Towards Computer-Aided Collaborative Subway Track Planning in Multi-Scale 3D City and Building Models

Martin Breunig, Stefan Hinz, Mathias Menninghaus, Thomas Vögtle
Karlsruhe Institute of Technology
Karlsruhe, Germany
{martin.breunig, stefan.hinz, mathias.menninghaus, thomas.voegtle}@kit.edu

Ernst Rank, Matthäus Schilcher, André Borrmann, Ralf-Peter Mundani, Yang Ji, Andreas Donaubauer, Horst Steuer
Technische Universität München
Munich, Germany
{rank, matthaeus-schilcher, borrmann, y.ji, andreas.donaubauer, horst.steuer}@bv.tum.de, mundani@tum.de

Abstract— **The planning of road, railway and subway tracks and similar infrastructure in the urban environment - along with the associated over- or underpass structures - is a manifold task. There are complex legal, environmental, economic and structural conditions to be considered. Furthermore, the number of participants, some with widely differing skills, knowledge and interests is immense. Therefore computer-aided collaborative planning for 3D city and building models is a challenge for the 3D geoinfo community. Even though in practice 2D plans are still the predominent instrument, time seems to be ripe to introduce 3D objects into the planning process right from the beginning. This paper describes the way to facilitate planning processes for subway track planning by developing a collaborative platform supporting the modeling, management, and visualization of 3D multi-scale models. An approach to combine research from the fields of collaborative planning platforms, 3D modeling, spatio-temporal databases, geo web services, and computer vision is presented.**

I. INTRODUCTION

The conception and development of three dimensional urban and building models, including underground structures and infrastructure such as tunnels, underground stations, as well as piping, transmission lines, canals, geological subsurface structures, etc. are a new challenge in the field of 3D geoinformation. The complexity of the planning task will be reduced providing a more appropriate basis for planning activities.

The polymorphic requirements to collaborative city and subway track planning have in common that they refer to geographic space. However, hitherto the planning of cities and especially of subway tracks is not well supported by 3D modeling and collaborative software tools. Especially the synchronous phases of the planning process need more interactive digital support. Furthermore, 3D modeling and the combined management of above- and sub-surface objects is still a challenge for GIS and CAD research.

Recently a researchers group at Karlsruhe Institute of Technology (KIT) and the Technische Universität München (TUM) has been set up to start basic research to address these challenges. For example, new approaches for the interactive 3D parametric subway track planning for multi-scale models and the image supported real time localization in 3D space are examined. Also geo web services and a spatio-temporal database will be involved for the management of heterogeneous planning data. The results are expected to have high relevance for both, research and practice. They will be demonstrated by the scenario of subway track sections and a subway station of a german city guaranteeing the close connection to practice is. A software prototype will demonstrate the implemented functionality.

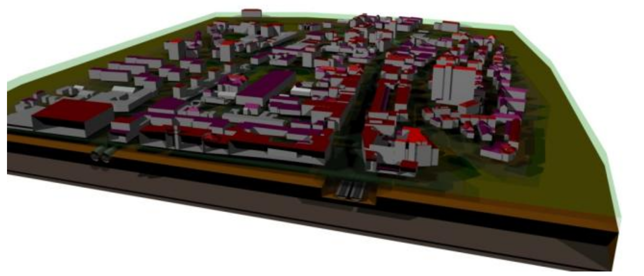

Figure 1. Integrated 3D city and subway model

II. COLLABORATION PLATFORM

One core part of this project is the collaboration platform, which handles all user access to the underlying (geometric) data and cares for the consistency of those data at any time. In contrast to classical CSCW (Computer Supported Cooperative Work) approaches which support asynchronous cooperation, i.e. concurrent 'offline' data manipulation and a consistency check only when submitting modified data back to the database (Sect.4), the collaboration platform aims synchronous cooperation in order to leverage collaborative computational steering, i.e. interactive concurrent data manipulation at the same time (online) with permanent consistency checks. While in the asynchronous case revision systems must be able to deal with design alternatives and different development branches, in our case the requirements on the collaboration platform are somewhat harder.

The major problem of synchronous cooperation is to provide consistency methods that can be carried out in real time. This is an important issue, as in an interactive cooperative scenario all different planners work on the same data at the same time, not necessarily at the same place. Hence, any change that is made by one planner must be immediately visible to all others and should not harm the global consistency of the entire data. Only in that case, collaborative computational steering is possible that allows all participants to interact and, thus, to manipulate shared data in order to jointly elaborate the next step in planning. Such an approach implies the requirement to control and restrict access to the shared data. In our case, the whole model (i.e. geometry and context information) is hidden from the user and can be accessed only via the collaboration platform. Therefore, the platform is designed as client-server-system where communication between clients and server takes place via sockets.

As frequent (model) updates from the clients entail a huge communication advent, here the server might become a bottleneck. A planner - in the beginning - retrieves data from the platform and stores a local copy to be processed. Any change on the local copy is not visible globally until the modifications are communicated back to the server. In order to keep the shared data consistent, an early update of changes is preferable, nevertheless leading to a high communication frequency in case of several planners. On the other side, a late update would save bandwidth and, thus, reduce the communication overhead, but in case of several planners most likely leading to diverging model states. Hence, the latest point in time an update can be postponed is when a user tries to locally access (parts of) data that have already been modified by another user (i.e. his local copy) but those modifications are not visible on a global scale yet. The user trying to access obsolete data must then be interrupted and the updates from the user having the modified copy must be made visible to all clients and the server in order to retain consistency.

Another problem to be addressed by the platform is related to the access of external data sources. As the platform should be able to include external data such as seismic data, geographic information or simulation results during runtime, a 'generic' interface for the data import is necessary. Here, web services are advantageous as the semantic description of the data can be transmitted along with the data itself (see Sect.5). This allows any client to incorporate additional data sources which were practically unknown prior to the integration and consider them during the planning process. Those external data sources are not maintained directly by the framework and, thus, have to be kept consistent via external methods, making the data read-only for the clients. Nevertheless, the possibility of including external (unknown) data sources during runtime is a huge benefit for the planning process per se and opens the door to more detailed and holistic considerations in planning.

In our approach, collaborative computational steering comprises a back-end (server) for the data storage and a visual front-end (clients) for the interactive data processing. Here, the whole spectrum of visualization hardware should be supported ranging from simple monitors to sophisticated immersive stereo equipment such as video walls or CAVEs (Cave Automatic Virtual Environment). Therefore, efficient visualization algorithms for the different types of data are necessary that allow the user to (seamlessly) explore the underlying multiscale models (Sect.3), which is a quite huge challenge on commodity hardware. Problematic are mainly mobile devices (laptops, smart phones etc.) which furthermore do not have a fixed connection to the server (T3 or larger) and retrieve data via WLAN or broad band networks (UMTS or slower). Here, data filtering before transmission is inevitable, especially when considering the limited capacities in memory and performance of smart phones (Sect.6). Such a filtering must happen on the server-side and also fulfill real time requirements.

The collaboration platform - as stated above - is a core part of the entire project which serves all participants and beside real time requirements must provide the possibility of interactive data processing as needed for collaborative computational steering. Data access (also to external sources) and data consistency are two major aspects concerning the design of the platform as well as efficient methods to handle multi-scale models as to be discussed in the next section.

III. MULIT-SCALE METHODS IN 3D CITY AND BUILDING MODELS

In subway planning, completely different scales have to be considered – ranging from the scale of several kilometers for the general design of the subway alignment down to centimeter scale for the detailed planning of traffic nodes. Accordingly, the concept of multi-scale geometric models is an essential issue to adequately support the subway planning process. The use of multi-scale models is a concept well established in the Geographical Information System (GIS) domain [29], and forms an integral part of the respective data exchange standards, such as CityGML for example [21]. However, these approaches focus on static models and primarily aim at supporting their visualization. Accordingly, they are less suitable for multi-scale models used in planning processes where frequent modifications result in high dynamics. Currently there is no sound methodology available to ensure and preserve consistency between such dynamic multi-scale models.

Accordingly, we focus on a methodical introduction of multiscale modeling in the context of subway planning. In a first step, the number of levels-of-detail (LoD) as well as the corresponding geometrical representation on each LoD is defined. Fig.2 shows as an example for the multi-scale modeling of a tunnel section. On the coarsest LoD, LoD 1, the tunnel is represented by only its main axis, while on the _nest LoD, LoD 5, it is represented by a precise 3D model including all planning details. The representations on the diverse LoDs result from different detailing demands in the individual planning stages.

In general, the storage and management of multiple representations of realworld entities involve logical redundancies which have to be carefully handled in order to avoid inconsistencies. This particularly applies when model modifications are as frequent as in an ongoing planning process. An important research aspect therefore is the development of methods for checking and preserving the consistency of the multi-scale models.

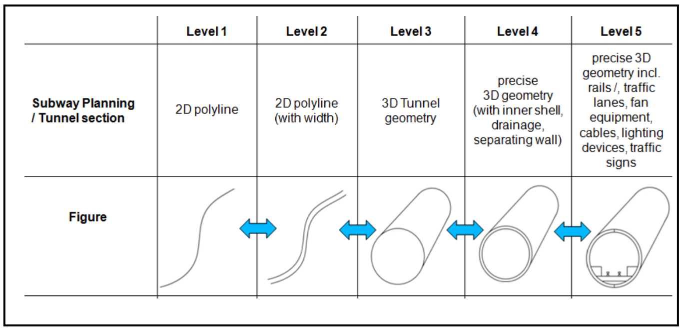

Figure 2. Geometric objects on different LoD in tunnel planning

As a first step towards the realization of multi-scale model consistency we are developing methods for transferring models from finer LoDs to coarser ones (Fig.3). To this end, mapping functions are constructed which are composed of rules for geometric simplification and generalization [15, 17] while preserving the topological consistency of the models.

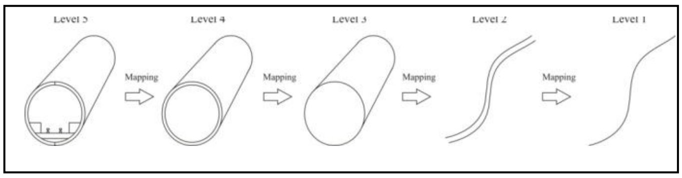

Figure 3. Automated transformation of the LoDs into coarser ones

In the second step, methods for defining dependencies between geometric entities on different levels of detail are developed. These methods allow to preserve the consistency between the representations on different LoDs during a dynamic planning process (Fig.4).

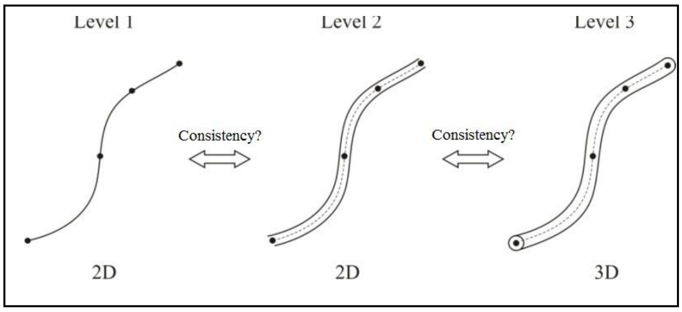

Figure 4. Checking the consistency of different LoD

To realize this functionality, parametric modeling methods are applied which have been originally developed for Computer Aided Design (CAD) applications [19, 33, 37]. They allow to define geometric, topological and dimensional constraints and dependencies between different geometric entities for the creation of flexible geometric models.

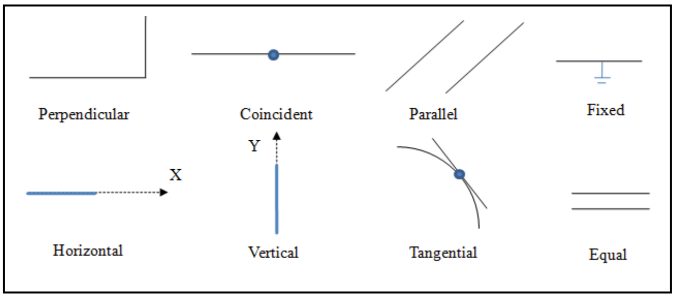

Figure 5. Different types of geometric constraints commonly used in parametric CAD systems

Fig.5 illustrates eight common types of geometric relationships used in parametric CAD, such as line being parallel, perpendicular or coincident. Another feature of parametric modeling is the possibility of defining dimensional parameters and setting mathematical relationships between them. So far, parametric modeling techniques have been applied only within a single geometric model. The methods developed in this project will make it possible to define constraints between different geometric models, namely the representations on different LoDs (Fig.6).

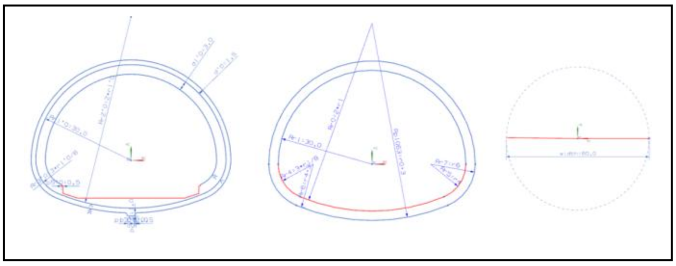

Figure 6. Example of parametrized tunnel cross-sections on different LoDs

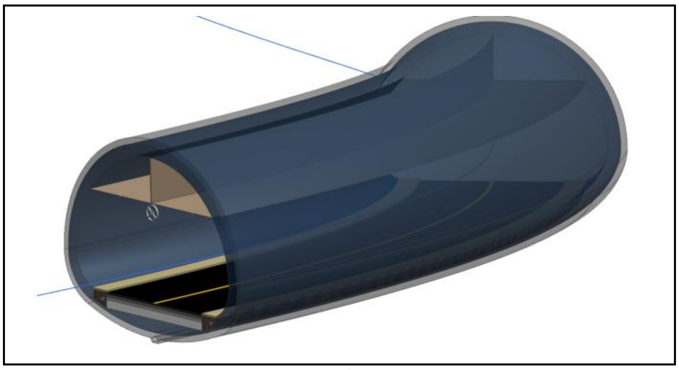

Figure 7. 3D model of a road tunnel section

For the exchange of multi-scale models between different partners or applications by means of a neutral data format it is desirable to include the consistency constraints between the different levels-of-detail in order to preserve the coherence of the multi-scale model. We will therefore develop approaches for extending existing data models (product models), such as IFC or CityGML, by entities that are able to capture geometric and dimensional constraints. Finally, parts of a multi-scale product model for tunnels are developed in order to demonstrate the feasibility of exchanging multi-scale models (Fig.7).

The developed methods for multi-scale modeling and consistency preservation will be integrated into the collaboration platform (Sect.2), the spatiotemporal database (Sect.4) and the system for on-site visualization (Sect.6).

IV. SPATO-TEMPORAL DATABASE

A. Requirements and Objectives

To manage and control a large amount of 3D objects as used in this project it is essential to provide a high performance database. Also the combination of CAD and GIS data including different levels of detail requires new data structures and operations to be implemented in the database. In addition the mobile AR platform (Sect.6) needs a quick access to a subset of data which can be visualized and manipulated on a mobile system in economically justifiable time. When the mobile system is in offline- mode it should also be possible to work on locally stored data and reintegrate it into the cooperation platform (Sect.2) back in online mode.

Therefore we state three main objectives for the implementation of the spatiotemporal database. First we need to analyze the requirements of the other parts of this project developing a concept for the integration of the data model. Second we will integrate these requirements into the geo-database DB4GeO [1, 6, 7] and third we will upgrade this geo-database to a mobile database system which is usable in both, online and offline mode.

B. Using Geo-Database DB4GeO

DB4GeO [1, 6, 7] has its roots in the research on GeoStore, a prototypical system for geologically defined geometries [5], and GeoToolKit, a library of 3D geometric data types [3], at the Collaborative Research Centre 350 at Bonn University. DB4GeO is fully implemented in the Java programming language and is based upon the open source object-oriented database management system db4o [10, 31] using R-Tree based spatial access structures. It has been developed in several projects funded by the German Ministry of Education and Research (BMBF) and the German Research Foundation (DFG) [1, 6, 7].

The underlying 3D data model is based on simplicial complexes, i.e. points / nodes, lines / edges, triangle nets / meshes and tetrahedron nets / meshes. This data model has also been extended to simplicial complexes varying with the parameter time. As well known, simplicial complexes are a special form of cell decomposition, which are especially used for the modeling of geo-objects in geoscientific applications. A special feature of the cell decomposition is the consideration of topology [39]. The decomposition is done with cells of the same type. For instance, a surface decomposition can be achieved with triangles (2-simplex) and volumetric decomposition with tetrahedrons (3-simplex). Simplexes in DB4GeO are topologically classified in the usual way, i.e. towards their dimension: 0-simplex = node, 1-simplex = edge, 2-simplex=triangle, 3-simplex=tetrahedron.

Fig.8 shows the general system architecture of DB4GeO. Upon the object model the operations and service infrastructure are realized. DB4GeO offers several simple geometric and topological web services, such as

- distance between 3D geo-objects;
- intersection between vertical plane and a set of geo-objects;
- calculation of boundary elements in each dimension;
- test of topological relations between 3D geo-objects and simplexes;
- extraction of a 2D representation from a set of 3D geo-objects.

GIS clients may access the database via its web services. Currently the REST [14] architectural style has been implemented. Also the version management is implemented "on-top" of the database and may be used by mobile clients to synchronize with the database [1].

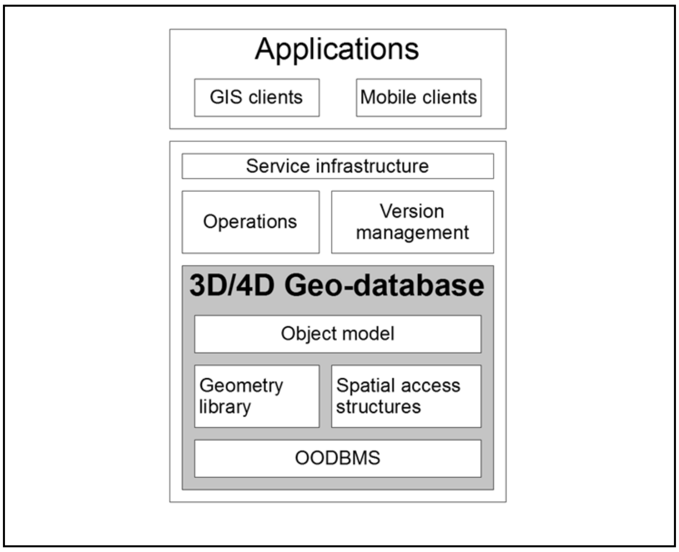

Figure 8. System architecture of DB4GeO

C. Cooperation with Other Components

The spatio-temporal database is planned to act as the backend of the collaboration platform. Therefore it is necessary to integrate other aspects such as 3D modeling and spatial integrity constraints into the conception of the database. Especially it is essential to develop data types and structures that

- fit into the concept of the collaboration platform (Sect. 2);
- support data sets with multiple scales (Sect. 3);

- are easy to access and do not cause high transmission costs (Sect. 5);
- facilitate the implementation of the synchronization for mobile clients with the database and vice versa (Sect. 6).

When integrating the data model for subway track planning into the existing database it has to be guaranteed that there will be no information loss. Therefore it should be considered to extend the underlying data model and search for an alternative to the simplicial complexes. Especially the large memory consumption stands in contrast to the last bullet. Hence the main focus in developing the database is the mobile aspect.

D. Mobile Spatio-Temporal Database Backend

In [22] several options to realize mobile database systems in both environments, with continuous and weak connectivity, are summarized. Most of them concentrate on the handoff management when a mobile device leaves one cell and enters another. However, no commercially used mobile database system supports spatio-temporal data types. Therefore new research will be necessary concerning connectivity of the mobile database and spatio-temporal access to mobile databases.

According to [8] we differentiate between three major types of applications for spatio-temporal data models and query languages i.e. moving objects, discrete changes in shape and position, continuous motion and changes of shape. In this project it has to be examined which of the three types will be relevant for subway track planning applications. Especially the consideration of time in both, the planning and the building process of the subway track is a challenge for future research.

V. ADVANCED GEO WEB SERVICES

A. Problem Statement

The planning of any large-scale inner city building project has to rely on a wide range of different input data sets such as data of existing underground infrastructure or soil properties as well as GIS-analysis functions. The input data is usually provided by different (public) institutions in a heterogeneous form. We aim at making input data available for every involved party in the planning process by developing geo web services providing access to geospatial data and GIS-analysis functions in a homogeneous way. Existing OGC (Open Geospatial Consortium) specifications for web service interfaces have limitations in several aspects regarding the requirements of a distributed, heterogeneous system for collaborative subway track planning which we will discuss in more detail below. We are going to research new methods and concepts for enhancing geo web service interfaces in such a way that they will meet the requirements of a distributed, heterogeneous system for collaborative subway track planning.

B. Limitations of Existing Geo Web Services and Related Work

The following limitations of current standardized geo web service interfaces were identified by matching their capabilities with the requirements of a distributed, heterogeneous system for collaborative subway track planning:

- At the moment there is a lot of work being done on 3D web services. For example there are two drafts for 3D OGC web services: the Web View Service (WVS)[28] and the Web 3D Service (W3DS)[27] which are already in use by several projects such as GDI-3D [35]. On the one hand the major drawback of these two web services is that they are only intended for visualization of 3D-data (by rendering an image on the server (WVS) or on the client, (W3DS) and do not offer functionality for handling "attribute rich geo data" [27] as required by planners.
- On the other hand, in the context of OGC web services "attribute rich geo data" is encoded using GML (Geography Markup Language), which expresses geometry as boundary representations whereas planning tools heavily rely on Constructive Solid Geometry (CSG) and parametric geometries because these representations natively support easy alterations of plans.
- Subway track planning requires 3D filter operators e.g. to carry out 3D collision detection. Topological filters (which can be used for e.g. extracting all objects inside a defined polygon) are defined only for two-dimensional data. Also most of the research dealing with publishing and filtering semantic 3D geospatial data (e.g. [9] and [11]) only uses 2D filters for three-dimensional data.
- In some cases, planning a subway track involves more complex GIS functionality than pure filtering. For accessing an arbitrary GIS functionality using a web service protocol the OGC defines the Web Processing Service interface (WPS). Since WPS is defined very generic there is no real interoperability of web based analysis tools. Their specification lacks in formal definition of analysis operations and their concatenation.
- A planner usually focuses on one aspect and therefore does not need all the available data at a maximum level of detail (LoD). At the moment geo web service protocols do not explicitly support the concept of LoD. Work has been done by [18] in order to develop a web service protocol for accessing a multi-scale geodatabase as defined by [36] again limited to two-dimensional data.
- A system for collaborative subway planning needs to have a well defined spatio-semantic data model. Input data sets to the planning process provided by different agencies through web services need to be harmonized not only syntactically by using a standardized web service protocol and data exchange format but also semantically e.g. by schema translation. OGC web services do not provide any means of schema translation capabilities and research dealing with schema translation and other data harmonization functionality accessed through web

service interfaces is again limited to 2D data in most cases [2, 13, 23, 30, 38].

- When integrating heterogeneous input data sets in the planning process, the data quality must be known. Quality information is usually provided on a per data set or on a per object basis. In a planning process more detailed quality information is needed as for example the accuracy of a part of some object. Furthermore, there is no standardized way of error propagation in nowadays geo analysis tools. Integrating data quality information into a geo web service environment is currently investigated (e.g. [40] and [12]).

C. Research Outline

We aim at developing concepts for advancing geo web service interfaces in such a way that they overcome the current limitations mentioned above. Our work will focus on the following topics.

Multiscale 4D (3D + time) Web Services We intend to research how interfaces for geo web services have to be designed in order to allow an efficient access for reading (selection, filtering) and writing to a 4D-geodatabase (see Sect.4) while regarding 3D/4D constraints and different geometry models (boundary representations, CSG and parametric).

Semantic Transformation Capabilities for Geo Web Services We intend to examine an enhancement of geo web services for supporting semantic interoperability. This new geo web service shall encapsulate a source data model (defined by the conceptual schema) and map it by user defined transformation rules (at conceptual schema level) on arbitrary target models.

Quality-Sensitive Geoprocessing Services and Process Chains In order to provide GIS-analysis methods by geo web services research work in the fields of formal descriptions of these methods and mapping complex analyses into geoprocessing workflows is necessary. Geoprocessing workflows shall be treated like a specialization of a semantic transformation. In order to receive information about the quality of the results of geo processing workflows at runtime, quality parameters like positional accuracy or level of detail have to be taken into account and propagated throughout the workflow.

VI. AUGUMENTED REALITY SYSTEM

A. Motivation

The integration of images taken before or during the construction of subway tracks and related objects into the planning process is a challenging task. The main motivation of developing this sort of Augmented Reality (AR) system in the context of this project relates to the fact that the utilization of images augmented with the current 3D plans provides the planner a more realistic view to the future layout of the objects to be constructed rather than the pure 2D / 3D vector plans. This way it becomes possible to analyze a 3D model on-site, to validate or modify the current plan, or to assess different planning alternatives. Planners in the office as well as their colleagues at the construction site should thus be supported by the system to work and discuss simultaneously the same state of planning. This allows an intensive cooperation between different teams of office and field workers.

B. Requirements and System Design

The system should provide various features to accommodate for mobility, flexibility and accuracy: A major challenge is the lack or unreliability of GPS signals in underground environments. To allow for maximum flexibility, the system should thus be able to localize and orient itself without any other measurement unit except of cameras and the existing plans. This is accommodated for by using two fish-eye (omnivision) cameras mounted on the helmet of the operator. Furthermore, the system should be convenient for a whole team (and not only for one person) to operate. Hence, the utilization of tablet PCs or similar devices seems much more promising than using head-mounted displays. Finally, to accurately overlay images and 3D plans and to measure potential discrepancies between plan and actual construction, the system must involve a precise 3D measurement unit. To this end, a calibrated multi-view camera system will be mounted on the tablet PC, so that precise 3D measurements of a certain detail under investigation can be made and immediately displayed and analyzed on the tablet PC. An artist's view on the system is given in Fig.9.

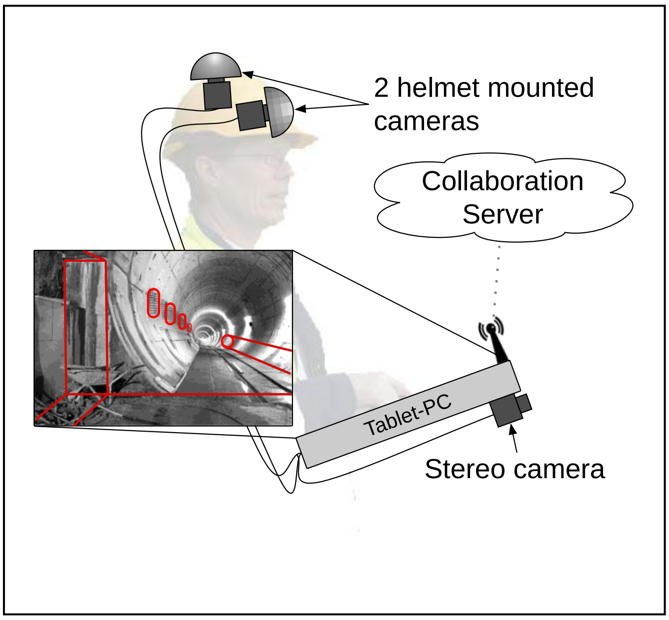

Figure 9. Schema of the AR-System

C. Concept and Methodology

As plans are usually designed in different scales, the AR system needs to consider multiple image resolutions to match the different multi-scale versions of the planned objects with the images. The images must be thus located, orientated and scaled properly. Hence, the methods to be developed shall fulfill following boundary conditions:

- Landmarks for matching 3D models and images must be found and evaluated regarding their saliency automatically. Only then, the self-localization and self-orientation of the camera system becomes possible in complex environments. The challenges here relate mainly to the automatic analysis of the underlying 3D models regarding salient features to match as well as the development of robust estimation procedures as there is to expect much clutter and a high number of ambiguous features in such environments.
- The automatic matching procedures must cope with automatic partly incomplete or partly imprecise model information, as in real scenarios not every detail visible in an image is present in the model and vice versa not every modeled part of an object is visible in the image.
- Besides self-localization and self-orientation also the ego-motion determination of the system must work autonomously, i.e. without support of GPS or INS data. Hence, also tracking the motion of an operator, once he is walking, must be purely based on matching 3D plan with features and landmarks extracted from the imagery.

Furthermore, the special characteristics of the involved sensors must be taken into account (optics, image distortions, noise characteristics etc.). Further developments of the sensors are however not in the focus of the planned research, although recommendations for the further development of the sensors will be certainly given within the frame of this project. The system needs furthermore to appropriately visualize the images together with planned objects, existing track or building parts and objects that can be temporarily removed during the construction period. Yet such special kinds of visualization techniques will also not be part of the research envisaged here. The first version of the AR device will be equipped with standard visualization technology.

D. Related Work

Our research is inspired by numerous related approaches, yet most of them are not able to operate underground without support of GPS (or even INS – Intertial Navigation System) signals. [32] have implemented an initial estimation of position and location of GPS and IMU (Intertial Measurement Unit). The initial position of the camera and its location in a laboratory surrounding is created manually as stated in the example of [25]: in this case the user first has to select several image features manually. [41] refers to the possibility of using an IMU in order to improve the cameras estimation of position and location. [4] apply model-based tracking in addition to their mobile AR-systems [24], which is also equipped by GPS and IMU.
Further characteristics of most of the approaches is that the models used for self-localization and tracking are fairly small so that they are completely visible in the image and their pose regarding the camera can be easily determined. In our context we must assume, however, that only parts of the object model can be seen so that finding its pose relative to the camera and deriving the localization and orientation therefrom become much more complex.
Considering operational systems there exist quite strong relations of our approach to the VIDENTE project [16, 34]. The system presented there provides mobile information for all kinds of lines. Underground infrastructure facilities like cables and lines can be visualized, yet in fairly easy environments. For the tracking process differential GPS together with IMU and an image-based tracking system with landmarks is applied. Similarly, the system developed in the ARVIKA-project [26] supports worker by overlapping 3D models and 2D plans with images from industrial facilities. It deals with clearly defined geometric structure containing only small clutter, as they typically can be found on industrial sites.

VII. Conclusions

In this paper the way towards collaborative planning of subway tracks as parts of multi-scale 3D city and building models has been demonstrated. The combination of research coming from the fields of collaborative planning platforms, 3D modeling, spatio-temporal databases, geo web services, and computer vision has been proposed in a common approach. The main concepts and implementation ideas for the development of a collaborative platform for subway track planning communicating with tools for the modeling, management, and mobile visualization of buildings and subway tracks have been presented. The focus has been set on consequent 3D modeling, management, and visualization of infrastructure data. Therefore this research is a contribution to the development of collaborative software tools used for 3D city and building models as well as to consequent 3D data modeling and management during the planning process of subway tracks.

Acknowledgments

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