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ORIGINAL ARTICLE

Smart Vidente: advances in mobile augmented reality for interactive visualization of underground infrastructure

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Abstract Many civil engineering tasks require to access geospatial data in the field and reference the stored information to the real-world situation. Augmented reality (AR), which interactively overlays 3D graphical content directly over a view of the world, can be a useful tool to visualize but also create, edit and update geospatial data representing real-world artifacts. We present research results on the next-generation field information system for companies relying on geospatial data, providing mobile workforces with capabilities for on-site inspection and planning, data capture and as-built surveying. To achieve this aim, we used mobile AR technology for on-site surveying of geometric and semantic attributes of geospatial 3D models on the user's handheld device. The interactive 3D visualizations automatically generated from production databases provide immediate visual feedback for many tasks and lead to a round-trip workflow where planned data are used as a basis for as-built surveying through manipulation of the planned data. Classically, surveying of geospatial objects is a typical scenario performed from utility companies on a daily basis. We demonstrate a mobile AR system that is capable of these operations and present first field trials with expert end users from utility companies. Our initial results show that the workflows of planning and surveying of geospatial objects benefit from our AR approach.

Keywords Mobile augmented reality · 3D GIS · Geospatial interaction · Location- and context-aware computing · Surveying

1 Introduction

Many industries, such as architecture or civil engineering, experience the need for managing their geospatial data during the whole life cycle of their assets; especially private and public utilities are already largely relying on geospatial databases for daily operation to manage their subsurface assets. The management of underground infrastructure is of major interest as it is the backbone of modern civilization. Poor utility location and management practices during the whole life cycle from design, construction and maintenance can increase property damage. We experience that utility works can cause significant daily disruptions to road users. This additional congestion represents a substantial social cost, while the environmental costs of congestion are well researched. Therefore, utility management methods that do not account for these costs impact economic, social and environmental sustainability. In practice, there is a noticeable gap between desktop geographic information systems (GIS) technology available in the office and access to this information in the field. As field operation is labor intensive and hence costly, improved technology for this area has a large potential in savings and improved productivity.

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1.1 Motivation

Recent advances in sensors, embedded microsystems, wireless communications and the like have led to the evolution of the next generation of distributed computing platforms and allow for novel approaches for the representation of data, interaction with data and acquisition of new data. Augmented reality (AR) is an emerging user interface technology that has the potential to provide significant advances for the field of civil engineering. AR is a user interface paradigm aiming at superimposing registered 3D graphics over the user's view of the real world in real time. In 1997, Azuma defined augmented reality as the extension of a user's perception with virtual information. It has three main characteristics: combining real and virtual elements, being interactive in real time and being registered in 3D [1]. Mobile AR is particularly suited for on-site visualization of geospatial data in a variety of industrial settings such as factory planning, as-built documentation or civil engineering.

Classically, utility companies use 2D maps for on-site inspection of underground assets, involving the tedious task of locating assets correctly. The purpose of maps, geographers know, is to model reality. The *Nature of Maps* [14] defined a map as a "graphic representation of the milieu." The use of the term *milieu* is interesting because it suggests much more than the flat, static maps users are familiar with. It presents a challenge to step beyond the comfortable reach of 2D representations to higher dimensions of visualization. To model reality most clearly, it certainly makes sense that users strive to map what they actually experience. Today, the established way to use GIS in the field is through paper plans, which are plotted as needed and manually annotated on a construction or maintenance site if changes are made. There is a certain trend toward 3D GIS that has not evolved as much as the area of 3D visualization. However, in the utility sector, the need to work with paper plans and the fact that underground assets are normally hidden have limited the interest in 3D GIS. Nevertheless, the real environment visited by planners and field workers is still three-dimensional.

Planning and surveying of new geospatial objects are recurring tasks for GIS users. Our vision is to simplify these tasks to allow for planning and surveying in one step. As this task requires multiple steps on-site and in the office, experts are needed to perform surveying, which is time consuming. AR can simplify such tasks by presenting an integrated view of the geospatial models in 3D and providing immediate feedback to the user and intuitive ways for data capturing, data correction and surveying. Location awareness and visualization of invisible information are additional valuable features.

Toward the realization of such a novel on-site field information system based on AR technology, the project *Smart Vidente* has the ambitious goal to provide a simpler, yet more appealing way to address outdoor applications such as asset localization, contractor instructions or surveying. Although the proposed technology can be applied to general geospatial data and objects, our domain is the utility industry operating underground infrastructure.

Despite recent technological advances, developing a functional mobile AR system to be used in an unprepared environment is a considerable challenge. Solutions require high-accuracy data and precise positioning of the user and their relation to the hardware to ensure correct registration between reality and the data to be augmented. The paper addresses these system design and issues by using a user-centric approach implementing industrial scenarios defined with industry partners. We explain the needs and characteristics of the high-level architecture and the components of an AR system that allows for highly interactive possibilities. Due to the complexity of such a system, the focus of the work is on the aspects that are the key enablers for building industrial applications. Therefore, accuracy and registration issues are discussed in more depth than, for example, visualization or model generation issues that are separately covered in Zollmann et al. [27].

1.2 Contribution

1. To realize our vision of performing real surveying tasks for civil engineering using AR, we present a novel fully functional mobile AR prototype fulfilling the high requirements in terms of ergonomics, performance, accuracy and interaction demands for an outdoor environment.
2. One key enabler of the system is the tracking solution, which needs to be highly accurate for centimeter-level registered overlays. This is achieved by combining sensors using Real-Time Kinematic Global Positioning Systems (RTK GPS) and vision-based techniques. Based on the tracking solution, we give quantitative and qualitative results of the measured re-projection error, when superimposing geospatial objects on the users view. Moreover, the accuracy of surveying geospatial objects using the AR prototype is investigated.
3. We implemented various AR applications for planning, surveying and multi-views. The main focus was on the industrial tasks of planning and surveying of geospatial objects, because these are recurring and important tasks in civil engineering. Using these AR applications, the on-site use cases developed in industry workshops can be successfully addressed by allowing a more intuitive interaction.
4. We demonstrate the elegance of the surveying approach by presenting a novel workflow aiming at the confluence of planning and surveying tasks. The

presented work allows for a very high degree of interaction that could not be achieved in previous prototypes. For testing the practical relevance, the system has been tested in the field with existing databases held by large Austrian utilities in a number of on-site tests involving real-world users.

2 Related work

GIS have been available since the late 1970s by then running as monolithic stand-alone systems. In the 1990s, GIS shifted toward desktop-based, but still stand-alone, applications. Recent developments show an increasing integration of GIS into enterprise-wide solutions where GIS communicates directly with other systems by means of Web services. In recent years, a trend toward mobile GIS and 3D GIS is observable. Moreover, web-based GIS, which is the process of designing, implementing, generating and delivering maps, geospatial data and GIS on the Web, is becoming more popular [19].

Mobile GIS extends geographic information systems from the office to the field by incorporating technologies such as mobile devices, wireless communication and positioning systems. Mobile GIS enables on-site capturing, storing, manipulating, analyzing and displaying of geographical data. Geographical interfaces have been moving toward more media- and graphics-rich applications for some time now. *Google Earth or Microsoft Bing Maps* can be seen as a generic 3D GIS platform, portraying the environment in 3D, using aerial imagery for landscape detail, with an open format for additional georeferenced content. It has been extended to mobile platforms with limited features.

Recently, mobile AR has gained interest as an emerging application type. AR systems need accurate registration to match graphics with the real world. The Touring Machine was one of the first mobile AR systems, tracking positioning and orientation with differential GPS and a magnetometer [3]. Tracking accuracy can be refined with so-called hybrid-tracking methods as shown in [17]. AR systems have been implemented on low-end devices such as cell phones [8] and higher-end systems, such as *Tinmith* by Piekarski et al. [10], King et al.'s [6] work for outdoor environments and Schall et al.'s [18] work for civil engineering. Reitmayr and Drummond [11, 12] were among the first to provide robust tracking using vision-based techniques for urban AR applications. Among systems using AR specifically for environmental issues, prototypes have been developed by White [25], Veas et al. [24] and Kruijff et al. [7] for on-site visualization of environmental data in outdoor environments for hydrologists.

Shin et al. [23] identified potential application areas of AR in the architecture, engineering and construction (ACE) industry and suggested its feasibility. The realization of the use of AR in this industry also needs the validation of its suitability next to a demonstration of feasibility. Shin et al. present eight work tasks (layout, excavation, positioning, inspection, coordination, supervision, commenting and strategizing) that can benefit from AR due to their visual information requirements. There are two major issues to be addressed for introducing AR into the ACE industry. First, there are technical issues. For example, tracking the users viewing orientation and position is a crucial factor for accurate registration of the virtual objects in the real-world scene. Another issue is to identify application areas where AR can significantly improve the performance. The work tasks need to be clearly analyzed and be implemented in pilot projects.

As large social and safety costs are associated with disruption to construction works and traffic, caused by intrusive utility location excavations, related research is performed by Rogers et al. [15] in the *Mapping The Underworld* (MTU) project. They started the development of *Subsurface Utility Engineering* (SUE) as a process for combining civil engineering, geophysical prospecting, surveying and data management to be able to sense the correct location of underground pipes using hybrid sensing technologies. The next logic step is to visualize such correct geospatial data models on-site using AR. Roberts et al. [13] were among the first to propose the use of AR for the visualization of underground assets. Furthermore, Schall et al. [16, 18] built the first practical AR system for experimenting with the visualization and mobile spatial interaction with underground infrastructure.

Hakkariainen, Woodware and Rainio describe a real-time AR system for the visualization of 4D CAD and *Building Information Models* (BIM) information by adding a time component to the visualization [5]. Moreover, Golparvar-Fard et al. [4] propose a fully automated approach for construction progress tracking and as-built model visualization using unordered daily construction images collections as well as BIM.

3 Interactive planning and surveying of geospatial data with augmented reality

3.1 Use case analysis

To understand the typical tasks concerning geospatial data in the utility sector, we held a series of workshops with industry experts and end users to develop practical use cases and ground our work in real-world application scenarios. For in-depth understanding of the workflows practiced in the utility sector, we observed employees of several companies over a full working day (see Figs. 1 and 2).

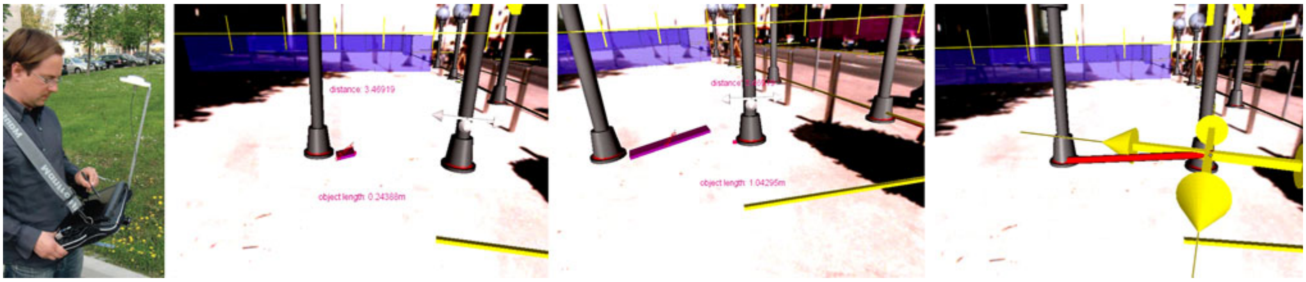

Fig. 1 Augmented reality visualization of infrastructure assets. *Left* User with a mobile augmented reality setup. *Middle–right* The geospatial model of infrastructure networks is superimposed onto the view of the street. While a new *line* is surveyed by laser measuring two points on the street surface, the corresponding preview geometry shows the resulting shape to the user

Fig. 2 Observation of practical workflows employees of utility companies

In addition to the on-site observations, a use case analysis has been performed. During the project, we followed a user-centered design process and conducted regular design workshops with end users.

We found that the following tasks have great potential for the use of AR: data quality control, on-site trench inspection, correction or surveying of assets, identification of assets via their position, documentation of damaged assets and the spatial visualization of complex and planned infrastructure.

We also found that integration of interactive visualizations into a typical field worker's set of tasks and tools would provide little direct benefit. The current surveying workflows distinguish strongly between projected planning data and as-built data. Planning of utility networks is usually done in an office using a desktop GIS. In a further step, a plan of a new trench has to be verified on-site before being submitted to the corresponding authorities. This task is traditionally accomplished by taking paper maps to the field and annotating them. Subsequently, the trench is built and then surveyed using a tachymeter. In the office, the surveyed points are integrated into the GIS, where the actual trench is re-constructed from the measured points, independently of the already available planning data. Thus, the visualization of the planned data is usually separated from the as-built, surveyed information. Furthermore, there is no re-use between the planned geometry and the surveyed geometry, leading to repeated work and potential for errors.

To address this inefficiency shown before, we propose a planning/surveying workflow that directly embeds the interactive AR functions and re-uses the geospatial data optimally for visualization and interaction.

3.2 Surveying workflow with AR interaction

Instead of strictly distinguishing between planned data and surveyed data, we propose a surveying workflow that is based on the planning task. Surveying becomes then the update of planning data for the documentation of the

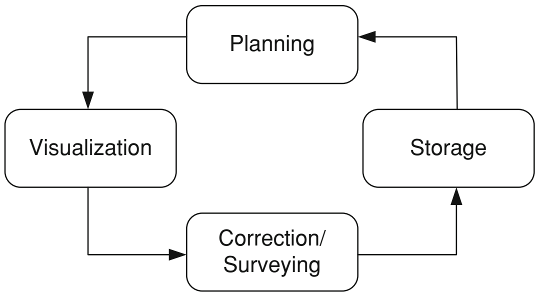

Fig. 3 Round trip of GIS data realized in the Smart Vidente AR application

Table 1 Use cases identified in expert workshops and the mapping of the use cases to the system round trip

Use case	Planning	Visualization	Correction/ surveying	Storage
Data quality control		X	X	X
On-site trench inspection	X	X		
Correction/ surveying of assets	X	X	X	X
Identification of assets via position	X	X		
Documentation of damages	X	X	X	X
Visualization of planned infrastructure	X	X		

as-built situation. Thus, the planned object is updated with the surveying data on-site. Post-processing in the office is not needed anymore.

Figure 3 shows the proposed workflow that specifically focuses on the building blocks *Visualization* and *Correction/surveying* and the connections to *Planning* and *Storage*. In a GIS, the planned data are available in a *planning layer*, which is available on-site as an interactive AR visualization. Next, the planned data are duplicated into a *surveyed layer*, which can be adjusted to the actual situation in the surveying task. In the following, the new layer can be manipulated. This new layer is then reconciled into the GIS and represents the actual as-built object. A novel aspect in this round trip is that the user is presented a preview geometry of the geospatial object while surveying it.

All use cases analyzed in the workshops with the industry partners can be mapped using this round-trip system (see Table 1). We also see that some stages may be disregarded for individual use cases. However, the general system can also support these simpler cases.

Which requirements exist to realize our vision? In workshops with potential users, we learned that for realizing the round trip, research needs to address the following topics:

- Automatic and efficient generation of 3D models based on legacy data. 3D models need to contain all semantic information that is also available in the legacy data.
- Tracking of the mobile user needs to be stable, robust and accurate in position and orientation. This is necessary for accurately registering the geospatial 3D models on the real world. The accuracy of the overlay must be better than 30 cm to allow field workers determining the asset's position.
- Flexible visualization requires the rendering of complex 3D models of underground infrastructure in a way that is easily comprehensible and useful to the mobile worker. There should be the possibility to change visualizations interactively based on both geometry and semantics.
- Interaction techniques are needed to support the correction and surveying procedures performed on the mobile device.
- The most challenging and promising goal is to perform true surveying tasks with AR user interfaces. For example, users should be able to survey water pipes, gas pipes, electricity lines and walls, etc. on-site and create digital assets representing them. During the surveying task, the user is presented a live preview geometry of the asset currently surveyed and reconciled to the database via a round trip. This immediate feedback can reduce the number of errors made in surveying and thus improves data quality.

3.3 System design

Developing future applications is always a dual challenge: how to take a major technological leap while still meeting the needs and expectations of the final application users. Traditional usability research focuses on evaluating user interfaces of the prototypes after the system is finished. To adapt to a user-centric design approach, we included utility companies continuously at several stages to develop the system. In the project *Smart Vidente*, we designed a system architecture realizing a mobile AR system fulfilling the discussed requirements.

Figure 4 shows the system design and data flow between the geospatial database and the mobile AR system. The data flow supports a round-trip workflow moving and transcoding the GIS data between a geospatial database and the mobile AR client. The three-dimensional geometry to be shown is not available per default, but is extracted from a conventional database system and interpreted on-the-fly

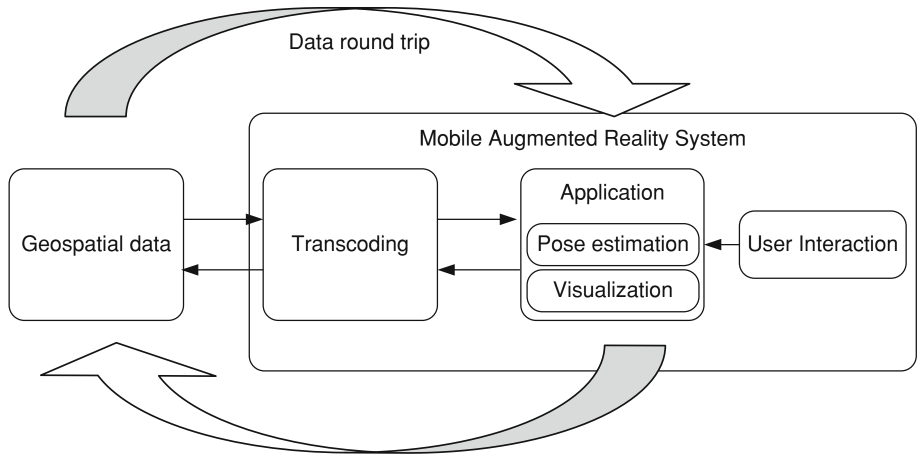

Fig. 4 Smart Vidente system architecture

as a 3D visualization (described in Sect. 5 in more detail). *Smart Vidente* supports interactive annotation and surveying tasks in the field, so the system allows updating information in the geospatial database.

We developed a number of visualization techniques to display geometric as well as non-geometric information from the geospatial database, in particular of hidden objects—such as underground installations—through the so-called "X-Ray vision." These visualization techniques need to be adaptive to scene complexity and environmental conditions (see Sect. 5). The information shown represents either as-built surveyed from any surveying layer or planned data for new structures.

Novel interaction techniques enable updates to the surveying layer. We integrated a laser range finder into the AR setup for providing a 3D cursor to select and manipulate the virtual objects. The laser range finder was modified in a way that it can be connected via USB and delivers its measurements directly to the application. Users can select and move objects interactively until they match the actual situation. In the same way, new geospatial objects can be created from measured 3D points. The resulting geometry is used for the integration into the geospatial database and simultaneously for visualization on the mobile device. Mobile AR offers immediate feedback to the user, thus reducing errors and enabling faster and more reliable quality control of data (see Fig. 1).

Figure 5 shows the AR prototype hardware setup that we built around a tablet PC (Motion J3400) with 1.6 GHz Pentium CPU and sunlight viewable touch screen for real-world, field-ready outdoor conditions. The tablet PC platform is equipped with various sensors such as a camera, a 3DoF orientation sensor, and a Novatel OEMV-2 L1/L2 Real-Time Kinematic (RTK) receiver for achieving a positional accuracy within the centimeter range. The tablet PC-based setup was received very well from end users because devices with this form factor are already in use in industry. So, they felt more familiar with the setup than

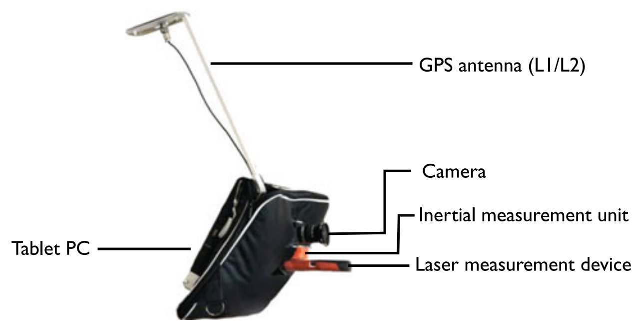

Fig. 5 The tablet PC–based AR setup and individual sensors

with a more experimental one providing more interaction possibilities. AR capability can then be reached by following a "sandwich" approach by simply mounting the sensors on the backside of the tablet PC. Section 7 describes the positioning approach used to achieve accurate 3D registration in outdoor environments.

The proposed workflow allows bridging the gap between the office and the field. Section 9 presents solutions how the different use cases can be realized using a mobile AR interface.

4 From geospatial data to semantic 3D models

According to Schmalstieg et al. [22], geospatial models for AR should be organized along a pipeline with generation, data representation, visualization and use. This suggests treating data representation and visualization of this geometry differently. In this sense, real-time 3D visualization and manipulation of geospatial objects requires a somewhat different data model than traditional geospatial data models. Abstract line and point features need to be processed to create 3D geometry representing more the actual shape than the surveyed line of points. Additional visualization geometry such as virtual excavations are

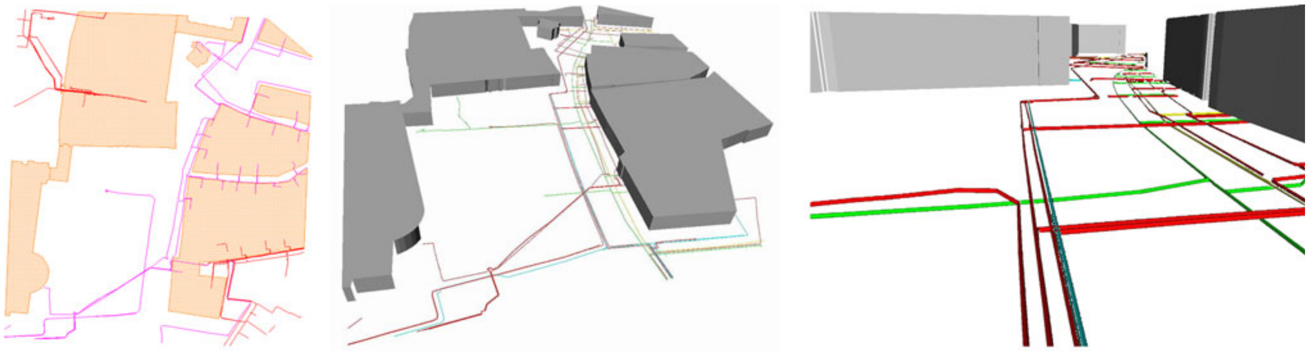

Fig. 6 Geospatial data of an area in the city of Salzburg, that is, the area around the residence. *Left* 2D view in the GIS. *Middle–right* 3D model including extruded building footprints and underground infrastructure networks

automatically derived from the stored data and used in advanced visualizations. All of these geometries need to be interactive and mutable, so that interactive manipulation allows an update of the features. Finally, the semantic information stored in the geospatial database is required as well on the mobile client to support filtering, display and editing of feature properties.

To support these operations, we developed several components that implement the conversion from GIS features to 3D data and back. A transcoding operation using a commercial tool extracts and translates geospatial data into a simpler common format for the mobile AR client, listing a set of features and their geometries. The client further filters the features for specific properties and applies transformations to generate 3D data from them. The 3D data structures are functionally derived from the geospatial data and stay up-to-date when it changes. Interactions operate directly on the feature data updating simultaneously the 3D visualization and features. The 3D data structures (see Fig. 6 middle—right) contain all geometric and semantic information stored in the underlying GIS database (see Fig. 6 left).

5 On-site interactive visualization of geospatial data

As the focus of the paper is on presenting the novel AR system as a whole with its special capability of interactive surveying and planning, visualization aspects are only described briefly for completeness. Research results on visualization topics of the system are described in [27].

Basically, the on-site visualization of underground infrastructures in interactive applications poses several challenges:

- Changing requirements between users and applications: How are objects visualized to meet the user's or application's needs? Which kind of color, shape or model is used to represent a specific type of object? The visualization should help to provide an understanding the data representation.
- Generic AR visualization requirements: Which kind of scene composition techniques is used to convey a comprehensible arrangement of virtual and real objects in the augmentation? How to provide depth cues or correct occlusions? How to avoid clutter in scenes with various virtual or real objects?
- Flexibility for editing operations: How can visualized objects be maintained flexible during an editing operation? It is not sufficient to generate geometries in advance; geometries should automatically adjust to data changes.

To approach these needs, we need a flexible visualization pipeline to accommodate the different requirements. A comprehensive visualization of the data is very important, especially for complex visualizations such as augmentations of underground infrastructure. Using simple overlays for visualizing underground objects via an X-Ray view can cause several serious perception issues, such as impressions of underground objects flying over the ground. To avoid these problems in X-Ray visualization, it is essential to either decide which parts of the physical scene should be kept and which parts should be replaced by virtual information or which kind of additional virtual depth information can be provided (see Zollmann et al. [26]).

The main challenge for interactive visualization applications is a flexible data management. Usually, the visualization of data strongly depends on the application, the intention of the application and the preferences of the user and differs in colors, geometry and complexity. For instance, a pipe could be represented in several ways, such as a normal pipe using an extruded circle or as an extruded rectangle to show an excavation around the pipe (see Fig. 7). To be flexible and still provide complex visualization methods for a single set of data, we differentiate between an underlying data representation, which is based on the data coming from the geospatial database, and the

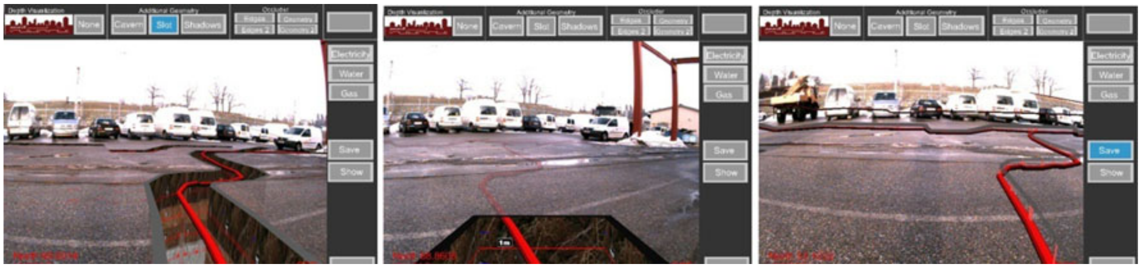

Fig. 7 Different visualizations of the same data of electricity lines. *Left* Simple blended overlay of a pipe using virtual ducts visualized along the pipes. *Middle* Advanced manhole visualization of a similar electricity pipe. *Right* Shadows of the pipes projected to the ground

Table 2 Interaction types. Selection, manipulation and navigation

Interaction type	Method	Characteristics
Selection	Selection of objects	Single or multiple feature-point selection, feature-based selection
Manipulation	Transformation	Constrained, unconstrained
Manipulation	Surveying	Pen-based, laser-measurement based
Manipulation	Creation of new objects	Selection of object type
Navigation	Multi-view	Selection of predefined remote views

visualization geometry, which is used to represent different visualizations of the data and which is directly derived from the data representation.

The implementation of different visualization styles is supported by a filtering-transcoding concept. The filtering step searches for a specific object type, and the transcoder step transforms the data into geometric objects, which can later be displayed by the rendering system. The separation of the two steps allows for a very flexible system that can support many applications. For instance, many civil engineering companies have different rules for visualizing objects. Therefore, colors and default sizes can be adjusted to company or applications needs. This approach of interactively changing visualizations of the geospatial object was proofed very useful.

6 Interaction methods

An important part of the workflow is the manipulation and interaction of geospatial data on the device itself. Tasks that benefit from this direct interaction include planning, inspection and surveying of new structures. Furthermore, in the case of surveying planned structures, we can re-use the planning data directly leading to the proposed round-trip workflow.

All of the tasks above need the support of various interaction techniques. To process a planning step, new objects are created, feature points are surveyed, and planned data are manipulated to fit the on-site requirements. For inspection and surveying applications, manipulation as well as surveying will be the main interaction techniques, but creation of objects may be useful as well, since objects may be undocumented or need to be captured and marked as damaged. For detailed information on the interaction methods, please refer to Zollmann et al. [27].

6.1 Surveying

The on-site AR surveying is a core interaction technique because features can be surveyed directly instead of surveying individual 3D points, re-importing them and reconstructing features in the geospatial database. We propose two different methods for online surveying. Surveying with a laser range finder and surveying with re-projecting the screen coordinates to a digital terrain model.

To support surveying with a laser range finder, we mounted a laser range finder on the bottom of the sensor pack on the backside of the tablet PC. Points measured by the laser range finder are mapped into the global coordinate system and used as input for surveying features points. The laser range finder only provides distances in a fixed direction with respect to the camera view. To map the distance back into a 3D point, the laser range sensor is calibrated in advance with respect to the camera. Furthermore, we developed various interaction types for the geospatial models. Table 2 lists the different interaction types and methods and describe their characteristics.

For illustration of how the interaction works, Fig. 1 depicts a user creating a new pipe in red color using the laser range finder and applying the surveying method. Experiments using the interactive surveying technique showed very promising applicability for on-site surveying of geospatial features.

Fig. 8 Augmented multi-views. The screenshots are taken on the mobile AR system and can immediately be imported into and visualized in Google Earth

6.2 Multi-views

The surveying of new features may be difficult, especially if the feature is exceptionally large. For instance, pipe features may be distributed over large areas, which makes it difficult to measure them directly by laser surveying or screen-based surveying, since start and end points may be not visible from the same camera view. To overcome this problem, we provide a method called multi-views that allows capturing camera views from different positions and switches between these views for surveying features.

Modern technology enables the development of intuitive and highly graphical interfaces. For example, *Google Earth* provides a platform whereby realistic aerial image–embedded terrain models are transmitted progressively, and onto which geospatial data can be overlaid. In addition to using the multi-views directly on-site, the user can apply them for documentation purposes. The screenshots are saved into a KML data file, which can directly be loaded into *Google Earth* (see Fig. 8).

7 Registration in outdoor environments

A major aim was to achieve a highly accurate position and orientation estimate of the AR system in outdoor environments. Typically, GPS is used as the primary tracking system in wide-area outdoor environments. But, GPS only provides a satisfying position estimate when enough satellites are visible to the receiver and when using differential corrections from a reference station network. For orientation estimation, a combination of inertial sensors measuring gravity and magnetic sensors measuring the Earth's magnetic field are employed. However, magnetic orientation tracking in outdoor environments faces a number of challenges due to permanent and transient electromagnetic disturbances.

To fulfill the high requirements of the application scenario concerning positional accuracy, a RTK GPS receiver is employed using differential corrections provided by a virtual base station network. An inertial measurement unit (IMU) with gyroscopes, magnetometers and accelerometers measures orientation with respect to local gravity and the magnetic field. To compensate for environmental electromagnetic influences, an additional drift-free visual tracker is used. Figure 9 shows the multi-sensor fusion system architecture. A dedicated Kalman filter component for position estimation is complemented with an Orientation Kalman filter for orientation estimation. To allow for correction of both deviation and bias, the visual panorama tracker is combined with the IMU in the Orientation Kalman filter.

The Orientation Kalman filter fuses the delivered data resulting in roll, pitch and yaw angles as output. Biases in the sensors are corrected in the Kalman filter. Furthermore, the magnetometer output deviates from geographic north. This can be computed from the GPS location or configured for a specific application area. By online tracking natural features and simultaneously mapping the environment, the visual tracker delivers drift-free and unbiased orientation estimates. Schall et al. describe the approach in more detail in [20].

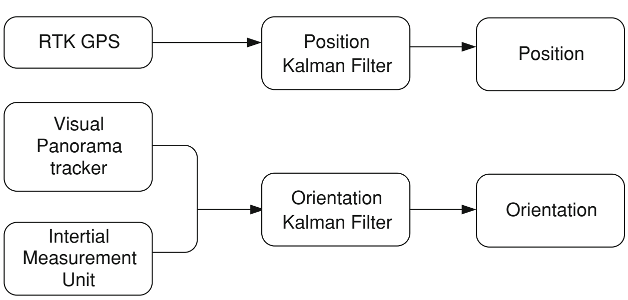

Fig. 9 Multi-sensor fusion system architecture. The architecture consists of the key elements *Position Kalman filter* and *Orientation finite* state machine fusing data from the *Orientation Kalman filter* and the *visual panorama tracker*

7.1 Positional accuracy

A series of measurements with the RTK GPS receiver was performed to evaluate the typical positional accuracy in 3D. As ground truth, surveyed reference points at nearby rooftops at the campus were used. The GPS antenna was exactly placed at surveyed reference points while the position measurements were performed. The EPOSA reference system [2] supplied the differential correction signals. The results of a representative position measurement at a surveyed reference point using the RTK GPS receiver are presented in Table 3. The mean error is in the range from 5 to 6 cm for northing and easting and 13 cm for height. Using this differential GPS receiver in the AR setup, we can assume to achieve positional accuracies with an error of 10 cm or below.

This experiment evaluated the accuracy of the GPS receiver only. But the overall registration error in 3D includes next to the position inaccuracy of the GPS also the orientation errors of the IMU. Furthermore, inaccurate base data from the geospatial database and camera calibration add to the registration (or re-projection) error. Thus, we performed another experiment focusing on assessing the overall re-projection error that represents the finally visible error in the AR display.

Table 3 GPS accuracy measurements of easting, northing and height (in centimeters) using the L1/L2 differential GPS receiver

	Mean	SD
Easting	5.30	1.63
Northing	6.10	1.87
Height	13.60	5.35

Table 4 Mean and standard deviation (in degrees) for the error of the sensors, the vision tracker and the hybrid tracker from both the tablet PC and the phone measurements

	Mean (deg)	SD
Sensors	−1.35	2.80
Vision-based tracker	−0.62	0.80
Hybrid tracker	0.26	0.50

7.2 Orientation accuracy

The absolute accuracy of the hybrid orientation tracker was estimated using a set of surveyed reference points which are known to within-centimeter accuracy. The accuracy of the tracker was measured by aiming the device's camera at one of the reference points from a fixed position and subsequently turning the device toward all other reference points without resetting the tracker. The device was kept still for about 30 s at each reference point, logging the orientations reported by the sensors, by the vision tracker and by the hybrid tracker. A viewfinder glyph was visualized on the device's screen to ensure pixel-accurate alignment of the camera with the real-world reference points in the environment. The measured mean errors from the reference orientations are shown in Table 4.

The hybrid tracker effectively averages over all these errors and produces a better mean estimate than either the sensors or the visual tracker alone. The following results show the behavior when using the devices in a free-hand manner showing the tracker's behavior in a more realistic and dynamic scenario. Figure 10 shows a plot of rotating the tablet PC from one reference point to another (represented by the two dotted lines), through a natural rotational movement. The raw sensors are compared with (1) a Kalman filter running on the sensors input and tuned for low latency and reasonable filtering of high-frequency noise

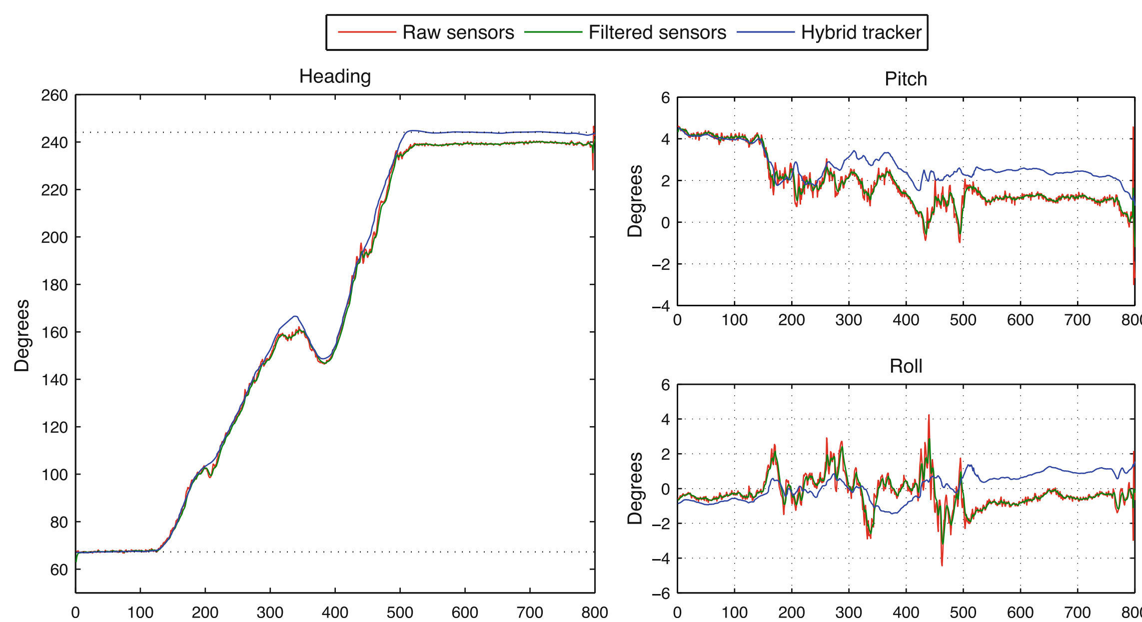

Fig. 10 Plot of heading, pitch and roll for a free-hand movement of the tablet PC between two reference points. Orientation for the raw sensor values, a filtered estimate and the hybrid tracker are plotted

and (2) the output of the hybrid vision sensors tracker. The plot shows clearly that the hybrid tracker achieves the highest precision in obtaining the true rotation angle. Furthermore, it estimates a less noisy trajectory. The proposed tracking approach increases robustness through the redundancy given by visual and inertial orientation estimates.

7.3 Re-projection accuracy

For assessing the overall re-projection error with the mobile AR system, a highly accurate surveyed reference point on a pavement is used as ground truth. The coordinates of that reference point are taken from the GIS, and the reference point is visualized as a green cross with a vertical line. Under perfect conditions (perfect position and orientation tracking with no errors, camera calibration, etc.), the cross would exactly be visualized at the real-world reference point.

To measure the re-projection error, we created a reference grid to compare the visualized location with the real one in the AR display. The grid consists of circular rings plotted starting with a radius of 5 cm for the inner circle and increasing the radius by 5 cm for each outer ring. A small hole in the middle of the plotted grid was exactly placed on the real-world reference point. Then, we took screenshots from a number of positions around the reference point and evaluated the apparent position of the virtual green cross using the grid.

The re-projection error of the reference point is around 5 cm. Figure 11 (left) shows the mean error and standard deviation for the re-projection of the virtual reference point at the real-world reference point as recorded in the experiments. Figure 11 (right) illustrates the offset of the observed positions from the ground truth. We can see that there is a shift westwards of around 5 cm. For more detailed information, please refer to [21].

To perform a complete data round trip, the reference point must be surveyed with the AR system and be reconciled to the database. High-accuracy global pose estimation is essential for assuring the data quality for the round trip.

7.4 Accuracy of interactive surveying

For assessing the surveying accuracy of AR setup, experiments were performed at a known reference point. The reference point was surveyed with the AR setup from more than twenty different positions with different angles.

Figure 12 shows the surveying accuracy results, which are better than 30 cm required by industry. Main reasons for these inaccuracies are orientation errors and laser calibration errors.

8 Expert interviews: interactive planning and surveying

The interactive planning and surveying scenarios have been developed in a series of workshops in a period of several years. The participants of the final evaluations and field trials were end users and had extensive background in the ACE industry. All participants were experienced in their working field and had many years of practical experience. For the single field trials, end users have been chosen who perform the tasks of planning and surveying on a daily basis. Moreover, experts from the management level from utility companies participated. All participants got an introduction and training prior to the tests.

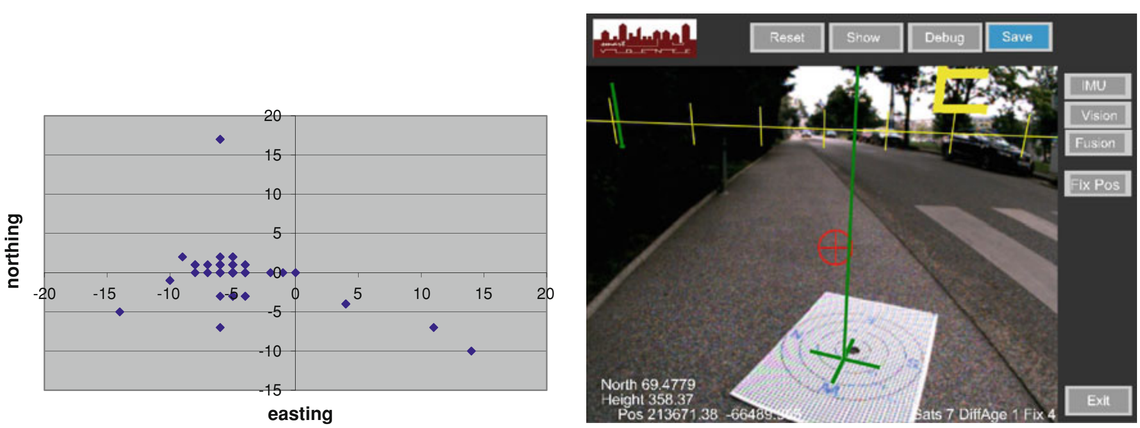

Fig. 11 Re-projection accuracy. *Left* Error distribution of the overall re-projection error. *Right* AR view of a re-projected physical reference point on the pavement using the AR system

	Mean (m)	SD
Easting	0.02	0.19
Northing	0.18	0.14
Height	–0.12	0.16

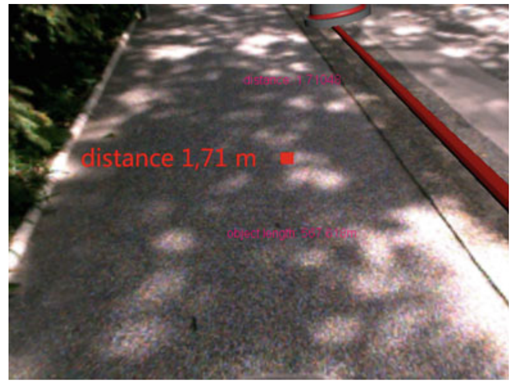

Fig. 12 Surveying experiments with the AR setup. *Left* Quantitative accuracy results. *Right* Example screenshot showing the real reference point on the pavement and the re-projected reference point near the *center of the screen*

8.1 Framework

The important question arose of how to evaluate a mobile AR application in outdoor environments in a meaningful way. Conventional evaluation techniques are not ideal to asses such complex systems in the real working environment. To address this issue, arguments were worked out considering the framework of Olsen [9] who investigated how to evaluate user interface systems that are off-the-desktop and nomadic. This will involve new devices and new software systems for creating interactive applications, such as LBS or mobile AR systems. Simple usability testing or usual studies are not adequate for evaluating such complex systems. Olsen suggests a set of criteria or claims for evaluating new user interface systems. Every new piece of interactive technology addresses a particular set of users, performing some set of tasks, in some set of situations. It is critical that interactive innovation be clearly set in a context of situations, tasks and users.

The *STU (Situations, Tasks, Users)* context forms a framework for evaluating the quality of a system innovation. Before all other claims, a system or interactive technique must demonstrate *importance*. Importance analysis proceeds directly form the intended STU context. The first question is the importance of the user population (U). In this case, the user population consists of field workers who are definitely important for a functioning infrastructure, which is a backbone of our modern lives. Next, the importance of the performed task (T) for the user population must be evaluated. Importance might be established by how frequently the task occurs. It might also be established by looking at the consequences of not being able to do the task. In this case, field workers are performing planning tasks and surveying tasks for infrastructure networks very regularly on a daily basis. Undoubtedly, the consequences of not performing these tasks on infrastructure networks can be catastrophic. Furthermore, the importance of the situations (S) needs to be evaluated. How often do the target users find themselves in these situations and do they need to perform these tasks (T) in those situations? In this case, the situations include planning and surveying activities on the underground infrastructure network. Field workers regularly need to deal with situations such as difficult environments that assets are not obvious or that there is danger ahead. Also, this third criterion for importance of a system interface can be answered with yes as well as the importance of the STU context as a whole.

According to Olsen, tools for creating new user interfaces can be improved by increasing the expressive match of the system. *Expressive match* is an estimate of how close the means for expressing design choices are to the problem being solved. There are several requirements when making a claim of grater expressive match. One must demonstrate that the new form of expression is actually a better match. Frequently, greater expressive match is tied to a claim to lower skill barriers. In the case of performing interactive planning and surveying with the mobile AR system, expressive match is significantly increased, as AR provides a closer match to the real on-site situation by visualizing registered 3D models on-site in real time. Moreover, the integrated 3D visualization provides a much more intuitive interface enabling users that are not familiar with reading maps, to assess the geospatial objects in their surroundings.

The objective *Simplifying Interconnection* is given if the new system under test can be better embedded in workflow than existing systems. This is true for the proposed AR system, because the workflow of typical tasks performed from field workers from the utility sector can be significantly improved. In this context, also the possibility of a loss-less data round trip must be mentioned. Current tasks often involve printing digital information on paper maps, making annotations per hand and typing these annotations into the GIS system when back in the office. The developed AR system can provide a data round trip without a digital gap, and consequently, tasks can be performed more efficient.

8.2 Results of expert interviews and field trials

Figure 13 shows people using the AR system during field trials. For assessing the surveying application, we gathered

Fig. 13 On-site field trials and expert interviews. Testing the AR prototype in real-world scenarios

data in a first field trial from 16 participants (12 m/4f) using a questionnaire. Users surveyed a new object on the terrain. Eleven users had experience with traditional surveying, and five users did not have practical experience. A semi-structured interview was performed evaluating the practical applicability of the tools for their tasks. Early field trials and expert interview were performed with the participants. All field workers confirmed the high potential of AR for time savings and error avoidance for the task planning and surveying. Most importantly, the visualization overlaying the underground infrastructure over the real-world needs to be highly accurate. High priority was given to depth perception of the buried assets, which reconfirmed the expectations. Field workers expressed their wish to see all underground assets buried at one spot, allowing achieving a complete overview. The experts were asked to rate the system using a 7-point Likert scale.

Figures 14 and 15 give an overview of the mean ratings. Users rated the outdoor suitability of the AR system for as-built surveying high (avg., 5.13; SD, 1.14). They stated that surveying with the AR prototype can be performed at least as well as with traditional surveying techniques (avg., 4.43; SD, 1.03). Users with surveying experience rated the prototype better because of the more intuitive interface compared with traditional surveying methods.

The simplicity of surveying new objects was rated higher than with conventional surveying techniques (avg., 5.44; SD, 0.96). AR can support the users with a more easy and intuitive handling of the task.

Visualization techniques were generally rated high, such as *X-Ray view* (avg., 5.87; SD, 1.02), “2D Projection onto street level” (avg., 5.63; SD, 0.80) and *duct along pipe* (avg., 6.19; SD, 0.66). The advantage of visualization techniques is that they improve the perception of the virtual objects, particularly the depth perception.

The effectivity of interaction was rated high (avg., 4.87; SD, 0.81). People stated that the intuitive interface allowed for more effective interaction although people did not have a long training phase with the device. A training phase is typically necessary in order to increase the effectivity in performing a task. Users perceived the usefulness of moving and correcting geospatial objects (avg., 5.31; SD, 1.19) as high as well as the usefulness of the AR application (avg., 5.94; SD, 1.19).

The registration accuracy was rated high (avg., 5.37; SD, 1. 81). Figure 14 shows an example of the registration of geospatial objects registered on the users view in 3D. Results show that users with surveying experience rated the accuracy higher. This may be due to their practical knowledge of in which situations sensors perform well. Users rated the coolness of the AR system as good (avg., 5.13; SD, 1.36). This can be explained by the fact that we did not experiment a lot with interaction possibilities, but rather tried to build an AR setup that has a form factor comparable to the currently used devices. The outdoor suitability was rated mediocre due to the prototype style of the setup (avg., 3.28; SD, 1.20). Although we tried to build the prototype in a rugged way, it cannot compete with devices that are specifically produced for industrial outdoor usage.

Generally, the results show that people with surveying experience rated the AR setup and application higher than people with no relevant experience. Furthermore, participants found that the AR system is suitable for surveying

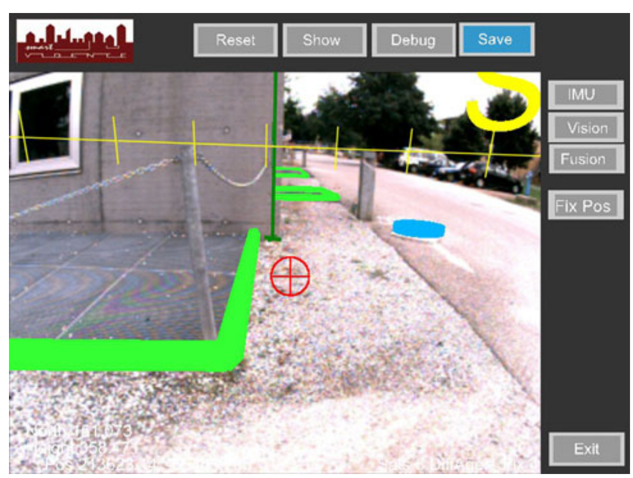

Fig. 14 AR view with superimposed enclosures and base point of the building corner and a capping registered in 3D

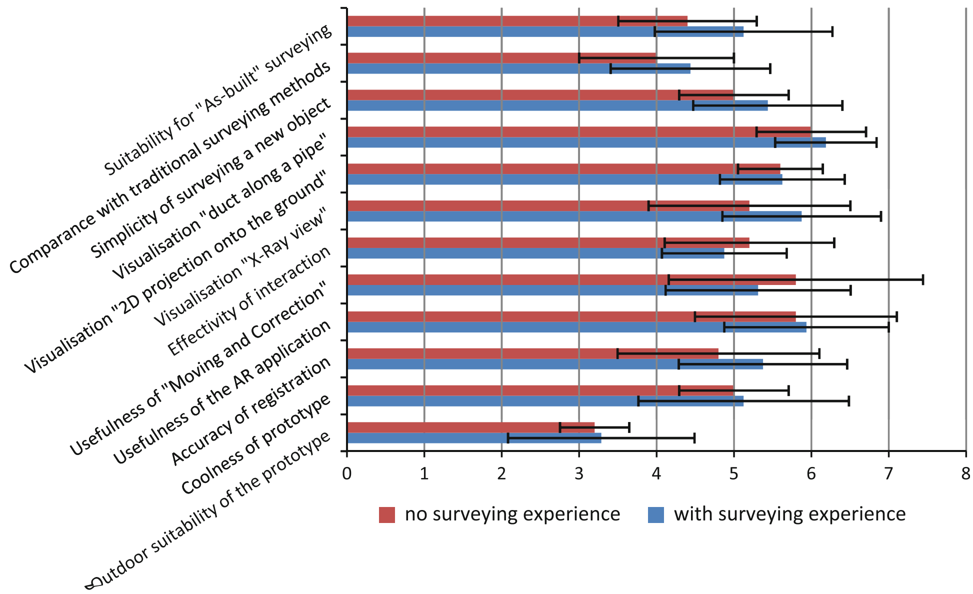

Fig. 15 Results from a surveying field trial

tasks, but simplifies the task compared with traditional methods. The simplification is mainly reached by a more intuitive interaction than with usual surveying equipment. Visualization techniques were generally rated high and useful. The outdoor suitability was rated only mediocre because it is still a prototype setup without a closed industrial manufactured shell.

9 Discussion

If AR is to be taken seriously, tracking must fulfill user demands. With the developed tracking approaches, we could achieve a quality of registration in 3D that was required by real-world users. The requirement for the position accuracy was to be more accurate than 30 cm. We could achieve positional accuracies better than 10 cm and relative rotational accuracies better than one degree.

The main limitations to this approach are the inherent characteristics of the used sensors that are often used in current state of art of AR devices: inaccurate positioning and orientation in unprepared environments, portability issues and lack of depth perception when using monoscopic displays. The presented prototype is the first fully functional AR prototype that fulfills the high requirements for being used in civil engineering task. This is possible through the combination of tracking and surveying accuracy, form factor and interaction possibilities. The results show that there is strong evidence that 3D AR interfaces have advantages over conventional 2D maps in industrial outdoor settings. The system can perform sufficiently well considering the limitations. In work environments where the AR system can achieve its highest accuracies, it is better than conventional methods; especially in terms of workflow improvements, the 3D user interface shows advantages over a pure 2D interface. Considering the results from the evaluations of the AR prototypes, 3D user interfaces emerged as useful extensions to existing interfaces with a realistic potential for improving business processes in civil engineering.

10 Use case coverage

The development of the mobile AR system has been driven by close collaboration with end users from industry. AR has the potential to support and improve work processes with visual demands in civil engineering. First, we look at a regularly performed work process or workflow in the utility industry, where field workers typically have the need to locate geospatial underground infrastructure objects during inspection tasks. Then, examples are presented of how the identified use cases can integrate AR functionality.

10.1 Comparison of 2D map and 3D user interface

Figure 16 (left) shows the workflow of an inspection task using a conventional approach based on 2D maps, whereas Fig. 16 (right) shows the workflow using a 3D AR visualization. This suggests that using AR, the workflow for an inspection task can be simplified.

A GIS database normally employs two-dimensional models to represent the geographic data. Accurate evaluation of a situation from a map and a GPS location requires applying a mental transformation from map to reality. This assumes that the user is familiar with the significance of map scale, generalization and symbol language. In many cases, this cannot be taken for granted. Even users

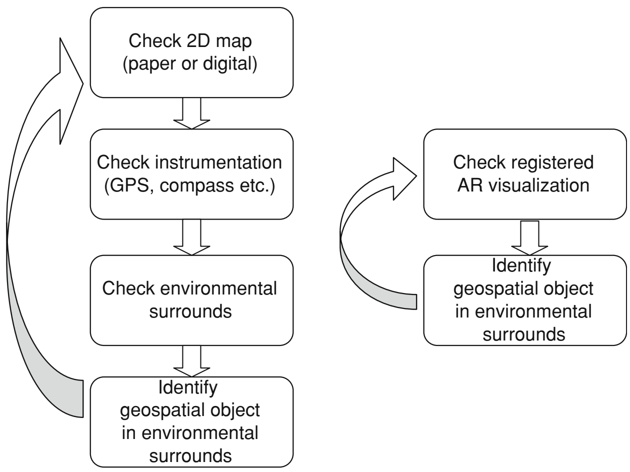

Fig. 16 The workflow of an inspection task to indentify an underground object. *Left* using a 2D map. *Right* utilizing a 3D AR visualization

experienced in map-reading may struggle if, for example, reference surface features are occluded by winter snow. AR thus has the potential to remove the need for a mental transformation from map to reality. Figure 17 (left) shows a digital 2D plan showing underground infrastructure printed on paper. This is what field workers often take to the field for inspection tasks. In contrast, Fig. 17 (right) shows the corresponding GIS features while standing at the position indicated by the red arrow shown. The mobile AR user is oriented toward the direction of the arrow. The AR visualization using a trench along the pipes can convey depth and 3D information better than on a 2D map only.

10.2 Practical use cases

The following section describes how the use cases in Table 1 can be realized using the mobile AR system and technology presented in this work.

10.2.1 Data quality control

Provided accurate positioning the accuracy of legacy data sets can be determined on-site visually. Thus, the visual overlay of legacy data offers data quality control to the user.

10.2.2 On-site trench inspection

Workers in the field have a strong need to locate their assets, for example structures scheduled for maintenance or to ensure safety for digging at excavation sites. Among the procedures that can benefit from employing AR in field work are contractor assistance and outage management. Simple localization is important for the on-site information of contracting staff. For this aim, a registered AR view can provide fast and accurate localization of subsurface assets, thereby reducing risks of accidentally damaging underground infrastructure during excavation. Moreover, AR can provide visual guidance while digging, for example, by means of a dashboard-mounted AR device in a shovel excavator telling the operator where to dig in real time. An important task in outage management is the detection of gas leaks and cable damage. Workers must trace a trench with special sensors such as a *gas sniffer*. Navigation along the trench with a mobile GIS is rather cumbersome. AR can provide a superior graphical overlay view, outlining the trench to follow and highlighting relevant underground assets.

10.2.3 Correction/surveying of assets

In case legacy data do not fit the real situation anymore, the user can interactively correct the 3D models to their correct position. Section 6.1 describes how surveying can be performed using AR.

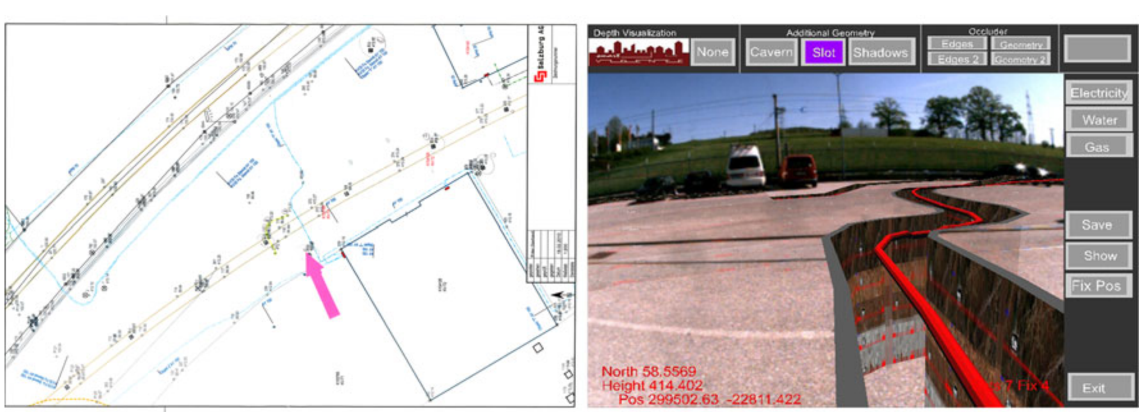

Fig. 17 2D GIS versus 3D AR visualization of the same location. *Left* 2D map showing GIS features. User is located where the *arrow* in the *center of the screen* is pointing. *Right* 3D AR visualization showing subsurface features

10.2.4 Identification of assets via position

Field workers regularly have the demand to identify assets on-site. Using AR, the information about the asset in question can be determined immediately via the position. Having identified the asset, relevant information about it can be presented to the user.

10.2.5 Documentation of damages

Using multi-view techniques, users can take augmented screenshots for documentation purposes (see Sect. 6.2). In principle, the screenshots contain the virtual information correctly registered to the camera image.

10.2.6 Visualization of planned infrastructure

AR can support planning and preparation of digging activities on-site, for example, assisting with spray marking. Moreover, it is an important task to verify the assets, which were projected in the office; on-site AR means that planners can be provided with a graphical overlay of the planned assets and can directly modify the plan to incorporate required changes using mobile spatial interaction tools without the need for any post-processing. The trend in the geospatial community clearly points in the direction of mobile GIS with advanced interaction techniques.

10.2.7 Trenchless digging technologies

Furthermore, trenchless digging presents an additional promising use case. Trenchless digging technology covers any techniques, processes or procedures, including the equipment, machines and materials involved, which minimizes or eliminates the need for surface excavation or reduces environmental damage or reduces the associated costs for underground work. Trenchless digging technologies have the demand for spatial overview because the underground infrastructure is not visible. Providing a solution to this problem, AR can contribute with improving the spatial overview with presenting registered overlays of the underground infrastructure.

This chapter has also shown some of the possibilities that a mobile AR system can provide in civil engineering. Clearly, there are various advantages over a conventional 2D representation, including more realistic presentation of geospatial object, automatic map scale and orientation, interaction and annotation possibilities. To illustrate some of the applications, we additionally provide a video captured at the *GE Digital Energy 2011* conference in Salzburg. The video material was captured from the AR display while performing a planning and surveying task for demonstration purposes in front of the conference hall (see Online Resource 1[1]).

11 Conclusion and outlook

Applying mobile AR to specific workflows performed in ACE industries, we demonstrated the potential for improving workflows such as on-site planning, data capture and surveying through interactive, on-site visualizations. Surveying tasks benefit by the immediate visualization of preview geometries and correction/surveying of the (planned) geospatial objects through showing the known and captured features in context. We evaluated the system successfully with expert users from the utility industry in several field workshops.

To achieve this level of functionality, several technical advances were necessary. In the area of localization, the integration of visual tracking in orientation sensor information demonstrated higher accuracy in measuring the orientation of the device. For visualization of hidden subsurface structures, we demonstrated a set of techniques. Most importantly, the integration of interaction tools for creating, editing and surveying new features shows how planning and surveying structures can be simplified with increased efficiency.

Further research and development of the prototype are currently explored in a set of pilot projects. An aim is to further advance the prototype to industrial needs to realize a novel on-site field information system providing a simpler, yet more appealing way to address specific productive industrial workflows.

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