualization, Citizen Science.

Abstract: Increased awareness regarding air pollution and environmental conditions is more relevant than ever. Notably, there is already widespread availability of do-it-yourself (DIY) environmental and air quality sensors across Europe. These data are accessible to the public through various web interfaces, providing insights into current and past environmental conditions across different regions of Europe. Augmented Reality (AR) stands out as a promising technology to enable citizens to monitor environmental conditions in their communities and comprehend their own impact, thus motivating behavioural changes. Nevertheless, effectively visualizing real-time environmental data in the 3D AR space remains a challenge. Innovative visualization techniques are necessary to present environmental data in a clear and engaging manner. In this paper, we introduce a framework, a visualization concept, and a prototype AR application capable of providing a visual overlay of environmental information such as air quality or traffic data. These concepts stem from the European project H2020 COMPAIR, which involved users throughout the development process. The application will undergo evaluation in various pilot cities and regions and will be publicly available via app stores by mid-2024.

1 INTRODUCTION

Due to the availability of affordable do-it-yourself (DIY) environmental and air quality sensors, there is already a good coverage of sensor data across Europe. Similar trends are observed in other regions such as India (EOS, 2022). These sensors are typically linked to platforms where users can access real-time and historical environmental data. One such established platform is Sensor.Community, which operates a globally-contributed sensor network generating Open Environmental Data (Sensor.Community, 2023). Various web interfaces facilitate data visualization and exploration, making the information accessible to the public. Figure 1 showcases a 3D representation of nitrogen dioxide distribution in London (MappingLondon, 2023). Utilizing Augmented Reality (AR) for understanding environmental conditions offers a more intuitive approach. With just a smartphone or tablet, users gain access to a visual overlay displaying environmental data like air quality or traffic conditions. This advanced visualization in 3D AR enables direct monitoring of air pollution levels in the surrounding area. Increased awareness of local environmental conditions can influence behaviour, promoting alternatives such as biking or using public transport. Such awareness may also drive changes in local government policies, such as

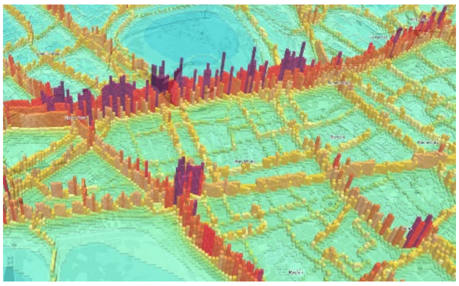

Figure 1: NO_2 distribution in 3D (MappingLondon, 2023).

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Renault, S., Feldmann, I., Raes, L., Silence, J. and Schreer, O.
Dynamic Exposure Visualization of Air Quality Data with Augmented Reality.
DOI: 10.5220/0012586700003696

In *Proceedings of the 10th International Conference on Geographical Information Systems Theory, Applications and Management (GISTAM 2024)*, pages 120-127
ISBN: 978-989-758-694-1; ISSN: 2184-500X

implementing measures to tackle high air pollution levels near schools.

While prior attempts at developing similar AR applications exist, many are no longer accessible on major app stores. This paper introduces a new concept and outlines the implementation of an AR application designed for mobile devices. It can visualize real-time environmental data from various Open Data platforms. The scientific contribution lies in diverse visualization techniques customized for distributed spatial data within the augmented environment. Developed within the European research project H2020 COMPAIR (H2020 COMPAIR, 2023), extensive user involvement throughout the development process ensured thorough examination of innovative visualization concepts in four pilot cities. The resulting modules and assets were integrated into an Air Quality (AQ) Framework.

2 STATE OF THE ART

Without a doubt, AR holds significant promise for enhancing education and learning, a fact supported by various surveys (Vargas 2020, Patel 2020, Khanchandani 2021). However, the exploration of visualizing environmental data within AR applications remains relatively unexplored. Few published AR applications concentrate on presenting air pollution data for mobile devices, but with limited geographical reach. To our knowledge, there is currently no AR application accessible that offers augmented visualization of traffic data sourced from public open datasets.

Torres and Campbell presented an AR app (Torres and Campbell, 2019) visualising main pollutants from the World Air Quality Index Project (WAQI, 2019). In 2019, it was available on the App Store, but not anymore. Mathews et al. presented AiR, which was available for Android devices (Mathews et al., 2021) (see Figure 2). In both applications, pollutants are displayed with flying dots and depending on the severity of the pollution, the number of objects increases. Additional functionalities are provided such as access and visualization of historical data. The AiR app was designed for residents of India, utilizing data from the country's 222 monitoring stations, which, considering India's size, forms a relatively sparse network. Developers said they might create an iOS version, but this plan never materialised. Furthermore, the last update on Google Play was in 2020, and the last comment in 2021. Despite a promising start (Google Play reviews, publication in IEEE), the team behind AiR discontinued the app. In the same year, the New York

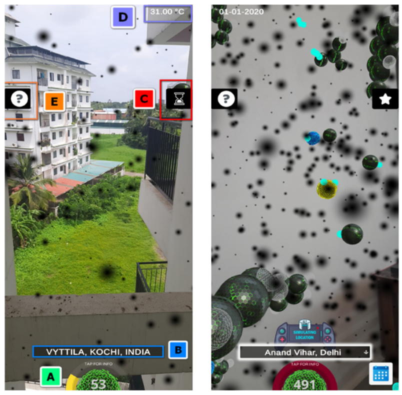

Figure 2: AiR app (Mathews et al., 2021).

Times added an AR feature to its app that visualised air pollution based on location (New York Times AR App, 2019). However, this app does not visualize real-time sensor data, but visualizes microsized pollution particles that were floating around on the worst day of the year at your current location. The Helsinki Air Quality AR app provides Air Quality data from Finnish Meteorological Institute, but only for the city of Helsinki. The last update was offered in2022. In Campana & Dominguez, (2021), a scientific prototype of a particulate matter visualization in AR is presented, but the app did not yet become public.

In this paper, we present a first prototype that is developed in the COMPAIR project. This Dynamic Exposure Visualization App (DEVA) accesses various servers that provide a wide range of sensor data distributed across Europe. The primary challenge lies in presenting a manageable amount of information in a clear and easily understandable manner. The app provides an alternative view of sensor data as depicted in a 3D visualisation environment of an Urban Digital Twin. Hence, we present a novel visualization concept for the representation of environmental data in 3D AR space. DEVA can run on any mobile device, either tablet or smartphone, which has the necessary tracking and AR visualization capabilities.

3 THE PROPOSED SYSTEM

The implementation of the application and the AQ framework is based on Unity 2022 LTS i.e. using the common user interface package uGUI, which allows the rendering of the user interface in 3D space. We also used the AR Foundation Framework, a unified workflow to build robust apps for various AR devices (Unity AR Foundation, 2023). To transpose geo-localisation information between the GPS-based sensor positions and the world coordinate system of the AR scenery, the framework uses an external GPS asset (Unity AR+GPS Location, 2023).

A system overview of DEVA is depicted in Figure 3. The application is able to receive sensor data from two different sources: from project internal sensors and DIY sensors as proposed by the Sensor.Community (Sensor Kits, 2023). Both group of sensors send their values via a PHP respectively RESTful interface to the two servers supported by COMPAIR. DEVA is then able to request all current as well as past sensor data via the dedicated API. As the interface definition is defined in OpenAPI (OpenAPI, 2023), it is easy to adapt the interfaces to the requirements of server and client.

The AQ Framework in Figure 3 shows the processing workflow within DEVA. The Communication module receives the sensor data via REST requests. The data are then transformed in an OGC compliant data structure. The Open Geospatial Consortium (OGC) offers a standardised definition for (i) geospatial content and location-based services; (ii) sensor web and Internet of Things; and (iii) GIS data processing and data sharing, as defined in the OGC SensorThings API Part 1 (OGC, 2022).

The Pipeline Management then processes the sensor values and their metadata and passes them to the different Unity Engine 2D and 3D graphic modules. A number of visualization methods are implemented to turn the sensor data into 3D geometries. One important issue of the app is the data accessibility and the access to AQ sensor data from various servers or services over the internet.

3.1 Environmental Data Servers

The COMPAIR project distributed DIY air quality and traffic data sensors to citizens in four different cities in Europe in order to capture a variety of environmental data. The air quality sensors from SODAQ (SODAQ, 2024) provide data such as CO2 (Carbon Dioxide), NO2 (Nitrogen Dioxide), BC (Black Carbon), PM1, PM2.5 and PM10 (Particulate Matter of size 1, 2.5 and 10 micrometres), humidity and temperature. The traffic sensor (Telraam, 2024) offers vehicle-counting information for individual classes such as cars, trucks or bicycles. The measurements of those sensors are collected and managed in a centralized Data Manager hosted by COMPAIR. Additionally, the app accesses the European Sensor.Community open data server, to include additional AQ data. Both services are auto configured by the app, so that a user can immediately start with exploring sensor data.

Once connected to the servers, the app requests the data in series, from each of them. Those requests are made for the surrounding environment of the geo-localized user, the close area where the user interacts with the data. When the user moves through the streets, the app regularly updates the sensor data. To reduce the transfer payloads, data requests can be restricted to specific sensor types by activating a filter.

3.2 Geo-Localisation

A proper AR visualization requires an accurate localization and orientation of the user and its device in space. Hence, the AQ framework contains three geo-localization modules (GeoPose, 2023), using the Global Navigation Satellite System (GNSS): (i) data request depending on the GPS position of the user; (ii) the geo-pose of the mobile device; and (iii) the geo-localized air pollutants for visualization in the AR/3D space.

The app observes the activity of the user while moving to present actual 3D data. It requests new surrounding sensor data in intervals as follows. The current GPS position is retrieved from the device as the user location in the world. Then, it continuously measures the current distance from this position to the

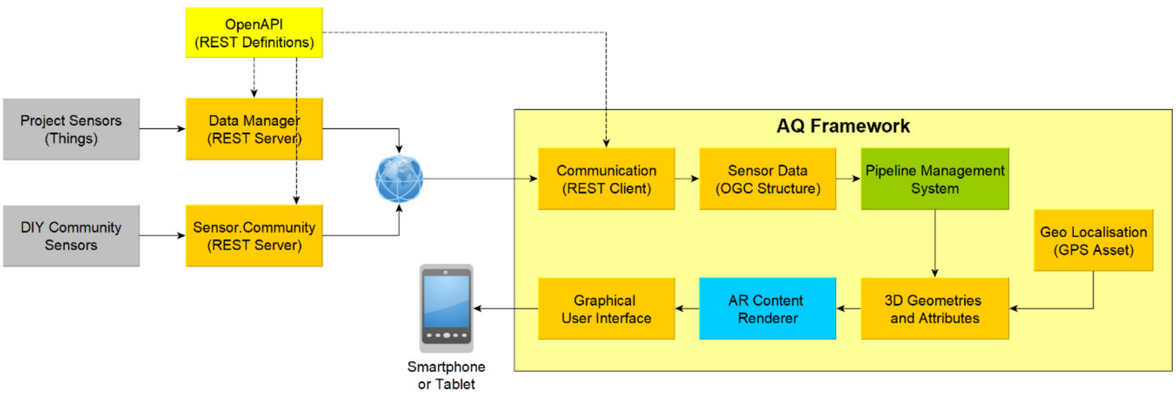

Figure 3: System overview.

centre of the current loaded dataset. Finally, if the distance exceeds the half of the view perimeter e.g. 500m for a maximum distance set to 1km (see Figure 4), the module starts the requests of new sensor data from the Data Manager and Sensor.Community. This approach limits the amount of data to be transmitted.

Once new data are downloaded, they are transposed in the internal OGC structure, injected into the pipeline via the container system and visualized by the AR Content Renderer. Old containers and their 3D geometries are removed before new ones are visualized. The Pipeline Management System takes care of the correct 3D positioning of data as described in the next section. The data update may require one to many seconds, depending on the perimeter size and the amount of loaded data.

4 AR VISUALIZATION

The main purpose of the app is to present environmental real-time sensor data in AR to the citizens. Past attempts on AR visualisation of pollution information relied on quite simple approaches, e.g. visualizing pollutants via flying balls or rocks. The major scientific challenge is to develop and investigate different approaches that suit best for a meaningful representation of a large amount of 3D data in the 3D AR space. This led to three different approaches following the Near'n-Far concept (see Sec. 4.2). This concept optimizes the placement of data that are far away from the user. In collaboration with the project partners, we are able to perform an end users evaluation of the novel visualization techniques. Once, sensor data are received and accessible in the OGC format, the framework enriches the data with graphical objects for the rendering step. Therefore, three processes are initiated: (i) the creation of the asset visuals from the current selected design elements; (ii) setup of the asset attributes corresponding to the sensor type; and

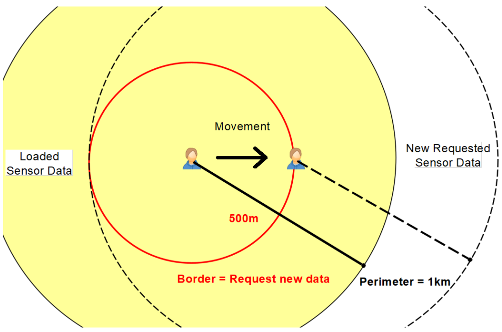

Figure 4: Update technique while the user is moving.

(iii) the placement of the objects in the AR virtual environment in the native coordinate system used by the render engine.

4.1 Data Visualization

The app offers various sensor visuals rendered in the AR view. All designs are created as a Unity prefab consisting of assets and scripts. The user can freely select a design appropriate to the user's level or taste. Three classes of sensor value representations in the AR space are implemented (see Figure 5 and 6):

- a simple version uses 3D primitive meshes like spheres, cubes or squares. They are very easy to render because of the low complexity of the polygon models and their material attributes;
- a more complex representation combines simple 3D meshes, 2D pictograms and GUI elements, like text fields and button canvas for values, sensor types and meta-data;
- a cloud visualization relies on particle animation exploiting the capabilities of the Graphics Processing Unit (GPU) of the mobile device. One or many clouds are created depending on the density of the sensor data, by using a DBSCAN clustering algorithm (Density-Based Spatial Clustering of Applications with Noise). This algorithm observes points in space that are close together and derives related clusters of arbitrary shape. Per cluster, the cloud visualization then creates one particle animation system based on cloud/fog tiled images. Clouds are animated by the render engine and offer a special dynamic to the AR view, because of its 3D volume.

Once a visual was instantiated, the properties of the prefab are set-up according the sensor type. Thus, not all property fields are used for all objects, e.g. a simple visual does not have a text field for the name of the sensor or metadata. The following attributes are

Figure 5: Various visuals for the same values (simple, complex, complex with gamification).

Figure 6: Cloud visualization, one colour for all sensor types vs. multi-coloured (simulation).

implemented to setup the visual of the graphical elements:

- Colour: Each pollutant corresponds to a specific colour and is also used in the legend. The gradient of this colour illustrates the current value's environmental impact.
- Text: Sensor values and units are displayed in a UI label field, utilizing a Unity text canvas. In some cases, the sensor type and brief description are shown in an additional field.
- States: In state mode, four icons indicate (i) active sensor, (ii) calibrated data, (iii) values within an acceptable range, and (iv) private data. Colours change between red-yellow-green to indicate states.
- Size (optional): Prefab size varies based on value impact (small for normal, large for high values).
- Transparency (optional): Data transparency is used to render distant data with decreasing opacity.

4.2 Near'n-Far Concept

In the presented AR visualization framework, we propose a new concept to rearrange geo-located data in the 3D AR space. The main purpose is to minimise occlusions in dense areas with many buildings, trees etc. and to allow the user to capture easily the distribution of 3D data in the AR space. Hence, we developed a new method considering the visualisation of data in the near and far distance separately. This render method helps avoiding some perspective and visualisation conflicts, so that the user is not anymore confronted with incoherent situations and can get a better understanding of the information in the AR space. The following issues are addressed with the Near'n-Far concept:

- Overlap: The geo-pose of sensor devices usually does not contain the altitude. Hence, all sensor values are located in the same height and the overlap of data increases by the density and values cannot be distinguished from each other.
- Perspective: The framework requests data for a perimeter surrounding the user, freely set by the user e.g. 1km. However, in some areas, only a few measurements are available due to sparse distribution of sensors. Therefore, enlarging the perimeter is an option to get more data in the AR scene. The problem then is that data become very small because its visibility decreases with distance.
- Occlusion: When travelling in a city, a user is walking or driving between buildings or trees that create potential occlusion. As the app does not use a 3D map (e.g. Mapbox, 2023) or object detection, objects do not occlude sensor visuals and data remain always visible. Hence, the perspective parallax of the real and the virtual objects contradicts each other in the AR view.

The Near'n-Far solution is similar to a technique named "proximity", where the user can interact adequately with a device at different distances (De la Barré et al., 2009). A proximity system places objects of interest in a main area with the possibility of interacting with them. The other objects are placed in an area beside, or in the background, and are visualized in a minimized fashion. The Near'n-Far concept relies on a double perimeter system: the inner perimeter is dedicated to near data and the outer perimeter to far data (see Figure 7). The initial data container in the pipeline is split into two new ones:

(i) a near data container manages the data inside the inner perimeter and uses the same visuals and positions as originally;
(ii) a far data container for data with a distance bigger than the inner perimeter using a simple visual, e.g. small spheres, with new calculated xyz positions and sizes.

While activating the Near'n-Far mode, the user can change the inner perimeter in real-time and the pipeline manager will update all active containers accordingly. The centre point of the Near'n-Far object is always the geo-location of the user. While moving, the system updates all data containers. In all modes, only the geometric formulas transforming the positions of far containers differ. We implemented three different Near'n-Far methods in the render pipeline:

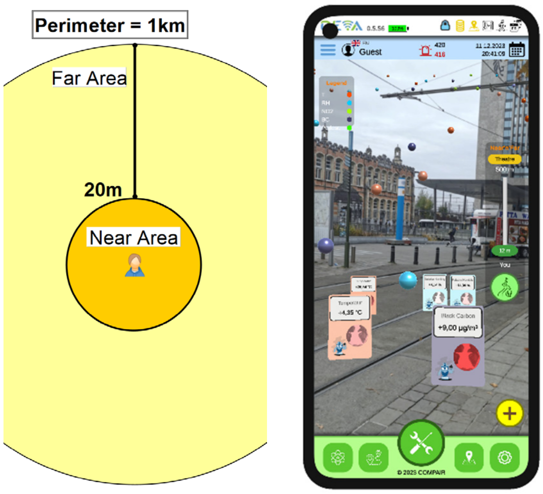

Figure 7: Near'n-Far concept.

Theatre: The first mode is an amphi-theatre like presentation, where data are arranged in different heights depending on their distance to the user (see Figure 8). We reduced the intensity of the AR view in the screen shot for better visibility of the data. Closer data are rendered on the same level as in the near area. Beyond, data rise up to the heaven. Hence, the user perceives the distance of the data by its altitude and size. This results in fewer conflicts of the far data with the real world.

Dome: The second mode is a dome-like presentation as depicted in Figure 9. The dome is an invisible half-sphere around the user. The formula is based on the one from the theatre, added with a projection of the far data onto the dome centred to the user's location. Closer data are arranged in the lower part of the half-sphere, while distant data are located higher up on the half-sphere. All data laying on the sphere has the same best optimal size. Depending on the environment, the radius of the sphere should be adapted: in a dense city location, a smaller sphere should be more suitable (e.g. inner perimeter to 50-100m).

Ring: A third option is a virtual ring that surrounds the user (see Figure 10). The geometrical formula is based on the one from the Dome with a projection of the sensor locations onto the ring. The idea is that the ring is close enough to the user (5m), so the user can easily select sensor data by clicking them. A rotation mode with a compass will facilitate the user to access information around him, without the need to turn the body or device. In Table 1, we compare the capabilities of the three different visualization methods according to the aforementioned issues. The dome representation respects all three aspects from a conceptual point of view.

Figure 8: Theatre: Top-left: Concept; Bottom-left: Authoring and Bottom right: Screenshot.

Figure 9: Dome: Top: Concept; Bottom left: Authoring and Bottom right: Screenshot.

Figure 10: Ring: Top: Concept; Bottom left: Authoring and Bottom right: Screenshot.

However, the Near'n-Far concepts presented, are not capable to visualize too many or too densely distributed data. In such case, it is important that the user filters the values by sensor types. Still, the dynamic re-ordering of data via the Near'n-Far approach offers the user a better visual experience, if sensor data collide with the real world.

Table 1: Comparison of different visualization methods.

Method	Overlap	Perspective	Occlusion
Theatre	YES	NO	YES
Dome	YES	YES	YES
Ring	NO	YES	YES

4.3 User Interface

In our app, the graphic engine Unity renders the full screen. The 2D user interface is an overlay of the 3D/AR viewport and does not require any operation system (OS) specific UI libraries. Our framework offers a number of assets and reusable Unity components allowing to adapt and extend the UI as desired. The app supports a simple and an expert mode, which is a result from our in-depth user evaluation especially with school kids. We identified that the UI should be used with minimal technical skills, no prior knowledge, self-explanatory and intuitive in use. By designing the 2D screen, we respected standards such as responsive design, white spaces, organic elements up to demonstrative gamification of the UI, such as animations and pictograms. The UI adapts automatically to the orientation of the device and its screen resolution, especially to support both, mobile phones and bigger sized tablets (see Figure 11).

Figure 11: Main elements of the GUI: Left: Hamburger menu and Right: Toolbox

4.4 Trip Recorder

To encourage citizen participation, we integrated a feature known as the trip recorder (see Figure 12). Upon activation, this tool records and saves the current GPS position at various time intervals. Once the trip concludes, the position and time data are transmitted to the Data Manager for subsequent analysis. This tool serves as the input for another project-developed application called the Dynamic Exposure Visualization Dashboard (DEV-D), available for access at (DEV-D, 2024). This separate application monitors and visualizes air quality along the recorded trip.

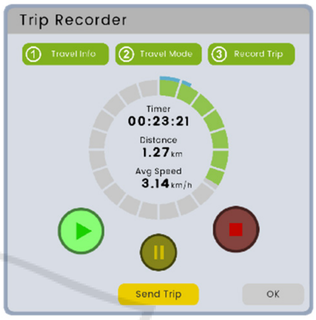

Figure 12: Trip recorder.

5 USE CASES

The main objective of DEVA is to offer the wider public the possibility to get awareness about the environmental conditions in their local neighbourhood. In the best case, this may change behaviour and will have impact on political decisions on the local level, e.g. implement low emission zones or change rules for traffic and develop mobility plans. In the context of the COMPARE project, a fully citizen science (CS) based approach is performed to involve citizens in many aspects of the project such as installation of DIY sensors in the local surrounding, participating in workshops, or contribute to user testing and evaluation of various tools developed in the project.

The close cooperation with citizens is implemented in five different pilot cities in four different European countries. The pilots are designed around the following topics:

- investigating air pollution over different periods in time (weekend vs. working days),
- investigating environmental conditions in school streets,

- measuring effects before and after certain mobility plans in a neighbourhood.

Especially for the development of the presented AQ Augmented Reality app, the CS involvement is crucial and very helpful. We were able to receive immediate feedback from end users in every stage of the development, starting with the requirements, the first prototype until the final application.

6 CONCLUSION

The presented Augmented Reality app offers for the first time a real-time visualization of air quality and traffic data based on publicly available environmental DIY sensor data. The overall framework of DEVA followed a flexible and dynamic software concept, which can easily be extended with additional functionality according to the user needs and the availability of new sensor data. For example, inclusion of gamification elements could be deployed in future versions, to increase the attractiveness and joy of the app, especially for the younger audience. The main contribution of this paper is the proposition of three different kind of visualizations for 3D data in the 3D AR space. Thanks to the H2020 project COMPAIR, the development of the different prototypes was continuously accompanied by project partners. Hence, the UI design, the necessary functionalities are a result of in-depth testing and evaluation thanks to the CS-based nature of the project. The app will be made available to the public by middle of 2024 on app stores.

ACKNOWLEDGEMENTS

The research presented in this paper has received financial support from the European Union's Horizon 2020 Program COMPAIR under grant agreement no. 101036563.

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