Towards 3D Geoinformatics and Computational Civil Engineering Support for Cooperative Tracks Planning

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Key words: 3D tracks planning, cooperative planning, 3D multi-scale modeling, 3D geo-data.

SUMMARY

The planning of road, railway, and subway tracks in urban environments is a manifold task because of complex legal, environmental, economic, and structural problems. However, skills and knowledge of the participants differ substantially and computer support for complex planning still is at its beginning. Especially computer-aided collaborative planning for 3D city and building models is a new challenge with many open research questions. Mainly two communities can interdisciplinary contribute to a solution: Geoinformatics and Computational Civil Engineering. Both fields have a tradition in 2D planning and both are developing towards a "3D science". For example, 3D models in different scales should be included into the planning process right from the beginning to complement 2D plans. Furthermore, 3D geo-databases should provide on-demand internet-based access to tracks and other infrastructure models. Therefore 3D geo web services should simplify the access to objects above and under the earth surface. Data management tools should interact with efficient 3D computer vision techniques. In this contribution research approaches of the researchers group "Computer-aided collaborative tracks planning in multi-scale 3D city and building models" are presented. The way to facilitate planning processes for subway track planning is described by developing a collaborative platform communicating with components to be developed for the modelling, management, and visualisation of 3D multi-scale models. Basic research combining ideas from the fields of collaborative planning platforms, 3D modelling, spatio-temporal databases, geo web services, and computer vision is presented.

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1. INTRODUCTION

The conception and construction of three dimensional urban and building models, including underground structures and infrastructures are a challenge in the fields of Geoinformatics and Computational Civil Engineering. However, hitherto the planning of cities and subway tracks is not well supported by 3D modelling and collaborative software tools. Especially the synchronous phases of the planning process need more interactive digital support. Furthermore, 3D modelling, management, and analysis of above- and sub-surface objects still are challenges for GIS and CAD research.

Recently a researchers group at Karlsruhe Institute of Technology (KIT) and 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 are investigated as well as image supported real time localisation in 3D space. Ways to involve new 3D geo web services and spatio-temporal databases for the management of heterogeneous planning data are examined. The results of this research are expected to have high relevance for both, research and practice.

2. COOPERATIVE TRACKS PLANNING

A core part of the work to be done in the researchers group is research on cooperative tracks planning realised by a collaboration platform, which handles the user access to the underlying data. Furthermore, the collaboration platform cares for the consistency of the geometric data. It aims at synchronous cooperation in order to leverage collaborative computational steering, i. e. interactive concurrent data manipulation at the same time while the consistency of the underlying data is preserved by the collaboration platform. Thus collaborative computational steering allows all participants to interact and to manipulate shared data in order to jointly elaborate the next steps in planning. The major problem of synchronous cooperation is to provide consistency methods that can be carried out in real time. For example, any update that is executed by one planner must be immediately visible to all others and should not influence the global consistency of the data. The city or infrastructure model including geometric and context information should be hidden from the user to be accessed exclusively via the collaboration platform.

For our purposes we are using a standard client-server system architecture. Thus at the beginning of the workflow a planner retrieves data from the platform and stores a local copy for further processing. Any update 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 all changes is preferable, nevertheless leading to a high communication frequency in the case that several planners are involved. The alternative solution – a late update – would save bandwidth reducing the communication overhead, but in case of several planners this would most likely lead to diverging model states. Hence, the latest 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. the local copy), but obviously those modifications are not visible on a more global scale yet. The user trying to access obsolete data must then be interrupted and the updates from the user - handling the modified copy - must be made visible to all clients and to the server in order to retain global consistency — as for instance also applied within the MESI protocol regarding cache coherency in shared memory systems.

As the platform should be also able to include external data such as seismic data, geographic information or simulation results during runtime, a 'generic' interface for the data import has to be provided. A possible solution to the problem is the development of geo web services enabling to transmit the semantic description of the data along with the data itself (see Section 5). This allows any client to incorporate additional data sources having been unknown prior to the integration and to consider them during the planning process. Those external data sources are not maintained directly by the collaboration platform and, thus, have to be kept consistently via external methods, providing as read-only data for the clients. Nevertheless, 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 computer support during planning processes.

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 visualisation 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 visualisation algorithms for the different types of data are necessary that allow the user to (seamlessly) explore the underlying multi-scale models (Section 3), which is a quite huge challenge on commodity hardware. Problematic are mainly mobile devices (laptops, smart phones etc.) which do not have a fast broadband connection to the server and retrieve data via WLAN or slower. Here, data filtering before transmission is inevitable, especially when considering the limited capacities in memory and performance of smart phones (Section 6). Such a filtering must happen on the server-side and also meet real time requirements.

3. COMPUTATIONAL ENGINEERING SUPPORT: TOWARDS 3D MULTI-SCALE CITY AND BUILDING MODELS

In subway planning, 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 GIS (van Oosterom and Schenkelaars 1995; van

Oosterom and Stoter 2010) and in geo-data exchange standards such as CityGML (Kolbe 2008) expressed as level-of-details (LoDs). However, these approaches focus on static models and still primarily aim at supporting their visualisations. 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 consistency between such dynamic multi-scale models.

That is why we focus on a methodological examination of multi-scale modelling in the context of subway planning. In a first step, the number of LODs as well as the corresponding geometric representation on each LoD are defined. Figure 1 shows an example of multi-scale modelling for a tunnel section. On the coarsest LoD, LoD 1, the tunnel is represented by only its main axis, while on the finest 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.

	Level 1	**Level 2**	**Level 3**	**Level 4**	**Level 5**
Subway Planning / Tunnel section	2D polyline	2D polyline (with width)	3D Tunnel geometry	precise 3D geometry (with inner shell, drainage, separating wall)	precise 3D geometry incl. rails /, traffic lanes, fan equipment, cables, lighting devices, traffic signs
Figure					

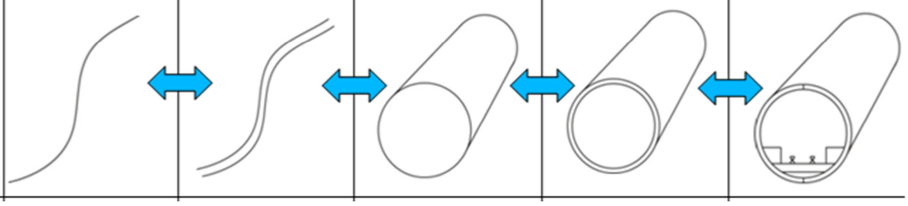

Figure 1: Geometric objects on different LoDs in tunnel planning

An important research aspect is the development of methods for checking and preserving the consistency of the multi-scale models. As a first step towards the realisation of multi-scale model consistency we are developing methods for transferring models from finer LoDs to coarser ones (Figure 2).

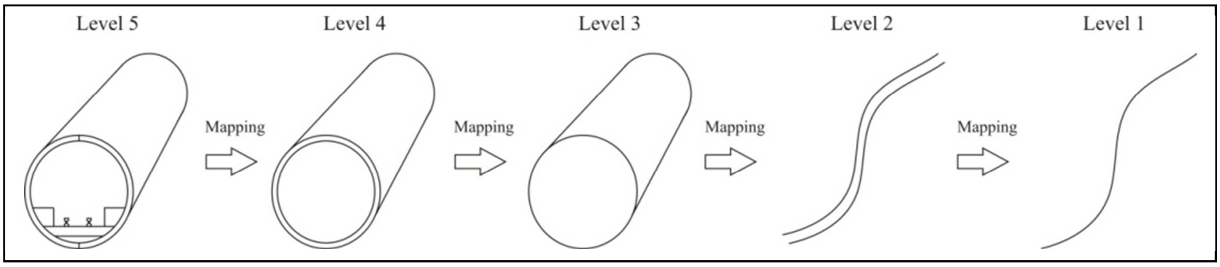

Figure 2: Automatic transformation of the LODs in one direction

To this end, mapping functions are constructed which are composed of rules for geometric simplification and generalisation (Gröger et al. 2004; Hampe 2007; Forberg 2007) while preserving the topological consistency of the models. In the second step, methods for defining dependencies between geometric entities on different levels of detail will be developed. These methods will allow to preserve the consistency between the representations on different LoDs during a dynamic planning process. To realise this functionality, parametric modelling methods have to be applied which have been originally developed for Computer Aided Design (CAD) applications (Ji et al. 2011; Sacks et al. 2004; Shah and Mäntylä 1995). They allow to define geometric, topological, and dimensional constraints and dependencies between different geometric entities for the creation of flexible geometric models. One of the objectives of the researchers group is to develop methods defining constraints between different geometric representations on different LoDs (Figure 3).

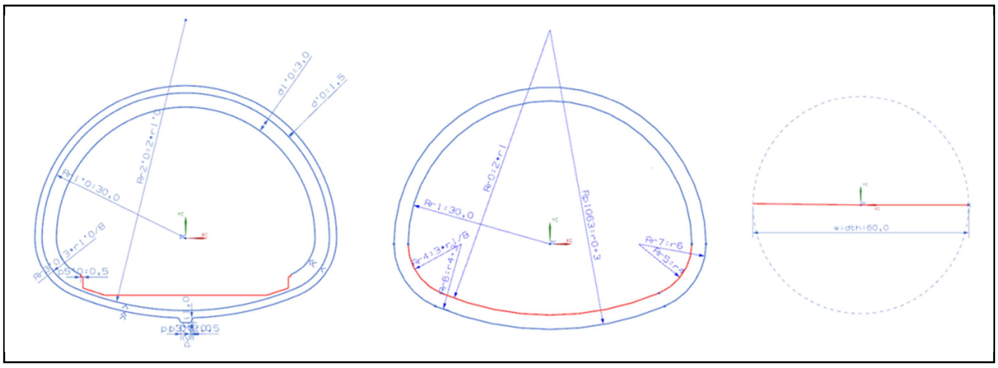

Figure 3: Example of parametrised tunnel cross-sections on different LoDs

To enable the exchange of multi-scale models between different applications by means of a neutral data format, it is desirable to include the consistency constraints between the different levels-of-detail. Thus the coherence of the multi-scale model can be preserved. 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 will be developed in order to demonstrate the feasibility of exchanging multi-scale models (Figure 4).

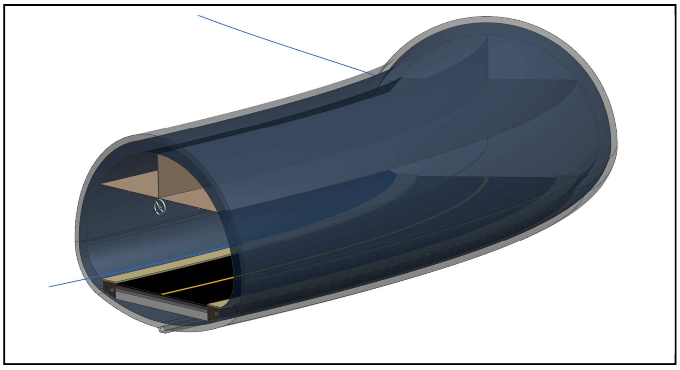

Figure 4: 3D model of a road tunnel section as part of a multi-scale product model

The developed methods for multi-scale modelling and consistency preservation are to be integrated into the collaboration platform (Section 2), the spatio-temporal database (Section 4), and the system for on-site visualisation (Section 6).

4 GEOINFORMATICS SUPPORT: TOWARDS A SPATIO-TEMPORAL DATABASE FOR CITY AND INFRASTRUCTURE MODELS

To manage and control a large amount of 3D above- and sub-surface objects consistently as needed in the researchers group, it is essential to provide a high performance database. Figure 5 shows an example of a 3D model containing above- and sub-surface objects to be handled by the spatio-temporal database.

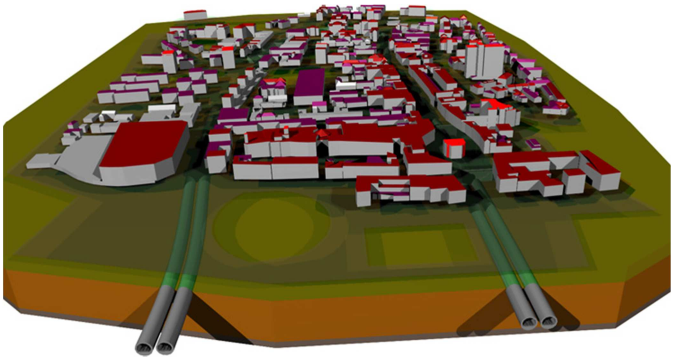

Figure 5: Combined above- and sub-surface 3D model

However, the combination of CAD and GIS data including different levels of detail requires new data structures and operations to be implemented in the geo-database. In addition, mobile AR platforms (Section 6) need a fast access to arbitrary subsets of geo-data that can be visualised and manipulated on static and mobile information systems in short time. When the involved mobile information systems are in offline-mode, it should be possible to work there on locally stored data and to reintegrate the data back into the collaboration platform (Section 2) when the server is online again (online mode).

The geo-database platform used in the researchers group is DB4GeO (Breunig et al. 2004; Breunig et al. 2011) which has its roots in (Bode et al. 1994) and (Balovnev et al. 2004). DB4GeO is fully implemented in the Java programming language. It is based on the open source object-oriented database management system db4o (Paterson et al. 2006; DB4O 2012) using R-Tree based (Guttman 1984) spatial access structures. The underlying 3D geometric / topological data model is based on simplicial complexes, i. e. points / nodes, lines / edges, triangle nets / meshes and tetrahedron nets / meshes, respectively. This data model has also been extended for time-dependent simplicial complexes. As well known, simplicial complexes are a special form of cell decompositions being especially used for the modelling of nature-formed geo-objects in geo-scientific applications. Cell decompositions implicitly consider topology that can be well used for city objects (Thomsen et al. 2008).

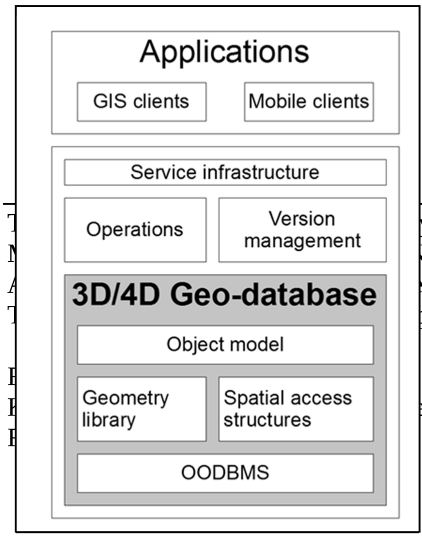

Figure 6: System architecture of DB4GeO geo-database

Figure 6 shows the general system architecture of DB4GeO. Upon the object model the operations, version management, and service infrastructure are realised. DB4GeO offers several simple geometric and topological web services, such as

- distance between 3D geo-objects;
- intersection between a 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.

Clients access the geo-database exclusively via its web services. Currently the REST architectural style (Fielding 2000) is implemented.

Parallel to this development DB4GeO will be extended for the management of spatio-temporal parametric data, i. e. procedural descriptions of geometries have to be stored in the geo-database. The spatio-temporal database will act as backend of the collaboration platform. Therefore it is necessary to integrate other aspects such as 3D modelling and spatial integrity constraints into the conception of the geo-database. Especially it is essential to develop database data types and structures that

- fit into the concept of the collaboration platform (Section 2);
- support data sets with multiple scales (Section 3);
- are easy to access and do not cause high transmission costs (Section 5);
- facilitate the implementation of the synchronisation for mobile clients with the database and vice versa (Section 6).

When integrating the multi-scale data model for subway track planning into the geo-database, it has to be guaranteed that there will be no information loss. This is another reason for extending the geometric model of the geo-database by an alternative representation to simplicial complexes.

Furthermore, fast spatio-temporal access to large data sets used for 3D tracks planning presupposes efficient spatio-temporal access methods. Therefore several temporal extensions of the R-Tree (Guttman 1984) will be examined. The best suited will be implemented in the geo-database. However, the definition of spatio-temporal database queries including open time intervals is not a trivial task. Furthermore, both the planning time (comparable with the transaction time known from temporal databases) *and* the execution time (comparable with the valid time known from temporal databases) have to be considered in the temporal model of the geo-database. Therefore the planning and the execution time have to be determined for each object in the geo-database. Finally, temporal updates of such objects should be provided.

The spatio-temporal database will be accessible by advanced geo web services that are introduced in the next section.

5. ADVANCED GEO WEB SERVICES

Large-scale inner city building projects rely on a wide range of different input data such as existing underground infrastructure, soil properties, and GIS-analysis functions. Thus input data should be available for every involved party in the planning process by geo web services providing access to geospatial data and GIS-analysis functions homogeneously. Existing OGC (Open Geospatial Consortium) specifications for web service interfaces, however, have limitations regarding the access to a distributed, heterogeneous system for collaborative subway track planning.

The following limitations of current standard geo web service interfaces were identified:

- Drafts for 3D OGC web services such as the Web View Service (WVS 2010) and the Web 3D Service (W3DS 2010) are already in use (GDI-3D 2009). However, the major drawback of these two web services is that they are only intended for visualisation of 3D-data (by rendering an image on the server (WVS) or on the client (W3DS). They do not offer functionality for handling "attribute geo data" (W3DS 2010) as required by planners. In the OGC context "attribute geo data" is encoded using GML (Geography Markup Language) expressing geometry as B-Reps. Planning tools, however, heavily rely on Constructive Solid Geometry (CSG) and parametric geometries.
- Subway track planning requires 3D filter operators such as 3D collision detection. However, hitherto topological filters are only defined for two-dimensional data. Most of the research dealing with publishing and filtering semantic 3D geospatial data, e.g. (Czerwinski and Plümer 2008) and (Döllner and Hagedorn 2007), only use 2D filters for 3D data.
- To access an arbitrary GIS functionality via a web service protocol, the OGC defines the Web Processing Service interface (WPS). However, the WPS is defined generically, that is why there is no real interoperability realized between web based analysis tools. The OGC specification lacks in formal definition of analysis operations and their concatenation.
- At the moment geo web service protocols do not explicitly support the concept of LoD as needed for track planners, although some work has been done (Hampe 2007) to develop a web service protocol for accessing a multi-scale geo-database as defined by (Sester 2000), again limited to two-dimensional data.
- A system for collaborative subway planning needs a well defined spatio-semantic

data model. Input data sets of the planning process need to be harmonised not only syntactically by using a standardised web service protocol, but also semantically by schema translation. However, OGC web services do not provide means of schema translation capabilities. Research dealing with schema translation and other data harmonisation via web service interfaces is again limited to 2D data in most cases (Balley 2007; Donaubauer et al. 2010; Lehto 2007; ORCHESTRA 2008; Staub et al. 2008).

- In planning processes mostly more detailed quality information is needed than the accuracy of an object or a part of the object. Furthermore, there is no standardised way of error propagation in nowadays geo analysis tools. Integrating data quality information into a geo web service environment is currently investigated in (Williams et al. 2010; Donaubauer et al. 2008, e. g.).

To overcome the current limitations mentioned above research is necessary in the following topics:

Multi-scale 4D (3D + time) Web Services

Here research is necessary to investigate how interfaces for geo web services have to be designed to allow efficient read and write access to a 4D-geodatabase (see Section 4). Especially 3D/4D constraints and different geometry models (boundary representations, CSG, and parametric) have to be considered.

Semantic Transformation Capabilities for Geo Web Services

The enhancement of geo web services for supporting semantic interoperability has to be examined. The new geo web services 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 Geo-Processing Services and Process Chains

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 geo-processing workflows is necessary. Geo-processing workflows shall be treated like a specialisation of a semantic transformation. To receive information about the quality of the results generated during geo processing workflows at runtime, quality parameters such as positional accuracy or level of detail have to be taken into account and propagated throughout the workflow.

6. AUGMENTED REALITY SYSTEM

A major motivation to include a mobile augmented reality system into the planning process relates to the fact that the 3D plans need to be checked against the current state of construction. Hence, images taken before and during the construction of subway tracks and related objects shall be integrated into the planning process to provide the planner a more realistic view to the current and future layout of the objects to be constructed rather than the pure 2D / 3D vector plans. This way it becomes possible to analyse a 3D model on-site, to validate or modify the current plan, or to assess different planning alternatives. The augmented reality system is thus expected to heavily support simultaneous planning and discussing based on 3D vector data enriched by real world images. This allows an intensive cooperation between different teams of office and field workers.

Various features must be considered for system design to accommodate for mobility, flexibility, and accuracy: A major challenge is the lack of GPS signals in underground environments. The system must thus be able to localise and orient itself regarding the 3D data without any other measurement unit – just based on visual data and the existing plans. This is accommodated by using two fisheye-like (omnivision) cameras mounted on the helmet of the operator. Furthermore, the system needs to be convenient for a whole team (and not only for one person) to operate. Hence, tablet PCs or similar devices are used for continuous displaying the image sequence or "freezing" single images. This 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 reasonably precise 3D measurement unit, so that precise 3D measurements of a certain detail under investigation can be made and immediately displayed and analysed on the tablet PC. Depending on the measurement range, different active or passive sensors come into play. A calibrated multi-view camera system mounted on the tablet PC is featured by the largest measurement range but needs good illumination and texture on the imaged surfaces. Active imaging sensors such as time-of-flight cameras (tof-cams) or kinect-like devices are not depending on texture and illumination, but have an upper limited of the measurement ranges at several meters.

An artist's view on the system is visualised in Figure 7. Figure 8 shows examples of image processing. The left subfigure depicts a result of image-to-image matching, i.e. automatically aligning the two stereo images (inner frames) with the fisheye-like overview image. A result of model-to-image matching is illustrated in the right subfigure. Here, the 3D vectors of the planning data are automatically aligned with the overview image based on matching 3D vectors (red) to 2D image contours (gray).

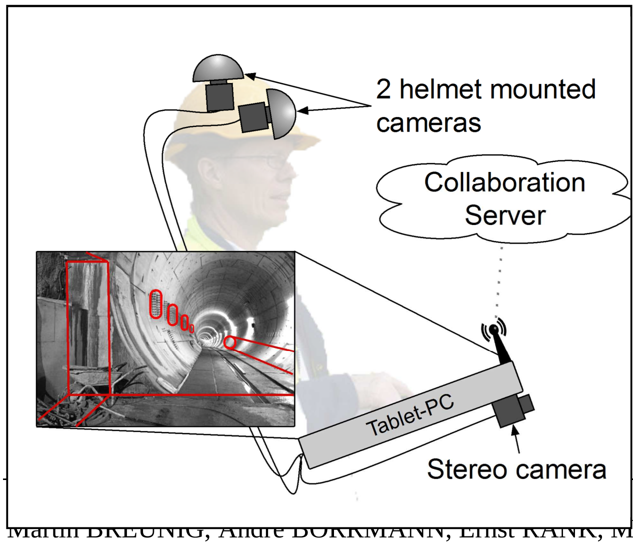

Figure 7: General set-up of the AR system

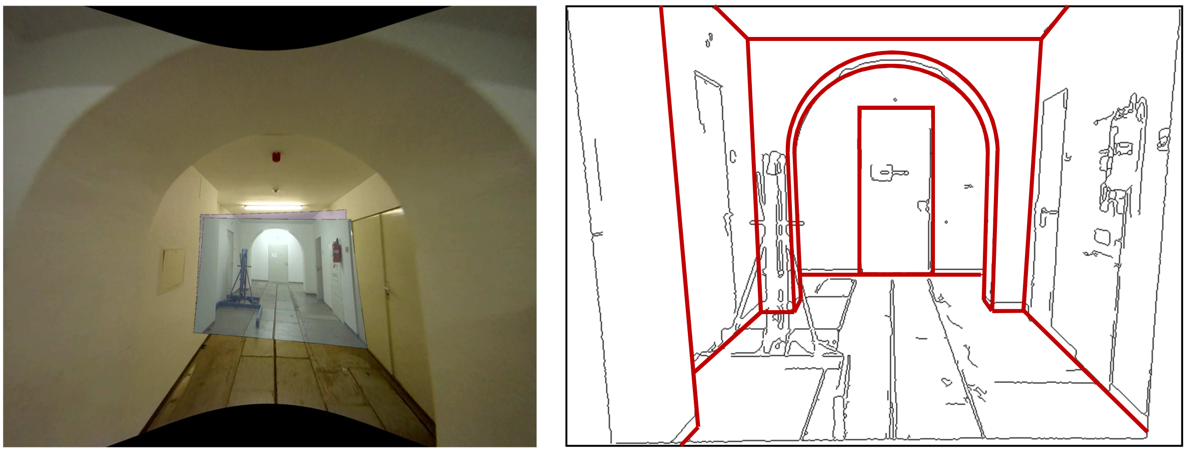

Figure 8: Result of automatic matching stereo images (inner frames) to overview image (left subfigure) and result of automatic matching of 3D vectors of planning data (red) to image contours (gray).

The methodical backbone of this research is inspired by numerous related approaches. Most of them, however, are not able to operate without GPS (or even INS) signals, which is a hard condition to work underground. (Reitmayr and Drummond 2006), for instance, used an initial estimate of position and location based on GPS and INS. The initial position of the camera and its location in a lab environment is set manually similar as in (Najafi and Klinker 2003): in this approach the operator has to select several image features manually. (Wuest et al. 2007) refer to the possibility of using an IMU in order to improve the cameras estimation of position and location. (Behringer et al. 2002) apply model-based tracking in addition to their mobile AR-systems (Livingston et al. 2002), which is also equipped by GPS and IMU.

There exist quite strong relations of our approach to the VIDENTE project (Gerhard et al. 2009; Schall et al. 2008), when it comes to operational systems. The approach presented there provides mobile information for all kinds of lines. Underground infrastructure facilities such as cables and lines can be visualised, yet in fairly easy environments. As in many other works, differential GPS together with IMU is applied for tracking and supported by an image-based tracking using landmarks. Similarly, the system developed in the ARVIKA-project (Navab 2003) supports worker by overlapping 3D models and 2D plans with images from industrial facilities. It deals with a clearly defined geometric structure containing only small clutter, as they typically can be found on industrial sites but not at construction sites.

7. CONCLUSIONS

Obviously the planning of road, railway, and subway tracks in urban environments is a challenging task. In this contribution, first approaches towards computer-aided collaborative planning for multi-scale 3D city and building models have been addressed. Concepts of the researchers group "Computer-aided collaborative tracks planning in multi-scale 3D city and building models" were presented. We described the way to facilitate planning processes for subway track planning by developing a collaborative platform communicating with components to be developed for the modelling, management, web-based access, and visualisation of 3D multi-scale models. Thus research to combine ideas from the fields of collaborative planning platforms, 3D modelling, spatio-temporal databases, geo web services, and computer vision was presented. The focus has been set on consequent 3D modelling, management, analysis, and visualisation of infrastructure data.

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