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Rich point clouds in virtual globes – A new paradigm in city modeling?

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ABSTRACT

In this paper, we discuss the emergence of a new paradigm in 3D city modeling, which we will call the *rich point cloud paradigm* and which is largely based on dense and semantically rich 3D point clouds. We first present existing modeling paradigms, namely the explicit modeling of 3D geometry and image-based city modeling, and discuss their strengths and shortcomings. Key elements of the new modeling paradigm include the following: (1) treatment of 3D point clouds with increasingly rich geometric, radiometric and semantic properties as actual urban 3D models and not just as an input to the traditional 3D modeling process, (2) potential for fully automatically capturing and generating large scale 3D city models, (3) capturing rich detail of the micro- to meso-scale environment from a ground-based 'human' perspective supporting numerous drive-through and walk-through application scenarios and (4) possibility to start from fully automatically derived simple visual models and to gradually enhance and enrich them on an as-needed basis. We contend that virtual globes have a key role in fully exploiting the potential of the new paradigm. These arguments are supported with the implementation of a proof of concept prototype based on the i3D virtual globe technology and with initial observations from tests with real-world data sets. Finally, we identify a number of future research issues and challenges that are triggered by the new paradigm.

1. Introduction

The generation of large-scale urban 3D models first became a significant research issue approximately 15 years ago, with an initial focus on the automated 3D building extraction from aerial imagery (see, Faugeras, Laveau, Robert, Csurka, & Zeller, 1995; Haala & Hahn, 1995). Even though significant progress was made within the first 10 years, for example, the introduction of airborne LIDAR as an important data source for the automated generation of 3D city models (Haala & Brenner, 2001) and the design and implementation of the first 3D GIS supporting the automated generation and management of large city models (Nebiker, 2003), many of these activities were hardly noticed by the majority of the geospatial community or by the general public. However, research on 3D city models very rapidly became a focus of interest following the launch of Google Earth in 2005 and Microsoft Virtual Earth (now Bing Maps 3D) a year later. While in the past digital 3D city models had primarily served a relatively small community of geospatial experts, beginning in 2005, they were available to a global community of millions of users. These technologies not only triggered the production of 3D city models by the two major competitors, Google and Microsoft, but also by many cities including Berlin (2009) that consider their 3D city models as attractive and important communication and information platforms for citizens, politicians and tourists alike. With these new developments, new user demands and commercial considerations have become the main driving factors in the production and evolution of 3D city models.

Research on the use of laser scanning technologies and point clouds in 3D landscape modeling was initiated following the introduction of first scanning airborne lasers (ALS) in the early 1990s. With the rapid advancement of pulse frequencies from the original 2 kHz to more than 200 kHz today and the corresponding increase in point density, airborne LIDAR was first used in 3D city modeling and 3D building reconstruction around the year 2000 (Vosselman & Dijkman, 2001; Haala & Brenner, 2001). Terrestrial laser scanners (TLS) were introduced in the late 1990s and soon applied to the modeling of individual buildings and the generation of detail-rich urban 3D scenes. The introduction of the first mobile laser scanners (MLS) approximately 5 years later marked an important step towards the efficient acquisition of highly detailed and accurate 3D geometry from different mobile platforms (Barber, Mills, & Smith-Voysey, 2008). 3D point clouds are expected to gain further importance once the emerging 3D range imaging sensors (Karel, 2008) become applicable to outdoor applications.

Due to the widespread use of virtual globes and the increasing incorporation of 3D models of entire cities, user demands for such models are expected to increase in parallel. The following main requirements have already been identified in a EuroSDR study

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(Nebiker, Bleisch, & Gülch, 2009) and are expected to become more urgent in the near future:

- *Coverage* – with the increasing availability of 3D models of major cities, users will increasingly expect their local environment to also be modeled in 3D.
- *Realism* – influenced by the gaming and film industry with their extremely high levels of detail and realism, users already now are expecting either a similar level of realism or – alternatively – different representations altogether (e.g., cartographic abstractions).
- *Up-to-dateness* – one of the most serious criticisms with respect to today's virtual globes is that geospatial contents are often outdated and no longer represent the current situation.

In Section 2 of this paper, we first identify some of the future key requirements in large-scale urban modeling and postulate a new city modeling paradigm based on rich 3D point clouds. In Section 3, we present and discuss the two main existing modeling paradigms: geometric 3D modeling and image-based modeling. Section 4 introduces the new modeling paradigm and explains the underlying modeling concept and strategy. In Section 5, we discuss the status in point cloud visualization and outline the important role of virtual globes in the context of the new paradigm. In Section 6, an implementation and initial observations are presented, which were carried out as proof of concept from a technical and cartographic perspective. Section 7 follows with a comparison of the existing city modeling paradigms with the new approach. We conclude with a comparison of the new paradigm with the existing paradigms and with the identification of some key research issues that are triggered by the new modeling paradigm.

2. Problem statement and thesis

Based on the user requirements listed above and on the perennial trend towards increasing productivity in (geo-) data production while at least maintaining today's quality level, the future key requirements in large-scale urban 3D modeling can be summarized as:

- *Better* – in terms of modeling richness and fidelity – especially of the immediate surroundings.
- *Faster* – with respect to ensuring a high production speed and up-to-dateness.
- *Cheaper* – in terms of automation in the production, processing and analysis phases.
- *Smart(er)* – by at least preserving or even enhancing the semantics of existing 3D city models.

Satisfying these city modeling requirements on a large scale and in an economical way poses a major challenge. We believe that this challenge cannot be met by simply scaling today's modeling efforts for a number of reasons. The high level of realism in the film industry, for example, comes at a very high cost and cannot be scaled to entire cities or countries without sacrificing spatial quality, richness in detail or up-to-dateness. However, the approach of crowdsourcing (Howe, 2006) has been successfully applied to scaling 2D geo-data collection at map scale quality to the entire globe in projects such as OpenStreetMap (Haklay & Weber, 2008). It will be shown below that crowdsourcing can successfully be applied to 3D urban modeling tasks. However, it is doubtful whether crowdsourcing-based 3D urban models will be able to fulfill the requirements of geo-referencing and modeling quality in the near to medium future. Thus, there are good reasons for looking into new 3D city modeling approaches that address the emerging user requirements in a more economical way.

We postulate a new 3D city modeling paradigm based on *rich point clouds*. In this new paradigm, rich 3D point clouds are considered as 3D city models on their own and not just as inputs to a modeling process. In this paradigm, 3D point clouds are acquired fully automatically – predominantly but not exclusively by using ground-based mobile laser scanners. Such 3D point clouds are able to capture the micro- to meso-scale environment in detail from a ground-based 'human' perspective and thus particularly lend themselves to walk-through or drive-through application scenarios (see Video 2). Rich point clouds will enable the gradual semantic enrichment of the 3D models by means of automated classification and object extraction (Gorte & Pfeifer, 2004; Pu, 2008; Schnabel & Klein, 2006; Vosselman, 2009). Therefore, point cloud based city models will range from automatically generated purely graphical 3D models to semantically rich models. We believe that the *rich point cloud paradigm* promises a solution to the current city modeling dilemma between the demands for rapidly available high quality 3D models of large parts of the built-up world and finite human and financial resources.

The term 'paradigm' was coined by the American science philosopher Thomas Kuhn (1922–1996) to describe patterns or models of thinking and practice that dominate a scientific discipline during a particular period of time (Kuhn, 1962). In view of the emergence of laser scanning technology, Kraus (2002) predicted a paradigm shift in geospatial imaging resulting from integrating active and passive imaging sensors. While his views were focused on the issues of geospatial data acquisition, the proposed notion of *rich point clouds* also includes the aspects of model interpretation, analysis and visualization.

3. Today's city modeling paradigms

In this section, we first look at the two established paradigms in 3D city modeling: *geometric 3D modeling* and *image-based modeling*. We address the prevailing data acquisition techniques, modeling strategies and scope and discuss some of the strengths and shortcomings of each paradigm.

3.1. Geometric 3D modeling

In the *geometric 3D modeling paradigm*, the urban model consists of an explicit three-dimensional geometric model, which typically includes a range of semantic and representation properties (Kolbe, Gröger, & Plümer, 2005). Such an explicit 3D model must first be reconstructed or generated based on real-world information before it can be used for visualization or analysis purposes.

3.1.1. Acquisition strategies

Today's 3D city models are predominantly derived using photogrammetric airborne imagery or airborne LIDAR data. Many operational modeling procedures additionally rely on ground-based data, e.g., building footprints from cadastral data (Brenner, Haala, & Fritsch, 2001). Point clouds from static terrestrial lasers are increasingly being used as an input for the detailed modeling of individual landmarks or buildings. More recent efforts have been focused on introducing imaging and laser scanning data from mobile mapping systems into the explicit 3D city modeling process and on constructing 3D city models by merging ground-based and airborne views (see, Frueh & Zakhor, 2003). Some authors have also used panoramic images as source for the explicit modeling of 3D urban environments (Ikeuchi, Sakauchi, Kawasaki, & Sato, 2004). A good summary of strategies for large-scale urban modeling can be found in Hu, You, and Neumann (2003).

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3.1.2. Modeling concepts

Current city models are almost exclusively based on explicitly modeled building geometries, either by using boundary representations (B-Rep models) or parametric models such as constructive solid geometry (CSG). In the first case, the surface geometry of 3D objects is represented by means of mainly planar surfaces and by node-edge-face-solid topology relations. Established and emerging standards and formats in the domain of 3D city models, such as CityGML (Kolbe et al., 2005) and KML/Collada, are based on the B-Rep geometry model. Several noteworthy city modeling approaches have successfully relied on CSG models. For example, Brenner (2005) discusses the extension of CSG towards weak primitives with adaptive geometric constraints. The CSG approach is particularly suited for automatically generating cartographically abstracted city models. More recent approaches rely on rule-based parametric city modeling, which tries to simultaneously address the aspects of geometry, representation and semantics. The parametric city modeling approach originates from computer graphics and was originally aimed at generating graphically appealing large-scale urban environments for computer games and movies. Just recently, procedural approaches have been merged with the established 3D modeling strategies. An example of such an integrated approach that tries to improve the geometric details of building facades by using TLS observations is presented in Kada, Haala, and Becker (2006).

In terms of representational modeling, we currently observe two diverging trends: maximal (photo-) realism and cartographic abstraction. Striving towards a maximum level of realism has been a driving factor in urban modeling for many years and has been inspired by developments in the film and gaming industries. However, the inspiring but largely overwhelming competition in these industries has also led to some of the fundamentals of cartography, such as abstraction and generalization, to be revisited.

Reality-based representational modeling typically relies on mapping geo-referenced photographic textures to the object geometries. There is a long tradition of mapping aerial imagery to building roof geometries, which has been extended to include mapping oblique airborne and terrestrial imagery to building façades (Böhm, 2004; Karbo & Schroth, 2009; Leberl, Kluckner, & Bischof, 2009). Major challenges in the reality-based texturing of facades are occlusions from vegetation, vehicles, pedestrians or other 3D objects as addressed in Böhm (2004) and Ortin and Remondino (2005), as well as occlusions, distortions and large scale differences due to the acquisition geometry – particularly in case of oblique airborne imagery. In procedural city modeling, the generation of buildings and building facades is driven by rules using either generic texture or geo-referenced imagery. A procedural modeling approach using oblique airborne or ground-based imagery is presented in Mueller, Zeng, Wonka, and Van Gool (2007). Here, the procedural approach is used to extract additional semantic information, leading to significantly improved facades in the case of large buildings with repetitive patterns of windows or floors. The second trend towards the use of abstracted representations of 3D city models based on cartographic rules and guidelines is well represented by Glander and Döllner (2009).

3.1.3. Strengths and shortcomings

Among the main strengths of geometric 3D city modeling are its proven 3D modeling concepts, which are mostly based on established CAD and GIS concepts, its emerging standards and formats, and the range of tools (e.g., CAD and 3D animation software) supporting these standards. Thus, the geometric 3D modeling paradigm ensures a certain level of interoperability and usability. Another strength of this approach is its great modeling flexibility, which allows almost anything to be modeled, if the necessary (human) resources can be made available.

One of the biggest weaknesses of the approach is rooted in the complexity of urban environments, which will make a fully automated geometric 3D reconstruction an impossible task for many years to come. Until then, high-quality, reality-based city models will require substantial human intervention, making the modeling process both slow and expensive. Due to the airborne (acquisition) perspective of most existing 3D city models, there is a mismatch between the producer's and the user's perspectives and scales. Even when ground-based observations are integrated into the modeling process, it will remain difficult, if not impossible, to handle the close-range environment for typical ground-based applications and users, including trees, shrubbery, obstacles, street furniture, among others, in an economical way.

3.2. Image-based modeling

In the *image-based modeling paradigm*, the 3D urban environment is represented by geo-referenced 2D images or 2D videos instead of explicit geometric 3D models as in the geometric 3D modeling paradigm. Therefore, there is no need for an actual 3D city model.

Image-based city models have become very popular following the launch of Google Street View in 2007. However, early work in image-based digital city modeling dates back approximately 30 years. One of the first examples is movie-map (Lippman, 1980), which allowed an interactive drive through the streets of the city of Aspen, which had previously been photographed using a vehicle mounted camera. Image-based city modeling became common practice with the release of QuickTime VR (Chen, 1995), supporting the image-based real-time rendering of linked sets of 360° cylindrical panoramic scenes. Dykes (2000) uses 360° panoramic imagery as a means of representing geographic information in a visualization context and presents a prototype implementation demonstrating the benefits of integrating panoramic imagery with a navigable base map.

An alternative image-based city modeling approach has gained popularity with the launch of Microsoft's Photosynth. The Photosynth web service (2009) is based on vast numbers of photographs that are automatically co-registered and can interactively be explored in 3D space. Some of the early key concepts and algorithms behind Photosynth are documented in Szeliski and Shum (1997). A good review of the numerous image-based modeling strategies from both the photogrammetric and computer vision communities is provided in Remondino and El-Hakim (2006).

3.2.1. Acquisition strategies

Data acquisition for image-based modeling is primarily ground-based, taking place along road networks for vehicles and pedestrians. Beyond this basic similarity, however, we observe completely different acquisition strategies. These range from crowd-sourcing approaches as used in Photosynth to approaches that require dedicated fleets of mobile mapping vehicles, such as the method employed by Google. The known characteristics of the Street View mapping system are the use of nine frame cameras providing a 360° coverage, three laser scanners used to acquire depth information, and GPS positioning but most likely no INS integration (Wikipedia, 2010; Williams, 2010).

3.2.2. Modeling concepts

The image-based city modeling paradigm relies almost entirely on co-registered and geo-referenced 2D imagery. This co-registration could consist of a relative orientation of image pairs or blocks of images (e.g., Photosynth in Szeliski & Shum, 1997) or of multiple images being stitched into an image mosaic, which is typically projected to a spherical, cylindrical or cubic environment map (Chen, 1995). In most image-based modeling approaches, the co-registra-

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tion of the imagery is automatically performed using extracted homologue tie points. Geo-referencing strategies and accuracies in image-based 3D modeling vary considerably. They range from very coarse and simple map- or GPS-based image geo-tagging (Photosynth, 2009) through GPS positioning in combination with map matching (e.g., Google StreetView) to highly accurate INS/GNSS-based position and attitude determination (El-Sheimy, 2008).

3.2.3. Strengths and shortcomings

The main strengths of image-based city modeling with vehicle-based panoramic imagery include a relatively robust processing chain with a very high level of automation, the rapid coverage of entire cities and states with very detail-rich geo-referenced imagery and a geometric accuracy potential at the sub-meter level. For many users of 3D urban models, including pedestrians, image-based city modeling offers data capture from a perspective similar to the 'human perspective'. This makes image-based city models particularly suitable for drive-through and walk-through application scenarios.

One of the major shortcomings of this approach is the limited degree of freedom, which constrains the user's position to the original exposure points of the panorama and to the traffic lane in which the mapping vehicle was driving. This severely limits potential professional applications of image-based city models such as driving simulators. Another weakness is the inherent need for transitions from one discrete panorama or image to the next when moving through image-based models, which is typically addressed by image warping and fading techniques.

4. The rich point cloud paradigm

The *rich point cloud paradigm* in 3D city modeling is based on dense 3D point clouds with comprehensive geometric, radiometric and semantic properties. We will show that rich point clouds offer alternatives to the existing paradigms not only from a technical perspective but also in the manner in which urban 3D models will be created and used.

4.1. Acquisition strategies

The main motivation for introducing a new city modeling approach is the rapid and cost-efficient generation and updating of reality-based 3D environments for applications requiring detail-rich and accurate representations of the immediate surroundings. Examples of such applications include road planning or driving simulators for fire brigades or police forces. In order to obtain detail-rich reality-based 3D environments, data acquisition needs to take place from a similar perspective of the envisaged users. Because our daily life experience very rarely consists of viewing the environment from a bird's eye perspective, but rather from sitting, standing, walking or driving perspectives, the rich point cloud paradigm particularly addresses the requirements of these latter ground-based activities and application scenarios. The new modeling approach heavily relies on mobile mapping systems because these systems share a similar perspective with the users of future 'drive-through' or 'walk-through' scenarios. Mobile mapping systems used for acquiring rich point clouds can either be vehicle- or human-mounted, using INS/GNSS-based direct geo-referencing and carrying multiple geospatial sensors. The latest generation of mobile mapping systems is equipped with multiple laser scanners and is capable of dynamically acquiring vast amounts of 3D point clouds with a very high point density at the centimeter level and a point position accuracy of approximately 5 cm (Barber et al., 2008; Haala, Peter, Kremer, & Hunter, 2008; Lenz & Lüscher, 2009).

4.2. Modeling concept

Currently, 3D point clouds from airborne and mobile LIDAR are primarily represented by *XYZ* position values, time-stamps, intensity values and pulse identifiers (e.g., the first or last pulse in the case of airborne LIDAR) for each point. Recently, there has been a trend to add co-registered image sensors to mobile laser scanning vehicles and to apply RGB texture values from co-registered cameras to the points. Thus, the attributes of 3D point cloud data can be expected to become more and more comprehensive and to incorporate many of the following properties:

- point geometry (*X*, *Y*, *Z*) values in a well-defined geodetic reference system,
- intensity value of the reflected laser pulse – typically in the near-infrared (NIR) spectrum,
- acquisition time stamp,
- RGB values from a passive imaging sensor,
- acquisition vector, which could be considered as a 'point normal',
- further multispectral reflection values with the corresponding wavelength information (e.g., near infrared or thermal infrared),
- point classification information (class id or even object id in the case of an object-based classification),
- full-waveform of the backscattered pulse carrying information on the reflecting objects (terrain, vegetation, among others) within the pulse diameter.

The 'point normal' property, to take just one example, allows us to distinguish between points at the front or the back of an object (e.g., a road sign) and to display only points facing the viewer. The above list shows that instead of four to six properties per point as in today's point clouds, this number might easily double or triple in the future, thus providing a rich description of the geometric, physical and semantic (e.g., object or class ID) properties of an individual point or a point cluster.

Initially, 3D point clouds will primarily serve as detail-rich graphical 3D models. However, the increasing number and diversity of these properties provides the basis for the subsequent automatic structuring and semantic enrichment of point cloud based 3D models on an as-needed basis. This semantic enrichment, for example, might include the detection and extraction of road signs within the point cloud and their replacement by 3D map objects. Other application-specific object extraction tasks might include the inventory of street furniture such as lamp posts or park benches or the detection and classification of vegetation objects such as trees or hedges. Thus, the subsequent semantic enrichment or *smartification* of point cloud-based urban 3D models could range from segmentation, clustering and classification right through to object extraction – or in some cases even the derivation of explicit geometric 3D models.

4.3. Strengths and shortcomings

The rich point cloud paradigm is based on a largely automated data acquisition process and does not rely on a modeling process requiring human interaction. It provides detail-rich representations of the micro- and meso-scale environment with 3D point position accuracies in the range of 5 cm or better. The new paradigm supports different modeling levels ranging from automatically generated graphical models to models with an increasing level of semantic richness. The rich point cloud paradigm offers smooth navigation with a considerable degree of freedom in camera location. Because the model, i.e., the 3D points, are all correctly positioned in 3D space, this degree of freedom is expected to be significantly greater than in panoramic image-based modeling, which introduces significant geometric distortions as users depart from the original camera position. Due to the strong motion parallax depth cue (Ware, 2004) when moving through 3D points clouds, the new paradigm gives a particularly good 3D space impression for dynamic visualizations such as present in driving simulations (see Section 6.4 and Video 2).

3D point clouds have a number of weaknesses that need to be addressed. Among them are the enormous data volumes of 3D point clouds, the lack of spatial context in terms of 3D scene background and empty space between the 3D points, and the spatially biased data density and sampling of 3D point cloud data. The first two shortcomings can be addressed by integrating rich point clouds into virtual globe environments as illustrated in the following section. The variable point density and directional bias of 3D point collection impose some limitations on the essentially free navigability within 3D point clouds and suggest the introduction of a semi-constrained navigation or *touring* capability within 3D geobrowsers or virtual globes. However, because we are dealing with a new paradigm, there are a number of unresolved and probably even undiscovered issues to be addressed in the future. Some of these are listed in the final section.

5. The role of virtual globes for the visualization of point clouds

In this section, we argue the importance of virtual globes for fully exploiting the potential of the rich point cloud paradigm and for overcoming the above-mentioned weaknesses. We present a number of key issues raised and opportunities offered when integrating rich point clouds into virtual globes. We use the term *virtual globe* as a synonym for any 3D geobrowser or virtual 3D environment, that is capable of streaming[1] and interactively displaying large amounts of geo-referenced spatial contents over the Internet. Among the key features of virtual globes that are presented below, this capability can be considered as the essence of making point cloud-based urban models accessible to a broad community of potential users.

5.1. Point cloud visualization

Visualization of large 3D point clouds is a very active and ongoing research area in computer graphics. Currently, there are two main approaches: point-based rendering (PBR) and volume-based rendering. Numerous PBR implementations for large point cloud data sets have been demonstrated. They all support view-dependent level of detail (LOD) in order to limit the number of points to be rendered at any moment in time. Rendering is normally performed by using hardware accelerated points, depth-sprites or triangle-based splatting primitives. A good overview and comparison of these different point-based rendering (PBR) implementations is given in (Sainz & Pajarola, 2004). In volume-based rendering, points are first transformed into a multi-resolution volumetric representation based on voxels. Voxels can be created by merging neighboring points. If voxels are held in a spatial data structure such as the octree, it is possible to create level of details by aggregating lower level voxels into higher level voxels. A rendering approach using sparse voxel octrees has been presented by Crassin, Neyret, Lefebvre, and Eisemann (2009). Their GigaVoxel approach allows high performance GPU-based rendering of billions of voxels by using streaming and multi-resolution. A similar approach was presented in Far Voxels (Gobbetti & Marton, 2005), which is fully adaptive and retains all original topological and geometrical detail for massive datasets. Furthermore, it is strongly GPU bound.

Several authors have investigated suitable technologies for visualizing and interacting with 3D point clouds in a geospatial context. For example, Böhm (2009) has documented the application of point splatting techniques to terrestrial LIDAR data and impressive investigations on the immersive visualization and analysis of LIDAR data can be found in Kreylos, Bawden, and Kellogg (2008). Volumetric approaches have been investigated by Pyysalo and Sarjakoski (2008) in a voxel-based volumetric landscape reconstruction from airborne laser scanner data or by Gorte and Pfeifer (2004) in the modeling and reconstruction of trees from terrestrial laser scans in a 3D voxel space.

With respect to technology, there exists an increasing selection of software tools for processing and visualizing large 3D point clouds. Fernandez et al. (2007) list roughly a dozen point cloud processing software tools and this list has at least doubled since its day of release. Point cloud support is now available in different types of products. These include the following: extensions of 3D animation software (e.g., Studio Clouds for 3DS or Maya), extensions of CAD packages (e.g., Leica CloudWorx for AutoCAD), CAD software with recently added direct point cloud support (e.g., AutoCAD Map3D 2010) or specialized software packages for point cloud processing and visualization (e.g., VRMesh).

While some of these software tools provide excellent processing and visualization functionality, they generally have two major shortcomings: the lack of backdrop or base maps providing geospatial context at the macro and meso scale and the lack of an intra- or internet-based streaming capability for all contents of urban 3D models – including interactive backdrop maps, points of interest, among others. The capability of interactive backdrop maps plays an important role in all the 3D modeling paradigms presented above and provides the means for overview, orientation, 3D model access, navigation, and interaction. In the image-based modeling paradigm backdrop maps typically consist of linked 2D maps (Dykes, 2000). This also applies to the well-known examples of Google StreetView with Google Maps or to Photosynth with Microsoft Bing Maps as their respective backdrop maps. In the geometric 3D modeling paradigm, the backdrop map is typically 2.5D – consisting of a multi-resolution terrain model and draped orthoimagery – and is merged with the geometric urban 3D model as part of the 3D rendering process. With suitable technology, the same type of backdrop map could be applied to the point cloud-based urban models.

5.2. Key functionality of virtual globes

Virtual globes can be characterized as distributed software environments capable of streaming and interactively displaying large amounts of geo-referenced spatial contents locally or over the Internet. Today, these spatial contents consist of elevation data, ortho-imagery, 3D objects, points of interest (POI), and possibly 2D vector layers. More recent work integrates data from mobile geosensors such as UAV-based videos into virtual globes, thus turning them into mixed reality environments (Eugster & Nebiker, 2008; Nebiker, Christen, Eugster, Flückiger, & Stierli, 2007).

A state-of-the-art virtual globe technology should provide at least the following key functionalities:

– *An accurate underlying mathematical model of a global geodetic reference framework* – permitting a geometrically accurate and reliable integration of different geo-data types and geo-sensor data from different geodetic reference systems (e.g., local and WGS-84 coordinates). In the case of point cloud based 3D models with their focus on high-fidelity models at the micro- and

[1] Streaming refers to the capability of a 3D client (3D geobrowser or virtual globe client) of constantly receiving geospatial contents (e.g., terrain data, 3D geometry, and points of interest) over a network, based on the current viewpoint and movement of the user. Streaming avoids having to load an entire 3D scene with all its contents before it can be displayed.

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meso-scales, ellipsoidal and geoid models have to be incorporated in order to support applications at the sub-meter accuracy level.
– *Global spatial indexing of very large geo-data sets* – supporting the rapid, often highly parallelized production of multi-terabyte geospatial databases and ensuring highly efficient data access over medium bandwidth networks, which, for example, does not permit loading large index files before accessing the actual data.
– *Level-of-detail and/or multiple representation support for all types of geospatial content* – providing view-dependent loading and displaying of geospatial contents at suitable aggregation levels and ensuring a high rendering performance on standard computer hardware.
– *Internet-based streaming support for multiple users* – enabling the constant access to potentially huge geospatial data repositories, which can be either distributed and operated by different organizations or operated within larger organizations. This streaming capability, in combination with server-based repositories, frees typical users of urban 3D models from the data handling problems outlined below and also facilitates the process of keeping the models up-to-date.
– *Smooth interactive visualization* – permitting the asynchronous dynamic loading of 3D scene contents, which also includes the requirement to be able to load new spatial partitions smoothly at a required level of detail and to free unused partitions from memory.

A particularly important argument for using virtual globes in conjunction with rich point clouds is the massive amount of geodata involved in 3D point clouds. Depending on the sensor constellation (e.g., multiple laser scanners plus multiple high-resolution still images and, increasingly, HD video sensors), raw data capture rates of mobile mapping systems are in the order of 100 MB/s, resulting in data volumes of 360 GB per hour and vehicle. Assuming an average operating speed of 30–40 km/h, results in approximately 10 GB of raw data per kilometer of mapped road lane. For a medium size city or a small state with a road network in the order of one to several thousand kilometers, this rapidly adds up to data volumes of approximately 10–100 TB per state and mapping epoch. While hard disk space of this magnitude is now becoming available at affordable costs, the time required to copy and update such volumes of data is becoming a limiting factor. Thus, it is generally not sensible to copy this kind of data to local systems, but it makes more sense to use server-based repositories and internet-based streaming technologies to access and use it. This is one of the core features of virtual globes.

Applying and extending the core functionality of virtual globes to 3D point clouds would make this new type of urban 3D model accessible to a broad range of potential users, well beyond the current community of LIDAR, CAD and 3D animation experts. At the same time, virtual globe technologies could liberate future users of point cloud based 3D urban models from the above mentioned data handling problems by delegating not only the data collection and mass data processing but also the point cloud repository hosting to internal or external specialists.

6. Proof of concept: implementation and initial observations

The objective of our initial studies presented below was twofold. First, we wanted to verify the core idea of a city modeling approach relying entirely on 3D point clouds from a technical perspective. For this purpose, we implemented a proof of concept prototype based on our own virtual globe technology i3D and used a real-world data set to demonstrate feasibility, identify technical issues and determine the future direction of research. Second, we wanted to make some initial observations on modeling fidelity and rendering quality as a proof of concept from a cartographic and visualization perspective.

6.1. Test environment

The tests were carried out using the institute's own i3D virtual globe technology. The i3D technology provides an extensible multi-level architecture and builds the foundation for multiple industry and research projects (Eugster & Nebiker, 2008; Nebiker et al., 2007). Initial point cloud support was added in order to carry out research activities in mobile mapping and mixed reality in virtual globe environments. The current implementation is based on a point-based rendering approach using point splatting. Points are subdivided using a preprocessed binary space partition and a multi-resolution representation is created by using regional point reduction. The LOD is view-dependent using an error metric based on point density. Points are rendered using hardware accelerated point sprites. An alternative volume-based approach is currently being implemented and it uses a sparse voxel octree, also created in a preprocessing step. The octree can be rendered either by using ray casting methods or by rendering cubes. The studies and visualizations shown below are all based on the point-based rendering implementation. The i3D technology supports the free exploration metaphor of virtual globes as well as a constrained navigation along predefined camera trajectories, e.g., recorded with a mobile mapping system. However, it does not yet support semi-constrained geobrowsing, for example, along a predefined route with user control over velocity and direction of view.

The following data sets were available for the first investigations: (1) a landscape model of the FHNW university campus and its surroundings consisting of accurate terrain data and (2) ortho-imagery with a GSD (ground sampling distance) of 0.5 m, a geometric 3D model of the buildings with textures derived from oblique airborne imagery. To obtain terrestrial laser scanning data with reflection values in the NIR and RGB spectra, a mobile laser scan was simulated by multiple static scans along the road axis with an average point spacing equivalent to that of a mobile scan. The point spacing in the test data set ranges from 1 to 3 cm for the micro-scale environment (along the road axis) to 5–10 cm for the meso-scale environment (up to 100 m to both sides of the road axis).

6.2. Fidelity of rich point cloud based 3D models

The goal of these first trials included the assessment of the ability of the software to interactively handle large textured 3D point clouds with point densities down to one point per cm^2. However, the main focus of the trials was on an initial assessment of the model fidelity, i.e., of the graphical representation of the micro- and meso-scale environment.

For this purpose, the rendered point cloud model was compared to photographs taken from similar viewpoints with similar fields of view. The viewpoints were chosen along pedestrian and vehicle routes on and around the FHNW campus along which point cloud data collection had taken place. An example of such a comparison is shown in Figs. 1 and 2, where Fig. 1 shows the rendered point cloud model of the surroundings of the main campus building and Fig. 2 shows a photograph of the identical scene (but taken at a different date). In a visual inspection of the point cloud 3D model the following features can be recognized: road sign (front left), bitumen road repair markings, curb, lamp posts, small boulder alongside the road, shrubs, trees with main structure of branches, building with well captured facade characteristics and three flag poles on top plus a chimney at the far left background

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Fig. 1. Rich 3D point cloud in the i3D virtual globe using point splatting with RGB texture.

Fig. 2. Photograph of the campus building taken with a similar viewpoint and field of view as the 3D model view in Fig. 1.

(only faint in the point cloud model). The current point cloud model also contains a typical error: the road sign is shown with a texture that was apparently captured from the opposite direction. This, for example, illustrates the importance of supporting point normals as a standard property of point clouds. As a first conclusion, the automatically generated point cloud based 3D model in Fig. 1 appears to provide a relatively natural, high fidelity representation of the micro- and meso-scale environment and seems to support a reasonably good recognition of important features and objects.

6.3. Rich point cloud 3D model vs. geometric 3D model

In the following trials, the new 3D modeling approach was to be compared with traditional geometric 3D modeling. These comparisons should have confirmed or rebutted the earlier claims about a better representation of the micro- and meso-scale environment by the rich point cloud approach. From a technical perspective we were interested in the geometric accuracy, in particular the co-registration accuracy, of the geometric 3D model and the point cloud model.

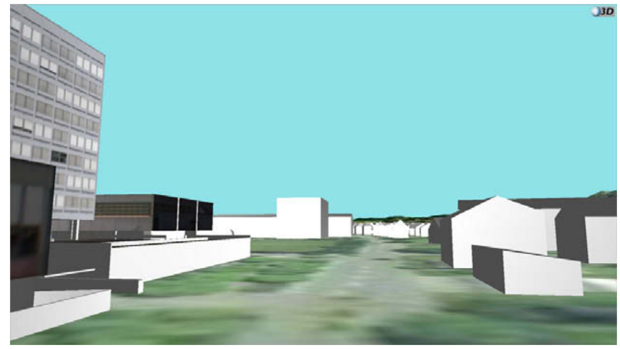

Fig. 3. Geometric 3D model of FHNW campus in Muttenz embedded in virtual globe.

Fig. 4. Rich 3D point cloud of FHNW campus embedded in virtual globe.

For this comparison, both 3D city models were displayed in i3D using the identical viewpoint and the identical 2.5D backdrop map, i.e., the base map of the i3D virtual globe. Fig. 3 illustrates that the geometric 3D model provides a good representation of the main landmarks and of the surroundings, i.e., of the meso- and macro-scale environment. The rich point cloud model in Fig. 4 is superior in capturing the landscape features dominating the immediate surroundings, i.e., vegetation and street furniture. However, it fails to represent the landmarks in the background – mostly because they were not captured with a laser scanner for these tests. This shortcoming could be overcome by a combination of the two model

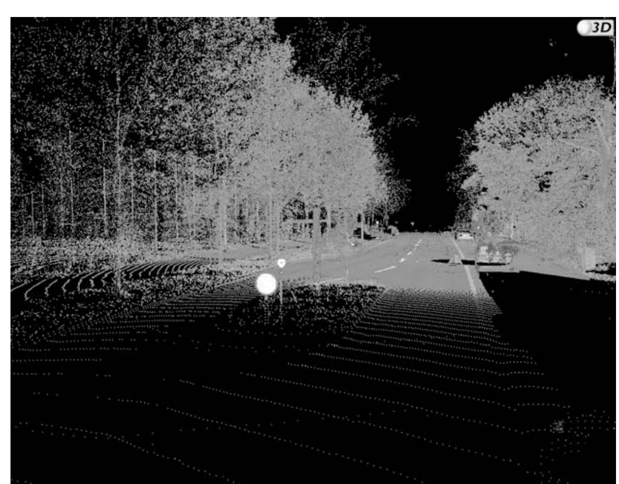

Fig. 5. 3D point cloud in a 3D scene without backdrop map, points represented by the reflected laser intensities in the NIR spectrum; values shown as a greyscale.

types. An overlay and comparison of the different model types, including the combination of geometric and point cloud model and evidence of this can be found in Video 1. The comparisons with respect to the scene representation and geometric accuracy of the two totally independent 3D models shows good agreement at the decimeter level (without manual interaction) which appear to justify the efforts invested into a sound geodetic framework for the i3D technology.

6.4. Value of point cloud texture

In the following comparison, the benefits and visual effects of different types of reflection values were reviewed. Fig. 5 shows the 3D point cloud with the reflection values of the laser pulse in the NIR spectrum, and Fig. 6 shows the same scene with the RGB values of the reflected light. The visual comparison underlines the complementary nature of the information in the visible and NIR bands (e.g., the very high NIR reflectivity of the road sign in Fig. 5 and the clearly discernible color and shape of the sign itself in the RGB point cloud of Fig. 6), which can be exploited in the subsequent classification and object extraction processes. One advantage of using texture information from the NIR laser pulse reflections is the perfect co-registration of the 3D point and the texture data. Fig. 4 shows the problems and challenges involved in optimally texturing a 3D point cloud. While, at least from a visual perspective, co-registration errors are less critical for objects with smooth surfaces such as the road sign in the middle of the scene, they become evident in the texture of the 3D points representing the trees. There the white color of the points representing small leaves and twigs originates from the background, i.e., from pixels representing the (almost white) sky and not the blossoming of the trees. It might be worth noting that Figs. 5 and 6 contain 3D point clouds only and that there is no backdrop map associated with them. When comparing these figures with the rich point cloud model in Fig. 4, the importance of a backdrop map becomes evident.

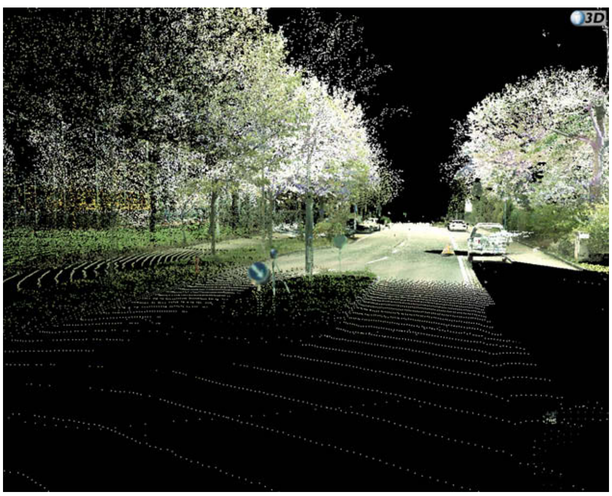

Fig. 6. 3D point cloud in a 3D scene without backdrop map, points textured with RGB values.

6.5. Dynamic visualization of rich point clouds

Many of the potential application scenarios of rich point cloud 3D city models will incorporate dynamic visualizations (e.g., driving simulators or urban planning employing mixed reality drive-by videos). Thus, dynamic visualizations are likely to play a particularly important role in conjunction with high fidelity point cloud based 3D models. The goals of this last set of trials were again twofold. From a technical perspective, we wanted to get first indications on the performance and smoothness of the rendering process. From a visualization perspective, we wanted to get some first observations on whether and how textured 3D points (of the immediate surroundings) might support spatial cognition by means of motion parallax. Video 2 shows the dynamic visualization of a simulated drive through the rich 3D point cloud model of the FHNW campus from a driver's perspective. This video was captured in real-time and included no offline rendering.

First trials demonstrate a rendering performance with over 60 fps on a normal high-end PC (even during video capture opera-

Table 1
Comparison of 3D city modeling paradigms.

Characteristics	Modeling Paradigm		
	Geometric 3D modeling	Image-based modeling	Rich point cloud based modeling
Modeling concepts	**Geometric 3D models** based on boundary representations, parametric models or procedural approaches	Urban environment represented by **geo-referenced imagery** (panoramic mosaics or image collections)	3D urban environment **represented by 3D point clouds** with rich geometric, radiometric & semantic properties
Representation modeling	Photo-realistic texture maps (reality-based or generic)/cartographic representation models	Zoomable, pannable 2D images linked in a spatial structure	Texturing of 3D point clouds with visible or non-visible properties (NIR, thermal IR)
Modeling strategy	Explicit modeling (3D object generation) **at the beginning of the process chain**	Automated generation of panoramic image mosaics or co-registration of image collections	**Immediate and direct use of 3D point clouds**/classification & object extraction **as and when needed**
Prevailing acquisition strategy and coverage	Airborne laser scanning and imaging/ full area coverage	Ground-based mobile mapping (panoramic models)/along road networks & hotspots	Ground-based mobile laser scanning/along road networks
Geo-referencing accuracy requirements	Medium to high	Medium to low (GPS position & azimuth or simple geo-tagging)	High (GNSS & INS)
Modeling scope	**Macro-to meso-scale**/primarily buildings and terrain	**Meso**- (to micro-) **scale**/anything visible	**Micro- to meso-scale**/high fidelity representation of immediate surrounding
Suitable visualization scenarios	**Fly-through**/bird's eye perspective	**Stepwise drive- and walk-through**	**Continuous drive-through and walk-through**
Navigability and camera orientation	Free navigability and camera orientation	Free panning & zooming, navigation constrained to image acquisition positions	Free camera motion and navigability but preferably along acquisition tracks (touring)
Use cases/scenarios (selection only)	3D GIS, urban planning (macro- to meso-scale), marketing, tourism, flight simulation	Location-based services (LBS), tourism, fun, road infrastructure management	Driving simulation, road infrastructure management, urban planning (micro- to meso-scale)

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tions). Informally collected reactions of first users who were given the opportunity to dynamically navigate through the point cloud scene were very positive regarding the fidelity of the point cloud representation and the smoothness of the navigation. Further evaluations of this or similar implementations will show their actual usability for different application purposes.

7. Comparison of city modeling paradigms

The main characteristics of the discussed three city modeling paradigms are summarized in Table 1. Some of the fundamental differences are highlighted in bold.

8. Conclusion

In this paper, we introduced a new city modeling approach based on rich point clouds. Our experiences and first observations from the implementation of a proof of concept prototype indicate that point cloud based 3D city modeling overcomes some of the main shortcomings of the existing modeling paradigms and promises to successfully address the future key requirements in urban 3D modeling presented in Section 2:

- The new approach offers *better* 3D city models for many applications due to the accurate and detail-rich capturing of the micro- and meso-scale environment with geometrically and radiometrically rich 3D point clouds.
- It offers *faster* production and updating of 3D city models due to the rapid acquisition and largely automated processing of the 3D point clouds using ground-based mobile laser scanning.
- The approach also offers *cheaper* 3D models for large-scale urban environments, especially for those applications requiring graphical models only.
- The emerging incorporation of an abundance of geometric, radiometric and semantic properties within 3D point clouds provides a solid basis for the automatic extraction of application-specific objects and information, thus providing the basis for gradually turning 3D point clouds into *smart* city models on demand.

The new city modeling approach raises a number of research issues, many of which are not even known today. Among the already identified issues are the following:

Texturing of rich point clouds – Prevailing approaches for applying photo-realistic textures to 3D objects with primarily planar surface patches are based on direct geo-referencing. For the texturing of 3D point clouds representing fine-grained objects, such as trees, poles, antennae, among others, direct geo-referencing is not suitable. New texturing approaches for 3D point clouds will be needed, which, for example, rely on image to 3D point-cloud matching approaches extending current work on image-to-3D-model matching (Eugster & Nebiker, 2009).

Integrated visualization of rich point clouds with data from other paradigms – Incorporating different city model types into interactive geo-visualizations raises a number of new issues. These include handling of visibility and occlusion in point clouds, (on-the-fly) matching of explicit 3D models and 3D point clouds and matching or even merging terrain points of 3D point clouds with the terrain representation of the underlying 3D landscape model.

Visual perception of rich point clouds – There is a strong need for studies investigating the usefulness and effectiveness of rich point clouds for different types of applications and tasks because 3D point clouds provide an unconventional, little investigated new visual quality.

Processing of very large 3D point clouds – These efforts will benefit from numerous activities in the computer vision domain, which address issues of processing, triangulation and simplification (Pauly, Gross, & Kobbelt, 2002).

Object extraction – 3D point clouds in their original form are unstructured, multidimensional data. If they are to be used not just as visual 3D models, the automated structuring and interpretation of 3D point clouds become major success factors for the new paradigm. Interesting work on the recognition of shapes in 3D point clouds has been carried out by Schnabel, Wahl, Wessel, and Klein (2007). Other noteworthy efforts on related issues include the knowledge-based reconstruction of building models from terrestrial laser scanning data (Pu & Vosselman, in press) and studies on recognizing structure in laser scanner point clouds (Vosselman, Gorte, Sithole, & Rabbani, 2004) as well as approaches for the semi and fully automatic algorithms for segmentation and modeling of 3D data based on large 3D point clouds (Boochs, Kern, Schütze, & Marbs, 2007).

We have described a 3D city modeling approach that strongly relies on rich 3D point clouds – not only just as a data source but also as the 3D city model itself. We described a number of characteristics of the new approach such as the acquisition relying on mobile laser scanning, the increasingly rich properties of 3D point cloud data, and the visualization of very large point clouds, in particular, in virtual globe technologies. We then presented a proof of concept indicating the technical feasibility and graphical quality of the approach.

Therefore, there remains the answer to the initial question, whether the combination of point clouds and virtual globes provides a new paradigm in city modeling. The following findings indeed indicate that rich point clouds not only provide some technical innovations in urban 3D modeling but that they offer and require new patterns of thinking and practice as postulated in Kuhn's original definition of the paradigm concept (Kuhn, 1962). First, high-fidelity 3D models can now be obtained very rapidly in a highly automated process and no longer require a complex, time- and resource-intensive explicit modeling process as in geometric 3D modeling. This offers new possibilities in rapidly creating and updating high-fidelity 3D urban models. Second, with smart point clouds the micro-scale environment of typical actors, such as pedestrians or drivers, can for the first time be captured economically in three dimensions and over large areas such as entire cities. This creates possibilities for new applications that were not feasible before, either for technical or economical reasons. Finally, by supporting smart point clouds in virtual globe technologies, high-fidelity urban 3D models will become available to a broad community of potential users. This will almost certainly create interesting new ideas for the use of urban 3D models and will improve the chances for commercially viable new applications.

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Appendix A. Supplementary material

Supplementary data associated with this article can be found, in the online version, at doi:10.1016/j.compenvurbsys.2010.05.002.

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