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Real-Time Visualization of Cadastral Information from German Authorities Using Augmented Reality

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Abstract

Real-time visualization of cadastral information through augmented reality (AR) has emerged as a significant challenge for public authorities in recent years. This paper addresses the potential, usage, and challenges of AR in the public sector. The prototype developed for this study demonstrates the visualization of geospatial data from ALKIS (Amtliches Liegenschaftskatasterinformationssystem, engl. Authoritative Real Estate Cadastre Information System), visualizing the boundaries and points of parcels in AR. Field tests conducted within this study assess the accuracy and usability of the AR visualization. As part of the study, existing AR libraries and frameworks were evaluated to select the most suitable platform for the prototype. The research underlines the potential of AR for geospatial applications, although it points out current precision limitations in the absence of external GNSS (Global Navigation Satellite System) receivers. The outcomes demonstrate the capabilities of AR visualization in a geospatial context and provide concrete approaches for optimizing future applications and research initiatives.

1. Introduction

Cadastral information plays a pivotal role in property ownership, urban planning, and land management. Traditionally, cadastral information has been visualized using two-dimensional maps. While this method is effective for many use cases, it is sometimes difficult to assign elements of the map to reality. Augmented reality (AR) presents itself as a potential alternative, allowing visualization of geospatial data as overlays on real environments. AR has the potential to notably improve use cases such as locating georeferenced objects, verifying property boundaries, fostering public engagement in urban planning, and educational applications in geospatial sciences.

The integration of AR in geospatial solutions provides a new perspective on how spatial data can be accessed and experienced. AR allows users to view data with a higher degree of immersion, thereby gaining a more intuitive understanding of spatial data. However, the successful implementation of AR in these contexts requires an accurate selection and configuration of libraries and frameworks that support geospatial data, geospatial positioning and provide AR functions as required.

Consumer-grade GNSS without external receivers usually offers meter-level accuracy, while cadastral surveying requires centimeter precision. This creates a clear gap between what the technology can achieve and what formal surveying requires. While Visual Positioning Systems (VPS) promise sub-meter accuracy through corrections based on photogrammetric images, their effectiveness in visualizing cadastral boundaries has not been systematically tested. This study examines whether GNSS-enhanced smartphone-based AR systems can achieve sufficient accuracy to visually represent parcel boundaries reliably, even if they do not meet the strict precision requirements of cadastral surveying.

2. Related Work

2.1 Augmented Reality

Nowadays, augmented reality serves as a proficient tool for adding virtual elements to the real world using devices such as smartphones, tablets, and AR glasses. According to Porter and Heppelmann (2017), AR primarily operates on data from sensors and cameras to overlay the real environment accurately with digital information. Milgram et al. (1994) identify this immersive interaction as part of the Virtuality Continuum, with AR residing between the real environment and augmented virtuality, a concept discussed by Biene et al. (2021). Unlike Virtual Reality, which substitutes the real world with a virtual one, AR enhances real-world objects with additional information by integrating virtual objects.

Within geospatial sciences, AR has been explored in several fields such as urban planning, construction, and tourism. For instance, St-Aubin et al. (2010; 2012) discussed how AR could facilitate collaborative urban planning by allowing stakeholders to interact directly and intuitively with 3D city models within an AR environment. Talmaki et al. (2010) and Su et al. (2013) explored visualizing underground infrastructure using AR to mitigate collision risks in construction works. Moreover, innovative applications in the tourism industry, such as those by Biene et al. (2021) in Lübeck and Soest, offer tourists novel experiences. Notably, these applications employ AR to represent historical landmarks as they existed before the World War II destruction.

AR has extended its reach to navigation systems as well. Chung et al. (2016) proposed an AR-based navigation system aimed at assisting individuals who may struggle with traditional 2D Maps. In 2019, Google Maps launched an AR navigation system that offered real-time directional guidance (Inman, 2019), underlining the potential of AR for developing intuitive navigation systems.

Ratajczak et al. (2019) explored AR applications within the construction and real estate sector, presenting an AR-based tool to visualize BIM within its actual surroundings. This tool allows stakeholders to track the construction project's progress effectively.

In addition to the application areas, Chen et al. (2019) pointed out that 3D orientation systems are essential for most AR applications, facilitating precise positioning of virtual objects within their real-world locations. The ability of precise positioning makes the difference between offering or not offering a reliable AR experience through sensor-based methods or camera image analysis and algorithms. Used together, both methods enable a higher accuracy and a more immersive AR experience.

In conclusion, the possibilities within the aforementioned application areas become almost endless as AR can often offer richer, more accurate, and more accessible visualizations than traditional visualizations. As highlighted in GIS Geography (2023), AR can lead to an enhancement or improvement of experiences in areas such as gaming, education, industry, and urban planning.

2.2 GNSS Positioning Techniques

Zangenehnejad and Gao (2021), and Heßelbarth and Wanninger (2020) presented various methods for satellite positioning in mobile devices with differing precision levels. These range from Single Point Positioning (SPP), Precise Point Positioning (PPP), Precise Point Positioning with Ambiguity Resolution (PPP-AR), to Real-Time Kinematic (RTK). Each of these techniques provides a range of accuracies dependent on the quality of the GNSS receivers. Usual consumer devices offer less precise solutions compared to specialized equipment.

Most modern smartphones employ dual-frequency GNSS with PPP, achieving an approximate accuracy of one meter, although this can vary due to lower cost GNSS chipsets typically used in such devices (Zangenehnejad and Gao, 2021). Additionally, inaccuracies in smartphone GNSS sensor hardware calibration can increase positioning errors up to several meters. RTK positioning can significantly reduce these errors, although it requires simultaneous measurements with reference stations unavailable on consumer devices.

In Germany, the satellite positioning service SAPOS (Satellitenpositionierungsdienst der deutschen Landesvermessung, engl. Satellite Positioning Service of the Official German Surveying and Mapping) provides RTK corrections. However, it has not been incorporated into this study. Post-processing of the data can improve the precision of the positioning. The post-processing itself means that the true satellite orbits are used afterwards for improving the precision, which cannot be applied in AR applications due to their requirements of real-time data processing. While an image-based approach can enhance positioning precision, it also increases the computational requirements and may lead to performance issues on smartphones (Sadeghi-Niaraki and Choi, 2020).

While precision within a few meters is usually sufficient for most mobile applications such as navigation, greater precision is advantageous for the accurate placement of virtual objects in the real world. However, precise GNSS chipsets that could resolve these issues are costly and not commonly found in commercial smartphones (Paziewski, 2020). Furthermore, the low-quality antennas in these devices and the absence of calibration models for specific antenna types reduce positioning precision.

2.3 Visual Positioning Systems

Beyond satellite-based positioning, recent progress in computer vision has led to Visual Positioning Systems (VPS), which improve GNSS-measured coordinates through photogrammetric image matching. A VPS combines the initial GNSS position with camera-based pose estimation by detecting and matching unique visual features, such as building edges, façade structures, or corners, against georeferenced images or point clouds as reference data. The system uses feature-based alignment and structure-from-motion (SfM) principles to refine the device's six degrees of freedom (6DoF) pose in real time. This combined approach can significantly reduce horizontal positioning errors, especially in urban areas where GNSS accuracy suffers from multipath effects and signal blockage.

Modern AR frameworks include these VPS mechanisms to improve global pose estimation. The Google Geospatial API merges GNSS measurements and extensive photogrammetric reference datasets taken from Google Street View images to allow image-based localization. Under good environmental conditions, this method can reach sub-meter positioning accuracy. However, its effectiveness relies on the availability of high-quality visual reference data and structured environments. The difference between GNSS-only positioning without external receivers and GNSS enhanced by visual correction serves as the theoretical basis for the comparative field evaluation conducted in this study.

3. Methodology

3.1 Research of AR Frameworks

The library or framework selected for this study had to fulfil two main requirements: providing an immersive AR experience and ensuring sufficient positional accuracy. An immersive AR experience can be achieved through features such as smooth object movement and accurate light estimation, which can make virtual objects appear as if they coexist in reality. The required level of accuracy in positioning is dependent upon the application area. For parcel boundary evaluation, an accuracy of one meter is sufficient. However, for precise boundary determination, an accuracy of about 4 cm is needed, as indicated by Annex 7 of the LiegVermErl (Erhebung von Geobasisdaten durch Liegenschaftsvermessungen, engl. collection of geobasis data through cadastral surveying) in Lower Saxony.

A comprehensive evaluation of a wide range of popular and well-established AR development kits and libraries was conducted to ensure that the chosen platform can deliver a robust and efficient AR experience. Among those considered were AR.js for web-based AR applications, Apple's ARKit due to its integration with iOS devices, and Google's ARCore SDK, along with several other notable AR solutions gaining significant traction within the AR development community. These frameworks need careful review based on their integration capabilities, device compatibility, and their ability to handle real-time geospatial data visualization, which is the focus of this study.

The chosen AR framework had to support a comprehensive set of features essential for developing the geospatial AR experience. The most critical capability in geospatial AR solutions is how accurately they overlay geospatial data onto specified coordinates within the AR environment. This is crucial for applications involving real-world mapping, such as cadastral visualizations, where real geographic locations must align accurately with the virtual data. Therefore, the framework needs to offer advanced GNSS integration for correct positioning of virtual elements in the real world and be responsive to real-time location data changes. Additionally, the framework must be capable of processing vast amounts of complex geospatial information efficiently without compromising performance. Efficient data handling and rendering are key, as poor performance in an AR application can lead to inaccurate visualizations and reduced user experience.

Beyond core functionality, it must also be considered how effectively the AR framework can scale with the increasing complexity of the application. This includes the ability to manage large datasets effectively without performance loss and openness for new feature additions as AR experiences increase in data size and complexity.

A systematic evaluation of different AR development frameworks for geospatial visualization was previously conducted by Sippel (2024). In this study, several widely used AR development kits, including Google ARCore, Apple ARKit, Vuforia, Wikitude and AR.js, were compared with respect to their suitability for geospatial AR applications. The evaluation considered criteria such as support for global georeferencing, integration of external geospatial datasets, positioning stability, development complexity, and compatibility with consumer mobile devices. The results showed that many frameworks are primarily designed for marker-based or locally referenced AR scenarios and therefore do not provide reliable positioning for georeferenced datasets. Based on this comparative analysis, ARCore combined with the Geospatial API was identified as the most suitable framework for further experimental investigation (Sippel, 2024).

3.2 Cadastral Data

The data used in the project are cadastral data. The primary functions of cadastral data, such as parcel boundaries and points, are to provide proof of ownership and to be used for the calculation of property taxes. In Germany, cadastral data are measured, managed, analyzed and presented by the federal states of Germany. The data are managed through ALKIS, making cadastral data one of the most important types of geospatial data in Germany.

The surveying, administration, analysis, and visualization of geodata from ALKIS are managed by the federal states of Germany, with additional organization from the working group AdV (Arbeitsgemeinschaft der Vermessungsverwaltungen der Länder der Bundesrepublik Deutschland, engl. Working Committee of the Surveying Authorities of the Laender of the Federal Republic of Germany). The survey can also be performed by officially authorized survey engineers.

Cadastral datasets in Lower Saxony are currently available in various formats such as XML, GeoPackage, Shape, and DXF. These formats may not be directly usable in many AR frameworks and may require conversion into more compatible formats. Moreover, depending on the structure, including attributes and geometry, adjustments might be required for this data in order to be used in an AR environment. Typically, cadastral data in Lower Saxony are provided in the EPSG:25832 coordinate reference system (ETRS89 / UTM zone 32N), which may require transformations.

3.3 Testing AR Frameworks

The testing of AR frameworks needs to be done in terms of accuracy and user experience. Testing on accuracy involves comparing virtual georeferenced data with their real-world counterparts. This can be done by choosing testing locations with known reference marks to allow an accurate comparison of virtual boundary points with real-world parcel points. These tests should consider different environments, like urban and countryside areas, to identify the impact of the quality of GNSS signals and environmental factors on the performance of AR. Moreover, positioning accuracy will be enhanced by integrating photogrammetry algorithms with reference data, which will be particularly useful in urban areas with many building facades and corner points.

To assess the user experience and the immersivity of the AR interface, it can be evaluated by observing the responsiveness of the virtual elements to the movements of the user and how well they align with the real world. These field tests will test both the technical accuracy of the AR framework and its overall usability. While user experience and immersivity are important, they are not the primary aspects of the study.

4. Implementation

4.1 Selection of the AR Framework

After an in-depth analysis of all options described above, the Google ARCore SDK was determined to be the best solution for this project. This decision is based on the wide range of functionalities provided by the tool in processing and visualizing real-time data. Furthermore, it is available for Android and iOS. Besides that, together with Geospatial API, ARCore provides a set of tools that allows the developer to build advanced augmented reality applications using geospatial information, which perfectly meets the scope of the current study. It also has a very active support community and is updated frequently, meaning most new devices and technologies are supported. Another important point that favored ARCore was its easy integration with Unity Engine.

The Unity Engine enables developers to work within a very versatile and powerful environment for AR applications. Traditionally, Unity was used for the creation of games, but the range of solutions has grown much in other fields such as architectural visualization, medical simulations, and education. It is extremely flexible and can support complex AR environments that can also facilitate real-time interaction along with high-quality visualization. Unity's broad compatibility with a variety of operating systems and hardware platforms ensures that this application will run on most common devices, from smartphones to AR glasses. Besides that, Unity's asset store and community-driven ecosystem provide loads of resources, such as prebuilt assets and plugins, that can further accelerate the development process.

The Google ARCore SDK (Google ARCore XR Plugin 5.0.7 for Unity) with Geospatial API and Unity Engine (2022.3.9f1) were selected to produce a functional prototype that integrates real-time geospatial data with augmented reality to practically demonstrate the potential of AR to cadastral visualizations and other geospatial applications.

4.2 Data Preparation

The prototype needs to be designed with the objective of visualizing cadastral geodata by overlaying it onto the real world as viewed through a mobile device. Therefore, the data have a key role in this study. Parcel information of Lower Saxony can be exported from ALKIS in various formats. Although GeoPackage is currently the most efficient format, it only supports geometries without any metadata. Therefore, the XML format, which contains all the metadata, is used. The workflow consists of the following steps: declaring the test area, exporting the cadastral data (EPSG:25832), importing it into QGIS, extracting the boundary points of parcel geometries, linking the boundary points with additional precision attributes, and sorting them according to point indices. The output is a CSV file, which is compatible with Unity Engine and ARCore SDK. The conversion from ETRS89/UTM (EPSG:25832) to WGS84 (EPSG:4326) is made to ensure compatibility with the Geospatial API.

The prepared data in this CSV file contain decimal degrees coordinates, identification numbers of parcels, area size, point indices, precision of the measurement, and reliability of data.

4.3 Field Tests

Field tests are essential to evaluate the accuracy of georeferenced data and the usability of the prototype in the real world. The tests are designed to evaluate the differences between the virtual boundaries and the true parcel boundaries when viewed through the AR interface. The selection of testing locations is based on the availability of reference marks, including both urban and countryside settings, in order to get variations in GNSS signal quality and environmental obstacles that could affect AR performance. Moreover, the use of Geospatial API, which improves the positioning, requires data from Google Street View. Tests without reference data by Google Street View are not included in the measurement result and are considered outside of the actual evaluation. The accuracy differences are too large compared to the measurements with reference data. Aside from that, most field tests are in urban settings.

The Google Pixel 6 was used as a test device. It is equipped with a dual-frequency global navigation satellite system (GNSS) receiver, which offers enhanced positioning precision compared to single-frequency receivers. During the tests, the device with the camera is aimed at the reference marks to compare the position of the virtual point with the mark. To create a comparison, first the calculated difference from a function of the SDK is used, and secondly, the distance from the virtual point to the actual point is measured. Figure 1 illustrates the determination of positional deviation and Table 1 presents the results of the second measured point. Three measurements on three different days were scheduled.

Figure 1. Measurement of positioning difference.

Measurement	Time [hh:mm]	Difference by function [m]	Difference by measurement [m]
1.1	14:34	0.443	0.341
1.2	14:35	0.489	0.276
1.3	14:38	0.316	0.356
2.1	14:58	0.336	0.453
2.2	14.59	0.382	0.465
2.3	15:00	0.322	0.384
3.1	10:20	0.493	0.365
3.2	10:21	0.427	0.282
3.3	10:22	0.417	0.535

Table 1. Measured differences of point 2.

4.4 Implementation of C# Scripts

The core implementation involves dynamically creating, updating, and deleting parcel boundaries in the AR environment based on the location of the user. This application, through Unity and C# scripts, continuously monitors whether the device is inside or outside of bounding boxes, which define the geographic area of each parcel. These bounding boxes are created based on the minimum and maximum latitude and longitude for every parcel, which allows them to be compared with the current user position.

If the user's device is in one of the bounding boxes of a parcel, the system generates 3D parcel boundary points and parcel information. The first functions of the script are the import of geospatial data from the CSV file, conversion of the coordinates for Geospatial API, and the adding of Google ARCore’s ARGeospatialCreatorAnchor to a game object. Each game object represents a boundary point. If a boundary point is set up in such a case, the script checks for an update and adjusts the position of the points or lines, connecting them to ensure that an accurate visualization of parcel boundaries is always realized.

The script also triggers the deletion of the corresponding boundary points and parcel information if the device moves outside the bounding box to optimize performance. The system ensures smooth performance even when dealing with large datasets by only rendering parcel boundaries near the user. Further enhancements to usability include that the script maintains the parcel information constantly oriented to the user by adding another function which adjusts the view direction of game objects that visualize the parcel information in front of the user.

Furthermore, by limiting the number of data points processed per frame, the performance is optimized in the current system.

5. Results

5.1 Accuracy of AR-based Visualization

The level of AR-based visualization accuracy varied significantly across different test locations. When reference data is available for the Geospatial API, the accuracy of georeferenced points is less than one meter, and the average is even less than half a meter. Figure 2 presents the results for five reference marks obtained from three series of three measurements each, conducted in urban areas using the Geospatial API. Table 2 shows the average positioning differences for each series of measurements as well as the overall averages.

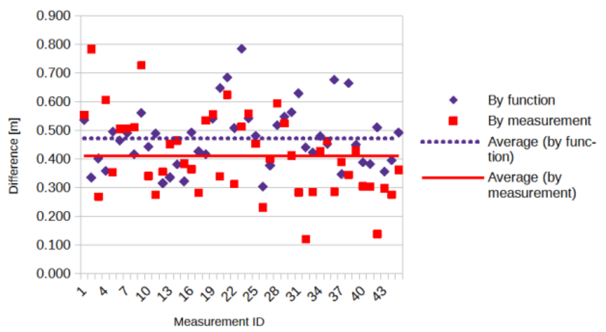

Figure 2. Positioning difference [m] of all measured points in urban areas.

ID	Average [m]		
	By function	By measurement	Diff. func - measurement
1	0.451	0.535	-0.084
2	0.403	0.384	0.019
3	0.541	0.443	0.098
4	0.526	0.378	0.148
5	0.443	0.316	0.127
total	0.473	0.411	0.062

Table 2. Average positioning difference in urban areas.

This level of precision aligns the virtual boundaries with the actual parcel boundaries, allowing users to visualize boundaries with a suitable level of reliability, as shown in Figure 3. In the absence of reference data for image-based correction during field tests in areas with clear sky visibility, the Global Navigation Satellite System (GNSS) positioning provided by the devices was found to offer an accuracy of 2 – 4 m.

However, in urban areas, due to many high buildings, vegetation and limited sky visibility, the GNSS only solution is less accurate and can have errors up to 5 m. The sensors of the device and functions of the AR framework e.g. Geospatial API helped solve this challenge in regions with a high density of referenced visual elements that significantly increase precision by comparing images. Nevertheless, the overall accuracy is limited by the precision of the GNSS data and the capabilities of the AR framework. Tests in areas without photogrammetric algorithms and only with GNSS, shown in Figure 4, lead to the previously mentioned errors of up to 5 m.

Figure 3. Visualization of cadastral points and boundaries.

Figure 4. Test without using photogrammetric algorithms with reference data. The red ellipse contains the reference mark.

5.2 Usability Assessment

The application proved to be intuitive for the user, while the AR interface indicated that the parcel boundaries are slightly shifted in the real world. Under certain conditions, the durability of the virtual overlays becomes problematic. If the AR environment has issues due to lack of light, for example, virtual boundaries in locations can often result in an unsteady response on the screen, which would impact the overall user experience. This issue can also occur when the GNSS data is not accurate and consistently provides different positions.

The AR application provides an immersive experience, which may enhance user interaction. Additionally, the performance of the AR application varies across different devices. While the Google Pixel 6 offers a stable and smooth AR experience, other devices may encounter issues.

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5.3 Advantages of the Prototype

The advantages of the prototype include:

- Sufficient accuracy (up to half a meter)
- Real-time dynamic visualization of cadastral information
- Automated data preparation processes
- High immersion achieved through terrain anchors and light consideration
- Customized visualization of boundary points based on data precision and reliability metrics

6. Discussion

6.1 Implications for Cadastral Applications

Augmented reality (AR) represents a potential breakthrough technology for cadastral visualization. This method of overlaying parcel boundaries on the earth’s surface at specific locations could improve measurement planning, parcel review processes, land surveying, and urban planning. However, to fully utilize this technology in professional settings, improvements in user positioning accuracy and AR stability are necessary.

These technologies have the potential to offer possibilities for intuitive visualization of georeferenced data. It could empower citizens to visualize cadastral data through AR without requiring prior experience. Additionally, AR can visualize planned changes in urban planning, enhancing decision-making processes and increasing public involvement.

6.2 Challenges and Future Improvements

While the prototype demonstrated the viability of using AR for cadastral visualization, several challenges have been identified that need to be addressed in the future. Most importantly, consumer smartphones have issues with Global Navigation Satellite System (GNSS) positioning accuracy. To address this, there could be advancements like using precise reference data for visual correction or implementing real-time kinematic (RTK) positioning.

The current prototype does not account for physical object occlusions, which can obstruct virtual boundary views and significantly affect realism. However, poor implementation might make it difficult to locate boundary points within vegetation. Future versions could consider advanced depth perception or LiDAR technologies during product development to identify these occlusions and adjust the hidden visualization, such as by using dashed boundaries, to improve immersion.

In terms of user interaction, improvements could be made by allowing users to manually adjust virtual reference data to align with real objects. This feature would enable the adjustment and minimization of any misalignments and GNSS errors, leading to better usability and precision.

While the current data preparation workflow generates a CSV file for testing purposes, this process could be automated in the case of future large-scale applications, such as through API queries using JSON data.

While this prototype currently uses bounding boxes as an efficient solution, a more accurate method should be applied in a production environment. Using bounding boxes can sometimes overestimate an area, particularly when parcel shapes are irregular. In the future, a solution could replace these bounding boxes with more accurate algorithms that provide better precision as the user moves along parcels.

7. Conclusion

This study has clearly demonstrated the potential of AR in cadastral visualization. A prototype developed for the real-time visualization of cadastral geospatial data has highlighted how AR is able to expand the current aspects of presenting spatial data, especially with enhanced user experience by immersive real-time interaction with georeferenced cadastral data. It has significant implications for fields such as land surveying, urban planning, and any application involving spatial data interaction.

However, AR for cadastral applications is not without its limitations. One of the most crucial limitations is the accuracy of estimating the position on consumer devices. Because this is important for the correct alignment of virtual data into real-world locations, further development of GNSS technology or further integration of additional services, like RTK positioning or correction data coming from systems such as SAPOS, will be needed to achieve results for solutions using AR-based applications. Improving imaging analysis and algorithms can also increase the accuracy.

The prototype is an effective tool for visualizing cadastral information, especially in those locations where accurate reference data exists and GNSS precision is sufficient.

In a productive development, a number of the analyzed limitations must be critically reassessed and solved. These include performance optimization, refinement of the handling of boundary objects, and extension of methods for data integration. Ensuring these issues are resolved will be important for the development of a stable and efficient application. By reducing these disadvantages to the lowest possible level, the prototype develops into a tool for productive use.

Future developments of AR-based cadastral visualization will also focus on scalability and using emerging technologies. The fact that web applications are gaining importance, web-based AR solutions will have more accessibility and cross-platform compatibility. In the future web applications could provide the same functionality and quality as native applications but with the added advantage of easier deployment and updates.

New technologies should be continuously assessed since improvements in hardware, software, and algorithms might achieve better performance. For example, new developments in GNSS, AR and geospatial data processing can increase the precision immensely.

In conclusion, AR has the potential to change the way people visualize and interact with geospatial data. The insights obtained from this study provide a solid foundation for future advancements and innovative applications in cadastral visualization using AR.

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