Automated Generation of an Historic 4D City Model of Hamburg and Its Visualisation with the GE Engine

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Abstract. Current 3D city models are already available for many cities worldwide. However, the production of historical city models is still in its infancy. In this paper a procedure is presented that combines different data sources in order to derive individual 3D city models of different time periods using the example of the Free and Hanseatic City of Hamburg. A wooden model of the city from the year 1644 and an official map from 1859 have been used as a basis for the generation of the 4D city model. The physical model (~1:1000) was scanned by a fringe projection system for 3D modelling, while the digitized data from the map were combined with height information from different data sources. These two geo-referenced 3D city models were used to derive further epochs (1200, 1400, 1589 and 1700) using different historical bird's-eye views (isometric views) of the city. For interactive navigation and visualization of the 4D city model a program was developed using the Google Earth Application Programming Interface.

Keywords: 4D, CAD, City Model, Modelling, Point Cloud, Visualisation.

1 Introduction

Due to the increasing number of users, such as urban planners, architects, monument conservators, environmental specialists, mobile telephony specialists, security forces, large internet providers and manufacturers of navigation systems, up-to-date 3D city models are at present a much discussed topic both scientifically and socially. Google Earth and Microsoft Virtual Earth offer already many 3D city models in their virtual globe. Additionally, the V-City project, a European research initiative, is currently creating a system for intuitively exploring large urban areas with a high degree of detail. Bringing together technologies from geoinformatics, virtual reality, computer graphics, and computer vision, the system constructs detailed 3D city models from geo-positioned aerial images and building footprints [1]. Although 3D representation of city models in web-based geo-viewers is state-of-the-art today (e.g. see for Berlin, [2]) , digital historical city models, which offer a view of a city in the past, represent a

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new and broad range of uses. However, historical city models cannot be generated using modern measuring procedures such as airborne laser scanning or aerial photogrammetry, so they are frequently derived from a broad diversity of data sources such as maps, photographs, lithographies, paintings or wooden models in museums. Therefore, close-range methods must be used for data recording.

In order to provide a historical city model from Hamburg, different recording methods appropriate to the data source were selected and used. For the generation of a 4D city model two data sources were used as a starting point – first a wooden model with approximately 5000 buildings representing Hamburg in the year 1644 from the Hamburg museum, which was manufactured in 1936 at a scale of approximately 1:1000 (Fig. 1 left) and second a map from 1859 at a scale of 1:4000 (Fig. 1 right), which represents one of the first official measurements and mappings of the city.

Fig. 1. Basis data for the generation of 4D city model of Hamburg – wooden model from the year 1644 in the Hamburg museum (left) and map of the city centre from 1859 (right)

Similar work has already been completed for the cities of Duisburg (Germany), Solothurn (Switzerland), Prague (Czech Republic) and Toul (France). For the medieval city of Duisburg virtual models of the years 1000, 1200 and 1566 were generated from three wooden models (including approximately 800 buildings) at a scale 1:500 for visualisation in Google Earth using terrestrial laser scanning [3]. The historical model of the city of Solothurn from 1830 (scale approximately 1:500, approximately 900 buildings) was recorded using different measuring systems (precision hand scanner Leica T-Scan, digital reflex camera Nikon D200 and a HD video camera) in comparison [4], in order to reconstruct the urban 3D scenery with texture for 3D GIS integration. For the reconstruction of the historical city model of Prague (scale 1:480), which represents the city in the years 1826-1839, a robot was developed to take approximately 300,000 photos of the entire paper city model with an area of 3.5m x 6m using a digital camera requiring two months' work [5]. The complex model contains 2000 buildings and 7000 additional objects on 60 sections such as sheds, walls, statues and trees. In contrast the automatic 3D reconstruction of the smaller wood and paper model from 1840-1860 of the city of Toul (located close to Nancy in France) represents a smaller expenditure, since the area to record by photos and laser scanning was only 2.3m x 2.2m containing approximately 900 buildings [6].

Due to the small scale of 1:1000 and the high number of buildings in comparison to the other models described above, the historical wooden model of Hamburg represents a special challenge for data acquisition and 3D modelling. In contrast to the three epochs of the city model of Duisburg the different time epochs of historical Hamburg in 4D were derived from additional data sources such as map and perspective views.

2 Data Acquisition

2.1 Recording of the Wooden Model

For the two selected data sources (wooden model and map) different recording methods were used. Due to the technical specifications and successful testing the fringe projection system ATOS I 2M was used for the recording of the wooden model (Fig. 2). The system consists of two cameras (2 MPixel) and a projector to record a spatial volume of 55 x 44 to 500 x 400mm^2 with 2 million points and a point distance between 0.04-0.31mm. The accuracy of the measuring system of approximately 40 micron is more than sufficient for this task. The stable column tripod and the long arm permit flexible and optimal scanning of the wooden model, which is installed onto two plates (eastern and western part with a total area of 2.8 x 2.8m^2) with densely built-up areas in the city centre.

After system calibration a total of 431 scans were acquired in one working day, which corresponds to a data volume of 821 million points. Complete scanning was ensured by overlapping each individual scan, whereby the scans were registered using circle targets attached in the model area (Fig. 4 right). Each scan was transformed into the defined coordinate system immediately after the measurement using the targets as control points. After adjustment and meshing of the scans the total number of triangle meshes was automatically reduced to 41.7 million triangle hubs (4.1 GByte), which were used as a point cloud for further data processing.

Fig. 2. Scanning of the wooden model in the Hamburg museum using the fringe projection system ATOS I (left) and illustration of a recording window with structured light (right)

2.2 Digitisation of the Official Map

The building ground plans were manually digitised in the official map of 1859 (scale 1: 4000 with a format of 94.3 x 60.6 cm^2, scanned with 300 dpi, 11,138 x 7,164 pixels). Since the map contains only planimetric information, the building heights had to be derived from available façade plans, photographs or paintings, in which the building height was calculated using the simple relationship between length and height of each building's basic side. In areas without precise information the heights of the buildings were estimated according the heights of the surrounding buildings. For a further refinement of the virtual model additional information relating to building heights from the public record office or the office for cultural heritage in Hamburg would have to be selected. However, collecting this information for all requested buildings represents a substantial manpower investment. The 3D modelling of the digitised building ground plans is described in section 4.2.

3 Automated Building Extraction

In order to be able to process the huge point cloud produced with the fringe projection system and to extract building models in the point cloud, a C# program was developed for automation in the processing of the point cloud. To quickly generate building ground plans by manual digitisation a horizontal sectional plane was defined in the point cloud at the eaves of the building (Fig. 3 left). This processing step was necessary due to the densely built-up areas (Fig. 3 right); otherwise no digitisation would have been possible. Unfortunately, no cadastre ground plans are available from that time.

Fig. 3. Digitised ground plans in the point cloud (left), illustration of the dense built-up area in the nadir photograph of a part of the wooden model from 1644 (right)

Since the ground plans were specified in the eave of the buildings in the further data processing all points below the eave could simply be eliminated to separate points from roofs and walls. Using the ground plans the points belonging to each particular house were then selected using a Point-in-Polygon procedure from the point cloud. To increase speed the ground plan was halved on the short building side, so that only one roof side had to be analysed. With these selected points a roof plane was iteratively computed. To achieve a symmetrical roof afterwards, the plane was flipped horizontally on the other side of the roof. Finally, eave and ridge height were then computed using this plane, in order to construct the other facade components (walls and gables). For the automatic construction of building models two substantial assumptions were met due to the building model structure: the wooden model consists only of buildings with saddle roofs and each building has only four basic sides. With these assumptions the buildings were automatically constructed using the developed software. Nevertheless, automatic generation of 3D models from complex roof types and ground plans with more than four walls was tested by implementation of the procedure described in [7]. To increase the flexibility of the software the Iterative Self-Organizing Data Analysis Technique (ISODATA) from [8], a sophisticated and well-engineered algorithm, was also tested with promising results. However, for this data set the simple procedure mentioned above was used to construct the 3D city model for each block (tile). For example, Fig. 4 illustrates the results of the automatic construction of all buildings in block 5 using the modelling software. Green buildings show the correctly modelled houses (the threshold for the normalized residual NV < 3.3), yellow houses show the results over the threshold (NV > 3.3), and all red buildings represent the results with failed computations, i.e. the inclination of the roof is zero. The software automatically generates DXF files for further post processing.

Fig. 4. Results from the modelling software after two iterations for Block 5 (eastern part); green: NV < 3.3, yellow: NV >3; 3, red: roof inclination is set to 0

In the modelling software the following parameters can be defined before computation: a) normalised residual (NV = 3.3) as stop criterion for the adjustment, b) Sigma NULL *a priori* (iteration 1 = 0.5mm, iteration 2 = 1mm), and c) percentage of the maximum number of points to be eliminated in the adjustment (20%). Points will be eliminated in the adjustment as long as the defined value for the normalized residual or the threshold of 20% is not reached. The automatic construction of the buildings was performed for all 20 blocks of the scanned wooden model. In the statistics it was obvious that the results of the computations could be significantly improved by changing the Sigma NULL *a priori* from 0.5mm to 1mm in the second iteration. Additionally, the evaluation of the statistics showed that the roof halves in the western part of the city model contain 960 points on average, while they contain only 370 points in the eastern part. These values represent the density of the urban development, i.e. only huge house blocks are available in the western part, while a dense building coverage exists in the eastern part between the fleetes (side-canals). In total, the software needed 17 hours for the computation of all 20 blocks comprising 5437 buildings.

The generated CAD model was finally compared with the point cloud to check the quality. In block 5 of the eastern part of the model only 115 (7.5%) of 1536 buildings were computed incorrectly. All incorrectly computed buildings were automatically marked as flat roofs, which were later adapted and/or corrected manually. 1257 buildings (74.3%) show deviations in the roofs within the range between -0.5mm and +0.5mm, while only 279 buildings (18.2%) have deviations within the critical range from -2 mm to + 2 mm.

4 Modelling

The modelling deals with the generation of 3D CAD objects for the setup of the historical 4D city model. In order to generate 3D city models from the prepared data of the fringe projection system and from the map, further work procedures are necessary.

4.1 Modelling of the Wooden Model

Using the modelling software specifically developed for this task the majority of the buildings could be automatically generated, as already described in section 3. However, more complex buildings such as churches cannot be automatically generated by this software, thus manual modelling was required. In the program AutoCAD using the Plug-in CloudWorx ground plans and profiles were produced in the point cloud using polylines, from which surface and volume bodies were formed. The bodies could be merged or combined using Boolean operations (difference, union and intersection) for the construction of complex objects. Since this 3D modelling in point clouds is standard today in the field of terrestrial laser scanning, the individual manual work procedures are not described here. Readers are referred to literature with appropriate practical examples from the HCU Hamburg (e.g. [9], [10]). In Fig. 5 the example of modelling of the church St. Katharinen is represented. 3D comparison of CAD model and point cloud showed an average deviation of 0.2mm. From the fringe projection system data not only building models but also a digital elevation model (DEM) was derived, as described in detail in [11].

A significant problem with the generated data was the geo-referencing (transformation into a common coordinate system), since logically no surveying data exist from the year 1644. In order to reference the model, first the two model parts were aligned to each other using manual measured points in the wooden model and sub-construction. The detailed procedure is described by [11]. The quality of the merging of the eastern and western part was examined visually by checking all roads and fleetes connecting both parts. For the final geo-referencing of the entire virtual model control points were required on buildings which did not change at all over the centuries. Although in other places such criteria would usually be fulfilled by churches, this was not always possible in this case because of the number of objects destroyed in the Second World War. However, some buildings did survive and a good example of this is the church St. Katharinen, which was already mentioned, from the year 1256 and which retained its characteristic shape despite changes since 1644; thus the corners of this building could be clearly identified as control points. In total six control points distributed over the city were found with UTM coordinates to compute a 2D Helmert transformation using PANDA. The residuals at the control points were in the range of -4 to +6 meters in the Y coordinate and -1 to +2 meters in the X

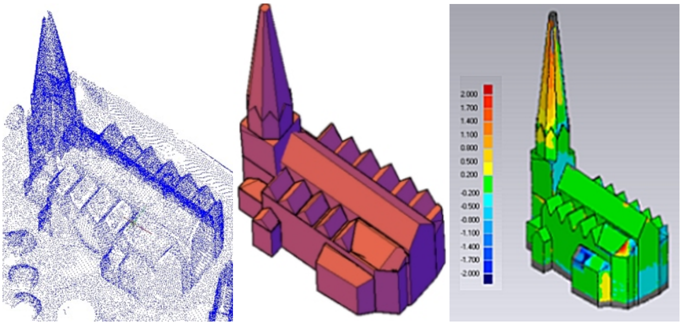

Fig. 5. Manual modelling of the church St. Katharinen – the point cloud (left), CAD model (centre) and 3D comparison of CAD and point cloud (right)

coordinate. Surprisingly it turned out that the wooden model has a smaller scale of 1:1250 than previously thought. Thus, the entire 3D model was geo-referenced into the UTM system (WGS84) making it available for subsequent data processing and presentation.

4.2 Modelling of the Digitised Ground Plans from the Map

The surveying work for the official map using in this project was carried out between 1855 and1859. The geo-referencing of the map by 2D Helmert transformation was performed in the software Geographer using eight control points (churches and bridges). Maximum residuals for the control points were 0.9m in the Y coordinate and 0.5m in the X coordinate. Subsequently, the manual digitisation of the ground plans from the map were carried out with AutoCAD Map 3D, while the height determination and generation of the volumetric building models were conducted using plans and photographs. The different basic data for the heights of the buildings represent a heterogeneous data quality, which is illustrated in Fig. 6: green = height from facade plans (scaled construction plans), yellow = heights measured in photos and red = no information available, building height estimated from surrounding buildings and accordingly adapted. Thus, the height information in green represents the best quality, while in red the height has been derived from the most uncertain sources. For all yellow marked blocks a different number of photos from one or more perspective views were available. Since it was too time-consuming to derive a height for each individual building, the building heights were adapted block-by-block as a generalisation process. However, this compromise can be corrected in future work, since all building models are simple and readily changeable in the database. Thus it should be possible in the near future, to change the status as represented in Fig. 6 from red to yellow or green for the entire city area if requested.

4.3 Data Export

After the modelling, quality control and geo-referencing of all parts of the wooden model and of the map was carried out, the data was converted block-by-block into the

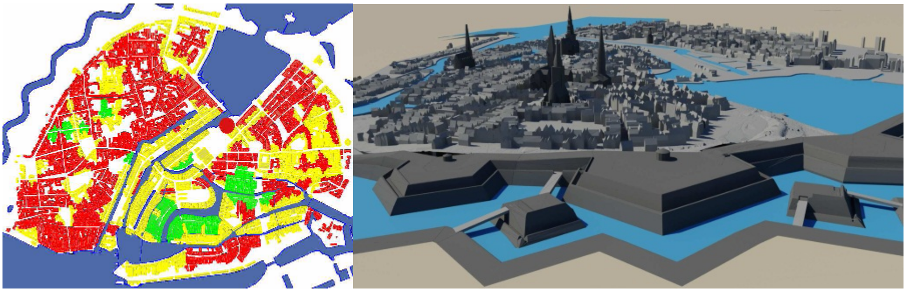

Fig. 6. Overview of the quality of the building height (left): green = facade plans, yellow = photographs, red = estimation/old maps, and perspective view of the 3D model from 1644 (right)

Fig. 7. Perspective view at the 3D city model of the Free and Hanseatic City of Hamburg from 1859 superimposed on the map from the same year

standard format KML/KMZ of Google, since the digital globe of Google would be used as visualisation platform of this data. Fig. 6 and 7 show the generated 3D city models of Hamburg from the years 1644 and 1859.

5 Generation of the 4D City Model and Its Visualisation

In the last step a time series was compiled using the two generated 3D city models and further city models derived from these two basic data sets. As well as the two generated models further epochs from historical maps and isometrical views were derived by interpolation. In particular isometrical views are suitable for the derivation of earlier epochs, since information about the number of buildings and their locations can be easily extracted from this type of representation. For the first epoch in the 4D city model the isometrical view from 1200 was selected, since this view is one of the first representations of Hamburg, thus allowing a statement to be made about the number and location of buildings existing at this time. The second model was derived from a map from the year 1400. At this time the layout of the city was completed in the form that it retained for the next 200 years. For the third epoch the isometrical view of Hamburg from 1589 was used, since this view shows Hamburg before the building of the ramparts. The model of 1644, which is the fourth epoch in the 4D city model, presents Hamburg as the strongest fortress in Germany. The 3D city model from 1700 was derived as the fifth epoch using the isometrical view from 1700 and the 3D model of 1859, which illustrates the sixth epoch of the 4D city model, as the basic information.

For the extrapolation of the three epochs from 1200 to 1589 the model of 1644 was used, while for the epoch 1700 the 3D city model from 1859 was the data basis. In the isometrical views the existence of roads and house blocks could be assigned to the different epochs, so that the 3D city models could be easily derived from the previous temporal epochs. With this approach a timestamp could be generated for each house block, which was registered into a database. In Fig. 8 the 3D city models of the years 1200, 1400, 1589 and 1700 are visualised.

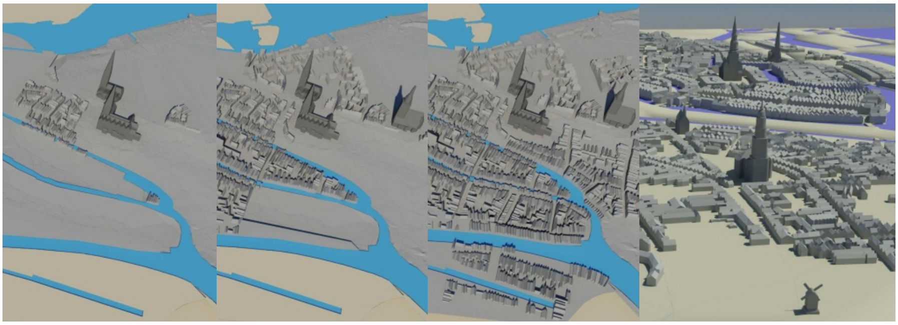

Fig. 8. View at the Hamburg 3D city models from 1200, 1400, 1589 und 1700

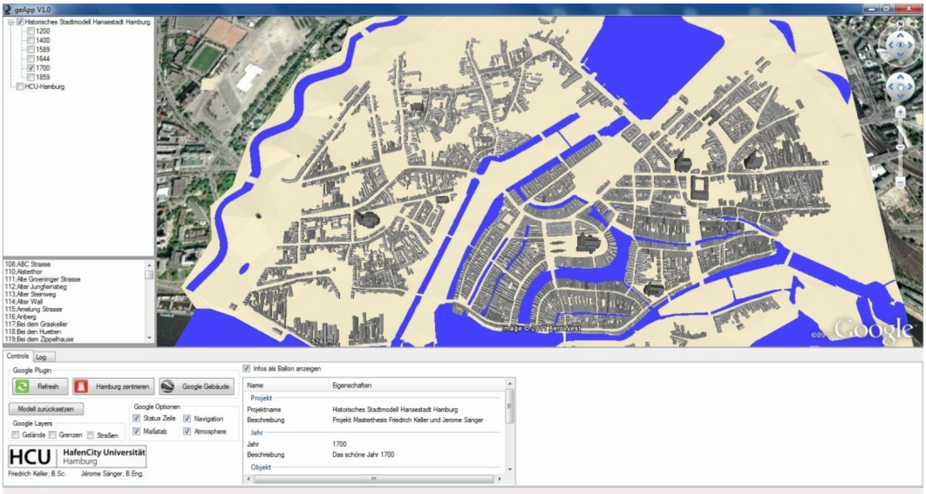

Fig. 9. Graphical user interface for the geo browser of the 4D city model of Hamburg

This 4D city model was visualised using a browser that was developed in-house with a database based on the virtual globe "Google Earth" to offer further analyses in the future. Finally, the technical integration of the 4D city model was realised in Google Earth (Fig. 9) using the Application Programming Interface. The program offers the possibility for navigation through the 4D city model with its six epochs as well as the representation of meta data (e.g. origin, description, history, etc.) for individual objects. All streets and buildings, which exist only once in the database with different timestamps, can be visualised by requesting the specific time epoch. For access to the 4D city model a network architecture was created, which is based on a client-server-model. Several servers are available, which store the different data sources and will be transferred if requested to the client computer for representation by SQL instructions. With this configuration it is possible to visualise the different epochs of the historic city model and to perform multi-temporal analyses.

6 Conclusions and Outlook

In this contribution the generation of a historical 4D city model of the Free and Hanseatic City of Hamburg is described using different data sources with different quality for the derivation of the 3D city models from six time epochs. The time series represents the development of the city of Hamburg until the 19th Century. In future it is even possible to extend this model to include the current 3D city model from the 21st Century. Despite the high degree of automation applied to the generation of buildings from the point cloud of the wooden model, important work procedures such as digitisation of ground plans, modelling of complex buildings and the digitisation and modelling of the buildings from the map were accomplished manually. This resulted in an entire project expenditure of 800 hours in total, which corresponds to a project cost of € 40,000 if we assume €50/hour for an engineer. Almost 50% of the time was needed for digitisation and modelling, which clearly shows that for future production of such historical city models automatic procedures for digitisation of ground plans, as described in [12], should be used for optimisation. Programming and software development used approximately 30% of the time. However, this could be significantly reduced for further similar projects since only fine-tuning of the existing software might be necessary.

The available historical 4D city model of Hamburg represents a very interesting data basis for several different applications (for example in urban planning, architecture, and history), which promises to have an enormous development potential for supplementary and intensified work. Apart from a refinement of the 3D models through addition of more detailed building information from the monument preservation office and from public records, further epochs could be added from the 19th and 20th Century. To increase the attractiveness of the models (synthetic) textures for the buildings and vegetation for the environment could be integrated into the scenery. For the museum increased use of multimedia tools to provide virtual tours of the medieval city using videos or interactive walk-throughs could be considered thus offering new facilities to modern museums as well as presenting new challenges.

From a scientific point of view these models could be linked with other data, such as (historical) census information, in order to make new visual or computational analyses possible. Moreover, the comparison of the modern city model with the historical models would be very interesting in order to visualise the urban development and changes in the city over a long period.

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