Mobile Outdoor AR Application for Precise Visualization of Wind Turbines using Digital Surface Models

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Abstract: Realistic visualizations illustrating the visual impact of planned large structures and buildings in the landscape are challenging and often difficult to create. In this paper, a mobile outdoor augmented reality application is presented that enables realistic and immediate on-site visualization of planned wind turbines at their intended geographic location superimposed on the live camera image of mobile devices. For this purpose, a manual localization procedure is described that uses 3D geospatial models (e.g., digital surface models) displayed in the camera view to enable precise global orientation and positioning of the mobile device resulting in very realistic AR visualizations. In addition, the functions, implementation details and evaluation results of the mobile application are presented.

1 INTRODUCTION

Geospatial data in Geographic Information Systems (GIS) are an important basis for planning, monitoring and controlling work processes in business and public administration. Mobile Augmented Reality (mAR) offers a new Graphical User Interface (GUI) paradigm (Höllerer & Feiner, 2001) for even more intuitive and versatile geospatial data display and manipulation in the immediate application context (Hugues et al., 2011): with mAR, geospatial data are superimposed directly into the camera image of a mobile device, overlaying the real environment, e.g., to display previous factual states, target values, or planned actions in the live image during planning and acquisition tasks (Langlotz et al., 2012; Schall et al.,, 2009). Due to this true-to-life representation of geospatial data directly in the camera view of the real environment, there is an enormous potential to make work processes with geospatial data in the field easier, more efficient, and more effective (Fuchs-Kittowski & Burkard, 2019).

Mobile AR visualizations are therefore also a suitable tool for flexibly showing the visual impact of planned large structures and buildings (e.g. skyscrapers, bridges, power lines etc.) in the landscape on site. Compared to traditional forms of visualization (e.g. paper-based photo montage), AR visualizations allow a direct view of the impact of such buildings on landscape aesthetics, on-site, immediate, and from multiple angles.

This paper presents an outdoor augmented reality application that enables accurate and realistic three-dimensional visualization of planned wind turbines (WT) in real time on site in the camera image of the mobile device in the user's immediate environment. The application is intended to support landscape planners and wind turbine project planners in their work process as well as to contribute to improving public information and acceptance. The AR display offers an advantage over current visualization techniques, as low-threshold information about the impact of planned wind turbines can be obtained by any person and is not limited to pre-defined view positions and number of images.

A great challenge for building realistic mobile AR scenarios is precise global localization of the mobile AR display. This is necessary for accurately displaying the virtual 3D model of the wind turbine on-screen at their actual planned geographic location. To address the global localization, this application uses widely available 3D geospatial data, including

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digital surface and terrain models as well as digital 3D building data. This 3D data is processed into small-scale 3D tiles and displayed in a live AR camera view. Using two common mobile touch gestures (drag and pinch-zoom gestures), the generated virtual models can be interactively aligned to match the actual perception of the real environment eventually enabling robust and precise global localization.

Therefore, the two key contributions of this paper are: 1) The presentation of a flexible user-aided localization technique using 3D geospatial data, e.g. digital surface models, and 2) the presentation of a mobile application for AR-based visualization of planned wind turbines illustrating the functions of the app based on the designed user interface, results of the implementation and the evaluation of the app.

The paper is structured as follows: In the following section 2, the application scope of the app is outlined and the development of the app is motivated. Then, in Section 3, the state of the art in research and technology for the visualization of wind turbines as well as for the realistic representation of virtual objects in outdoor environments using mobile augmented reality is presented. Then, in Section 4, the architecture of the mAR app system is presented and important design decisions regarding geospatial data integration, AR calibration, and realistic visualization are described. In Section 5, the functions of the app are described based on the design of the user interface. Finally, key aspects for the implementation (Section 6) and evaluation (Section 7) of the app are presented. The paper ends with a summary and an outlook on further research in Section 8.

2 SCOPE AND MOTIVATION OF THE mAR APP

In order to achieve climate protection goals, a steady expansion of renewable energy plants and thus also the planning and construction of new wind turbines are part of possible climate change strategies. Although a majority of the population in Germany finds the increased use and expansion of renewable energies important (Agentur, 2019), large sections of the local population are often rather dismissive of concrete plans for new wind turbines. Reasons for this negative attitude include uncertainty and fear of impending adverse effects from acoustic emissions (noise) or visual emissions (lighting, shadows cast) or from feared changes to the landscape (Hübner et al., 2019). However, the actual impacts of new facilities (e.g., landscape impacts) often remain unclear to many non-experts and may also be influenced by misconceptions or faulty representations. Measures to achieve a higher understanding of such projects within the local population are therefore necessary.

An important tool is therefore a realistic and objective representation of the effects of planned construction projects. In addition to traditional visualization methods (static photo montage/ simulation/construction sketch), mobile augmented reality (mAR) technology offers an innovative and novel method to make planned projects mobile and tangible on site in the real landscape. In this way, a mAR application could provide a realistic picture of the impact of new wind turbines on the landscape from any position within the planning phase of new wind turbines. Therefore, in order to avoid a possible influence by erroneous reporting or faulty representations, the developed mAR application should start as early as possible in the planning phase of new wind turbines.

Furthermore, with the help of such an application, additional functions (evaluation, communication, feedback) could be realized and further information (technical data of the plants, etc.) could be communicated in order to enable a transparent design of the planning process. The main users of the application would be residents near planned wind farms as well as municipalities or municipal authorities and engineering and planning offices.

3 STATE OF RESEARCH AND RELATED WORK

3.1 Visualization of Planned Wind Turbines

Photorealistic visualizations of construction projects have so far usually been created in advance with the help of "special software" on a PC, for example by photomontages, e.g. with Photoshop (a virtual model is retouched into a real landscape photograph), or by 3D simulations in virtual landscape models, either by visualization tools within established planning software (e.g. 3D animator of the planning software "WindPro") or by specially developed software solutions (e.g. 3D analysis in the Energy Atlas of Bavaria (Nefzger, 2018)). While such visualizations provide a relatively realistic view of planned construction projects, the creation of these graphics usually has to be done by "experts" in advance. Furthermore, the visualization is limited to certain previously defined viewpoints (e.g., in the case of photomontage) or purely virtual environments (e.g., in the Energy Atlas of Bavaria).

3.2 Mobile Augmented Reality for the Outdoor Area

With the help of mAR applications, visualization can be done "on site" using commercially available smartphones; the integration of the virtual content takes place within the real landscape view at any location on site, so that an even more realistic impression of possible landscape changes caused by the construction project on site is possible.

AR applications and developer SDKs for realistic AR display of virtual objects or information at close range ("indoor") are established and work quite reliably and robustly, for example for displaying virtual furniture in one's own home (e.g., the app IKEA Place). The idea of mAR-based representation of virtual objects outdoors (mobile outdoor AR) has also been analyzed and also implemented in several other projects. For example, several example applications for mobile outdoor AR visualizations can now also be found in the environmental field (see e.g. (Burkard et al., 2021) and (Rambach et al., 2021)). Many of these applications visualize virtual content outdoors but within a known, small-scale environment, e.g., for AR-based visualization of flood hazards (Haynes et al., 2016) or 3D visualization of historic (Panou et al., 2018) or planned buildings (Zollmann et al., 2014). For precise registration of the mobile device within the known, local environment as a prerequisite for correct placement of virtual AR content in the camera image, this can be done by relying on artificial markers or natural reference images (e.g., house facades) known in advance (Haynes et al., 2016; Panou et al., 2018) or 3D models (3D point clouds) of the environment created in advance (Zollmann et al., 2014).

In contrast, the realistic representation of information at a specific geographical location within a large-scale environment (e.g., planned wind turbines) is particularly challenging: This requires not only local tracking of the mobile camera for a stable AR representation, but also precise localization with respect to a global geo-coordinate system (geo-localization; global registration).

3.3 Methods for Global AR Localization and Registration

Applications for outdoor mAR rendering of geospatial objects often do not use image-based localization methods for global registration, but **simplified positioning methods** primarily based on GPS signal and digital compass (location-based AR). However, these methods are too inaccurate to enable precise 3D visualizations (Schmid & Langerenken, 2014). Therefore, a realistic visualization of the impact of new wind turbines is not possible with such AR technology. While accuracy can be increased by using external D-GNSS receivers for precise positioning, using such external sensors for mobile AR visualizations would be complex and costly (Schall et al., 2013).

Image-based Global Localization Methods (SLAM-based) represent a more elaborate but precise approach to realistically display virtual geospatial objects in the outdoor real world at correct geographical positions. However, this would require a high-resolution georeferenced 3D point cloud of the entire environment to be available or created in advance (Zamir et al., 2018; Kim et al., 2018). Due to the high effort required to create, store, and deploy such 3D models for large areas, these AR positioning approaches have so far only been used and explored in selected urban areas (e.g., Google Maps Live View).

Alternatively, already available georeferenced data (e.g., 3D terrain models, 3D city models) can be used for global registration of the mobile device, e.g., for automatic image-based (SLAM-based) global localization using 3D building models from OpenStreetMaps datasets (Liu et al., 2019). Other approaches use digital terrain models for global image-based registration, e.g., by automatically matching the horizon silhouette (Baatz et al., 2012) or automatic image tracking of prominent terrain points (Brejcha et al., 2020). However, the functionality of these automatic image-based tracking approaches is limited, in part because these image recognition approaches only work accurately in mountainous, prominent environments with distant views or are constrained by other general conditions, e.g., the presence of planar house facades.

In contrast to such automatic image-based registration strategies, few approaches are found that use **user-driven forms** of AR-based interaction to register mobile devices in global reference systems. For example, Kilimann et. al. implemented a method to align virtual AR markers with highly visible, manually defined landmarks while correcting for a single rotation angle of the global camera orientation (Kilimann et al., 2019). As an alternative to point-based reference markers in the environment, available **3D geospatial models** can also be reshaped and incorporated to allow manual **geolocation** using these models. Combined with image-based tracking methods (SLAM) at close range, realistic AR representations, e.g. visualizations of virtual wind turbines, can be created. This approach is also part of current research and was developed as part of the implementation of the app presented here. Similar to the method presented here are the **manual, touch-based AR registration approaches** presented by Gazcón et al. (Gazcón et al. 2018) and the method used in the commercially available PeakFinderAR application (Soldati, 2021). However, compared to our system, both systems are limited to mountainous environments with coarse terrain models and do not use additional local image-based tracking for greater stability.

3.4 Systems for AR Visualization of Wind Turbines

For the mAR-based visualization of planned wind turbines, no practical systems are available on the market so far.

A first app for AR visualization of wind turbines was already available in the UK in 2012 by the company LinkNode (Hoult, 2012). Although this app performs localization solely based on the internal localization sensor technology of the mobile device and the visualization is therefore quite inaccurate, the potential of such mAR application could be demonstrated, as significant improvements in the assessment possibilities of the impacts of planned wind turbines by laypersons could be shown (Szymanek & Simmons, 2015).

In addition, only two other prototype implementations are now known from research projects: First, an implementation by LandPlan OS GmbH (research project "MoDal-MR", https://www.landplanos.de/forschung.html; Kilimann et al., 2019), in which global device registration is performed by manual calibration using point-like reference markers (e.g., church steeples) in the landscape that have to be defined manually. On the other hand, a prototypical visualization tool exists from the project "Linthwind" of Echtzeit GmbH and ZHAW Switzerland (https://echtzeit.swiss/index.html#projects_AR). In this case, a manual global device registration is performed based on previously defined mountain peaks of the environment. Both systems are prototype applications with basic functionalities whose practical suitability has not been investigated in more detail.

4 GEOSPATIAL DATA INTEGRATION AND LOCALIZATION

The main goal of the proposed localization method is to use 3D geospatial models as a virtual aid for efficient user-assisted global registration.

Accurate determination of global camera position and orientation (global camera registration) is not only a requirement for this mAR app (see requirement R3 in Section 5), but a key requirement for accurate AR visualizations in mobile outdoor AR applications in general. In the system presented here, a novel user-assisted registration method - developed by the authors of this paper (Burkard & Fuchs-Kittowski 2020) - was used, which uses georeferenced data to accurately register mobile devices with respect to a global geographic reference system. In this method, the calibration of the device pose is based on visible objects, e.g. on the terrain. Digital terrain, 3D building and surface models are integrated and used for this purpose. The user manually moves - via two common mobile touch gestures (drag-touch and pinch-zoom gesture) - the projected model of the environment (e.g. terrain model) on the screen so that it matches the actual real-world view in the live camera video. This user-controlled shift of the virtual environment thus results in a correction of the global device position and orientation.

This section describes the underlying technical design of the mAR application for visualizing planned wind turbines. For this purpose, the architecture of the mAR app system is presented and important design decisions regarding the geospatial data integration as well as the geospatial data-based AR registration and calibration are explained.

4.1 Architecture

The technical architecture of the designed mAR application is roughly sketched in Figure 1. The architecture consists of the following three main components:

1) mAR Client: the mobile AR client represents all components of the mobile AR application on the mobile device, these include:

- **mAR Application:** This application-specific component implements all the required user interface (UI) functionalities to operate and control the mobile mAR application (see GUI design in Section 5). It also controls the server communication for retrieving and administering the required geospatial data. To realize these functions, the application component uses several application-independent components (Local Storage, GeoCMS as well as GeoAR Library).

- **Local Storage:** Previously stored AR views, 3D models of the wind turbines as well as temporarily stored calibration data are stored locally within the AR client and can be loaded from there into the mAR application.
- **GeoAR Library:** This client-side library provides all necessary GeoAR core functionalities (placement and manipulation of virtual wind turbine models) as well as functions for device calibration (geo-localization). The technology used for device calibration is presented in detail in section 4.3.

2) GeomAR-CMS: The main task of this server-based component is the storage and administration of geospatial data needed to run the mAR application. For this purpose, this server component provides:

- on the one hand, **interfaces** to add, modify, and retrieve application-specific geospatial data (e.g., wind turbine data) as well as geospatial data needed for device calibration (e.g., 3D terrain models) (REST API and GUI front-end for administration), and
- on the other hand, a **database** for persistent storage of geospatial data.

3) Pre-processing Pipeline for Geospatial Data: Since 3D geospatial data for device calibration is often not initially available in formats suitable for immediate server-based storage and AR integration, the overall system also includes an offline component to convert the 3D geospatial data into smaller-scale 3D tiles that can be efficiently displayed as a 3D model (3D mesh) in the mobile AR client (see Section 4.2).

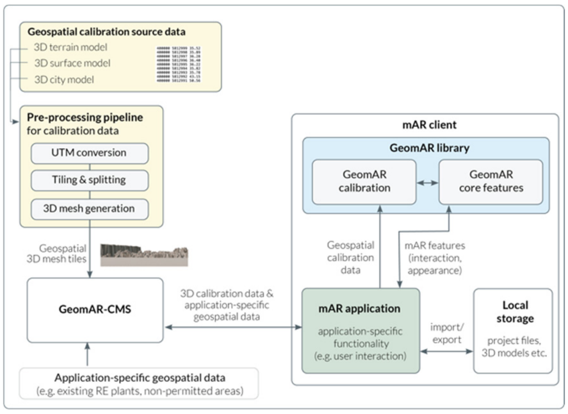

Figure 1: Architecture and interfaces of the mAR app.

4.2 Geospatial Data Pipeline

The component for converting 3D geospatial data into AR-enabled 3D models for manual AR calibration is designed to support three different types of 3D geospatial data that virtually represent the user's outdoor environment, each with different properties and resolutions:

- **Digital Surface Model (DSM):** 3D point cloud commonly acquired by LiDAR systems to model the earth's surface including immobile objects (vegetation, buildings).
- **Digital Terrain Model (DTM):** Description of the earth's surface excluding vegetation and man-made features.
- **Digital 3D City Model:** three-dimensional description of building outlines (3D building models).

Both the type of geospatial data used for calibration and the extent of the area covered by the virtual models can be determined by the user based on the spatial nature of the environment (e.g., rural vs. urban) and the availability of each geospatial model (e.g., 3D city model in urban areas and 3D terrain model in mountainous areas with distant views).

Usually, 3D data is provided in text-based form by GIS data providers. To convert them into 3D models suitable for AR display within the mobile AR client, several conversion steps are required:

UTM Conversion: First, the source data is transformed into a Universal Transverse Mercator (UTM) coordinate system that uses a metric grid (meter).

Tiling & Splitting: For more efficient data handling, the source files are then split into smaller parts with defined square dimensions. This way, when rendering the virtual user environment, the mobile client only needs to load and process tiles with smaller file sizes. This processing step employs a customized naïve tiling approach without incorporating open standards for 3D tiles.

3D Mesh Generation: Using incremental Delaunay triangulation (Heckbert & Garland, 1997), the generated 3D tiles are finally transformed into optimized Triangulated Irregular Network (TIN) surface meshes with different levels of detail. Wavefront OBJ is used as the target file format for the textureless 3D meshes.

Storage in GeomAR-CMS: These obj files are finally stored in the server-based management system (GeomAR-CMS) together with the associated metadata (position, size and type of 3D tile). From there, they can be provided to the mobile AR client on demand.

4.3 AR Registration and Calibration

Accurate determination of global camera position and orientation (global camera registration) is a key requirement for accurate AR visualizations in outdoor mobile AR applications. In the system presented here, a novel user-assisted registration method was developed that uses georeferenced 3D data to accurately register mobile devices with respect to a global geo-reference system (geo-coordinate system).

Before starting this user-driven calibration process, suitable 3D geospatial models of the user environment are first loaded as calibration data from the GeomAR-CMS. An initial rough estimation of the device position and orientation is possible using the localization sensors (GNSS receiver for rough position determination and IMU sensor for rough determination of the device orientation) installed in the mobile device (see Figure 2).

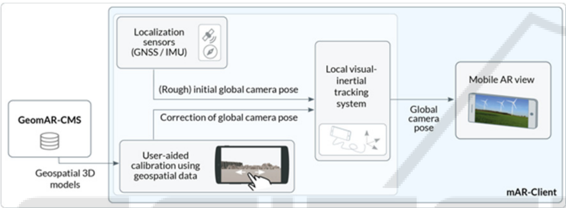

Figure 2: Real-time registration and tracking system.

Thus, the 3D geospatial models can be displayed as a rough - but usually still very flawed - virtual 3D projection of the user's environment in the camera image, e.g., as a rough virtual representation of the terrain surface structure or the 3D structures of nearby buildings. Then, the user manually moves the projected 3D environment on the screen to match the actual real-world view in the live camera video. Using two common mobile touch gestures (drag-touch and pinch-zoom gestures), the generated virtual models can be interactively aligned to match the actual perception of the real environment (see Figure 3.):

- A **drag-touch gesture** (one finger) can be used to move the virtual geospatial model on the screen, resulting in a rotation correction of the global camera orientation.
- A **pinch-zoom gesture** (two fingers) can be used to scale the virtual geospatial model, resulting in a correction of the global camera position.

This user-controlled shift of the virtual environment thus leads to a correction of the global device position and orientation. In addition, a state-of-the-art image-based tracking system (visual inertial odometry system; VIO tracking) continuously tracks device movements in the local space in the background. This ensures a consistently stable AR projection of the virtual user environment without drift effects.

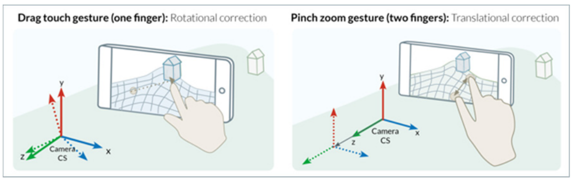

Figure 3: User interaction gestures for aligning the virtual geospatial data models to correct global camera orientation (left) and position (right).

5 MOBILE AR-APPLICATION FOR THE VISUALIZATION OF WIND TURBINES

The following section will describe the functionalities and interface design of the mAR app for 3D visualization of wind turbines in the landscape. The functionalities and graphical user interface were developed based on requirements identified in discussions and workshops with representatives of user groups. A structured overview of the collected requirements is presented in Table 1.

Table 1: Functional requirements for a mAR app for visualization of planned wind energy plants.

No.	Requirement
R1	Placement of planned wind turbines on map and in camera image.
R2	mAR visualization of planned wind turbines as a 3D model.
R3	Precise and correct placement of AR content in camera image.
R4	mAR visualization of wind turbine rotor movement in 3D model (animation)
R5	Simultaneous mAR visualization of multiple planned WTs.
R6	mAR visualization of meta data of a planned wind turbines
R7	Modification of the appearance of the planned wind turbine (model type and height)
R8	Modification of the orientation and location of the planned wind turbines
R9	Consideration of non-permitted areas when placing wind turbines
R10	mAR visualization of planned wind turbines as POI markers
R11	mAR visualization of already existing renewable energy plants as POI markers
R12	Local import/export of the current mAR planning configuration
R13	Video recording of the current AR view

Table 1: Functional requirements for a mAR app for visualization of planned wind energy plants (Cont.).

R14	Mobile AR hardware without special sensor technology (commercially available smartphones/tablets)
R15	Server-based data provision and online capability.

With the designed graphical user interface (GUI) of the mAR application for visualization of planned wind turbines, all essential functional requirements were implemented. The designed screen designs as well as their interrelationships are shown in Figure 4.

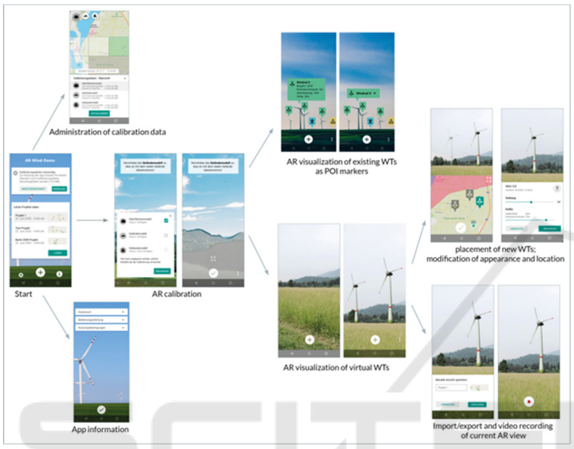

Figure 4: Graphical user interface (GUI) designs for a mobile app for mAR visualization of wind turbines.

They are briefly described in the following:

Start Screen: This is the first screen after launching the application. It provides a quick selection of the last saved AR visualizations (AR projects), the option to open the calibration data management and view app information, and the option to start the main AR functions (visualizing virtual wind turbines as well as AR information about existing renewable energy plants).

Calibration Data Management: Before AR rendering of virtual content is possible, AR calibration data of the environment (e.g., 3D geospatial models) must be loaded. A dedicated screen provides expert options for custom display, loading, and activation of individual calibration data.

AR Calibration: As prerequisite for precise AR visualizations a manual calibration needs to be performed to precisely register the AR display globally. During calibration, the AR view is to be aligned via user interaction so that the virtual view and the real view match. This is done by moving the virtual calibration objects (3D geospatial models). The user can also open a settings menu in the AR calibration view to determine the type of calibration data to be displayed. After manual alignment is complete, the user confirms the calibration, which launches the main AR view.

View Virtual Wind Turbine Models in the Landscape (AR Main View): On this main screen, one or more wind turbines are displayed using AR visualization at specified geographical positions in the camera view. Depending on the distance, the display is either a 3D model or a POI. From this main view, further functionalities related to AR visualization of wind turbines in the landscape can be started via button.

Adding a New Virtual Wind Turbine to the AR View: In the AR main view, a new wind turbine model can be added in the user's field of view via button. Clicking the "New wind turbine" button will automatically add a standard wind turbine model directly in the user's field of view to the AR view.

Changing the Location (Position) of the Wind Turbine Model: Via a map view, the position of the placed virtual wind turbines can be adjusted manually. Unsuitable areas are marked accordingly on the map via map overlay. By moving a wind turbine icon in the map view, the global position of the virtual model changes. This is immediately reflected in the AR view.

Changing the Appearance of the Wind Turbine Model: The user has the possibility to change the size (height), the orientation (rotation) as well as the model of the virtually placed wind turbines in order to view or compare the effects of wind turbines with different appearance or height. For this purpose, the user selects a placed wind turbine model in the AR view or the map view, so that a wind turbine settings menu appears. There, a 3D wind turbine model can be selected from a list of predefined 3D models and the size (hub height) and orientation can be specified.

Loading and Saving AR Projects: The current AR configuration, i.e. the wind turbine models (location and appearance) currently placed in the AR view, can be saved as a project file in order to restore and view this AR configuration at another time and/or location.

View Existing Renewable Energy Plants as AR POI Representation: The user has the possibility via button in the start screen to view meta-information about relevant renewable energy plants in the surrounding area as POI-AR representation to get an impression of availability and type of renewable energy plants in the surrounding area. When clicking on an AR POI marker, the marker view expands with additional meta-information about the selected plant. Clicking on a "list button" opens a (non-AR-based) list view of renewable energy plants in the surrounding area.

6 IMPLEMENTATION

The presented components for the realization of the mobile application were implemented for usage on commercially available smartphones and tablets within predefined test areas (Land Berlin and region Augsburg). Users of the application thus receive an impression of the potential impact of newly planned wind turbines on the landscape within these areas.

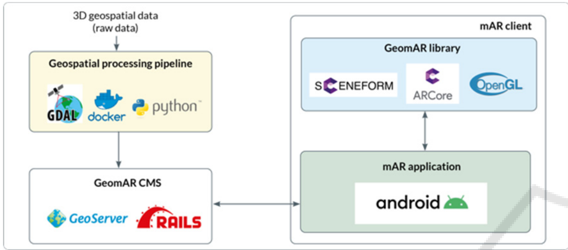

Figure 5: Technologies used in the implementation of the mAR system.

The app was implemented as a native Android mobile application that can run on commercially available mobile devices with built-in IMU and GNSS sensors and using Google ARCore SDK as a local VIO tracking system. The rendering of the AR content in the camera image was realized OpenGL-based using the Sceneform SDK. The raw data of the 3D geospatial models for AR calibration were provided by the Bavarian Surveying Administration (LDBV) for testing purposes as part of the research work. Alternatively, the - often freely available - raw data of other state surveying offices can be integrated in the same way.

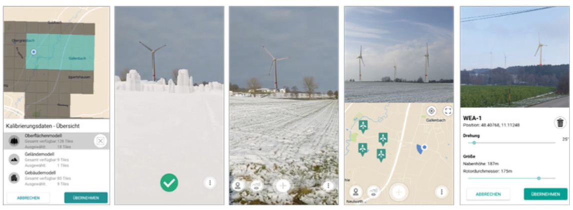

Figure 6: Screenshots from the mAR app - manage calibration data, move 3D geospatial models, display wind turbine as AR visualization, place wind turbine, modify appearance of wind turbine.

The geospatial data pipeline was realized based on open-source tools for geospatial data processing, in particular based on the GDAL library. These tools were encapsulated in Docker containers and automated using Python scripts. The GeomAR-CMS for geospatial data management, storage, and provisioning was implemented based on the GeoServer software and using a Ruby-on-Rails web framework. Figure 5 shows an overview of the technologies used in the system. Screenshots from the implemented application can be seen in Figure 6.

7 EVALUATION

The functionality of the mAR app as well as the GUI were developed from the very beginning in cooperation with representatives of the target user group. In initial tests with potential end users, the app was evaluated positively. In particular, the realistic visualization as well as the correct, robust positioning of the wind turbines were emphasized. In particular, the high degree of realism is achieved due to the positionally accurate integration of 3D environment models leading to correct considerations of possible occlusions of the wind turbines through vegetation, terrain or buildings.

The additional manual effort for the user required for calibration, i.e., correcting the position and orientation of the wind turbines, was rated as acceptable. This manual effort does not make the app as easy to use as users would like, but due to the inaccuracies of the sensors on commercially available mobile devices, such additional calibration effort is mandatory to ensure correct visualization. While this provides a source of error due to incorrect use, similar user errors can occur with other visualization methods (e.g., photomontages). The experimental results have nevertheless shown that the user-driven calibration approach - combined with a robust local VIO tracking system - can achieve efficient and accurate global registration of mobile devices in various outdoor environments and with reasonable user effort, determining the device's orientation with less than one degree deviation.

Also, our approach enables a fast global registration solution as the shifting of the pre-loaded virtual environment models to the correct on-screen position can be achieved ideally within a few seconds. This process therefore is not simpler and more straightforward, but also more time-saving compared to other similar manual calibration techniques, e.g., the approach developed by Kilimann et al. (2019) where the user has to manually select suitable landmarks as reference points on a map and before moving them in the camera image to the correct position.

8 SUMMARY AND OUTLOOK

The objective of this paper was the development of a mobile mAR application for the visualization of planned wind turbines. For this purpose, the functions of the mAR app were designed, implemented and evaluated. In particular, the underlying technical concepts of the geospatial data pipeline for the generation of AR-suitable 3D geospatial models and the global registration approach for correct positioning of the mAR objects in the camera image were explained.

The major advantage of a mAR app - especially compared to classical visualization processes - lies in an easier and immediate visualization on-site in the real application context. Using the example of the visualization of planned wind turbines, this more flexible visualization technique could be clearly demonstrated. However, this advantage could also be used for further mAR applications in the renewable energy sector, e.g., for the mAR representation of planned power lines or photovoltaic systems.

Limitations of the proposed solution arise from the complexity of the geospatial data incorporation as well as the partial lack of availability of such data. In order to make the geospatial data available for large-scale areas, large infrastructure has to be available to manage and provide these data. In this work, the application has only been tested in a small test area as the focus was on the technical feasibility and the implementation of the functional requirements.

In order to achieve greater practicality and appeal to broader user groups, the next step would also need to focus more on usability - especially for non-experts. In this context, a more intensive user evaluation is planned in the next step to identify and implement optimization approaches for better usability and to make the calibration process easier and more user-friendly. These possible further developments also include the idea of integrating and testing additional types of geospatial 3D models, e.g., textured colored surface and city models.

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