A COMPREHENSIVE OVERVIEW OF A CORE OF 3D GIS

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Abstract
This contribution focuses on 3D GIS, compares it to the classical 2D GIS: maps analogies and points out differences. The contribution focuses on all three conceptual approaches (views) to GIS (geographic data-base, cartographic and analytical).
Talking about fundamental differences, the true 3D data (comparing the 2.5D data) is the crucial change in data handling (~ capturing, modelling, processing and analyzing) ~ in a geographic data-base. The need of attribute enrichment of 3D data is stressed to keep the geodata semantic aspect.
From the cartographic point of view, there are various issues, needed to be taken into account: 2D symbolization methods are not sufficient for 3D, some of them can be used directly, some have to be modified, some new need to be developed; moreover the traditional 3D method of handling large data ~ a scale dependent map ~ has to be altered to a solution dealing with the observer position and line of sight.
Last but not least it is obvious that spatial analyses have different results when dealing with 2D or 3D data. Therefore the differences are highlighted and even current situation of implementation of true 3D analytical tools is provided.

Keywords: *3D, GIS, semantics, process, geodata*

INTRODUCTION – (3D) GIS DEFINITION

The introductory chapter of this contribution briefly sum up the history of GIS definitions, focuses on different approaches on defining the concept of GIS and answers a question if 3D GIS requires a special definition.

Discussions about a GIS definition and categorization of geographic information systems (GIS) exists from the very beginning of first so called GIS solution appeared. A comprehensive overview of GIS definition was published by Maguire (1991) and his *three* distinct but overlapping *views of GIS* (geographic data base, cartographic, and spatial analysis) together with *elements of GIS* [hardware, software, data and “liveware” (later divided to: methods and people)[1]] are still valid.

Even earlier, Burrough (1986) also stated an important GIS definition based on tools and processes: “GIS is a powerful set of tools for collecting, storing, retrieving at will, transforming and displaying spatial data from the real world”. Even this definition is still often used, see e.g. a contemporary definition used by USGS[2], ESRI[3] or even Wikipedia[4].

Burrough’s definition describes GIS by its processes making even an (usually) consecutive chain of them. It is obvious that firstly it is necessary to collect and store the (geo)data; then the data can be transformed/processed, analyzed and displayed/visualized.

Please note that any of above mentioned definitions (or even their later clones referenced in footnotes) do not mention a dimension of spatial data. The only reason, why GIS dealt almost exclusively with two dimensional data in the past, was because of both hardware and software limitations.

Therefore, a concept of “3D GIS” perfectly fits into above mentioned definitions. However, incorporation of the third dimension to geographic information system has influenced an implementation of all GIS processes, starting in data collection continuing in data processing and analysis and ending in the presentation of results (such an influence to each

[1] https://www.geographyandyou.com/science/technology/five-basics-gis-components/

[2] https://www.usgs.gov/faqs/what-a-geographic-information-system-gis

[3] https://www.esri.com/en-us/what-is-gis/overview

[4] https://en.wikipedia.org/wiki/Geographic_information_system

process is analyzed four following chapters). Obviously, also the three views of GIS have been influenced (as can be identified in bullet lists in the chapter Discussion and conclusion).

COLLECTING DATA FOR 3D GIS

This chapter points out changes of existing collection methods or even new methods of data collecting according to requirements of 3D GIS.

Surveying methods

Naturally, traditional **surveying methods** do not need a change, similarly to **measurements by Global Navigation Satellite Systems** (GNSS) as all of these methods support 3D data collection and can produce three dimensional *vector data*.

Talking about methods of **remote sensing** (incl. **photogrammetry**), even those methods can reconstruct a 3D shape of a scanned area of interest using a principle of stereo perception, see e.g. Paine (1976). What is (relatively) new in those methods is an implementation of automatization of the process of 3D shapes reconstruction by **Structure from Motion** (SfM) algorithms whose produce a three dimensional *cloud of points* or a *mesh* from overlaying imagery. The SfM calculates the geometry of the scene, camera positions and orientation automatically without the need to specify a priori, a network of targets which have known 3-D positions by using a highly redundant, iterative bundle adjustment procedure, based on a database of features automatically extracted from a set of multiple overlapping images, Westboy (2012). Both aerial and terrestrial assemblies are used. Aerial systems can be equipped on even on Unmanned Aerial Vehicles (**UAV**s), so called drones. A drone based assembly significantly reduces the cost of acquired data.

Next, **laser scanning** (also called Light Detection and Ranging ~ **LiDAR**) is a powerful method using laser beam to acquire a three dimensional *point cloud*. The principle of laser scanning (see e.g. in Lohani, B. (2008)), consists of emitting a laser beam and recording of its multiple reflections. This key feature is exploited heavily by airborne systems, as (after data cleaning process, excluding gross errors) first return is interpreted as a *digital surface model* – a representation of top faces of all objects on the terrain (both vegetation and manmade features) or terrain itself in open areas; the last return is then considered as *digital terrain model* - representation of terrain relief of bare Earth surface (without any natural or artificial features), Jedlička (2009).

Methods of 3D shapes modelling

The above mentioned data collection methods produce a raw version of 3D data. It means that such data needs to be further processed to be stored in data structures enabling further effective use (such as analysis and presentation). A majority of the collected data can be directly imported in a geographic data base and handled by GIS tools.

However, data with complex 3D information (typically buildings) needs to be processed by a modelling tool to create a 3D model before an import to geographic data base. Typically a **Computer Aided Drawing** (CAD) software is used for creating the 3D models, which are then converted to a geographic database. Even there are attempts to offer the modelling functionality natively by GIS tools[5], the results which can be achieved by those tools are still weak in comparison to CAD systems.

On the other hand, a detailed 3D modelling process is time consuming even in CAD based systems and therefore a different approach, called **procedural modelling of cities and buildings** has been designed (Parish & Müller (2001)) and developed[6]. This approach consists of generating a 3D model by applying procedural rules[7], exploiting attributes of the data (such as number of floors, building height, roof type, or even of number or types of windows, etc.). See details about using this approach in Tobiáš, Cajthaml, & Krejčí (2017).

Also a combination of both approaches is possible and can be effective, by using CAD models for objects important for the purpose of the 3D models and procedural modelling to generate the less important objects.

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[5] A City Engine solution from Esri is the contemporary most developed solution https://www.esri.com/software/cityengine

[6] https://cehelp.esri.com/help/topic/com.procedural.cityengine.help/html/quickstart/overview.html

[7] See an example of procedural rule language called CGA: https://cehelp.esri.com/help/topic/com.procedural.cityengine.help/html/cgareference/cgaindex.html

DATA STRUCTURES AND STORAGE USED BY 3D GIS

Data structures used by 2D GIS

Talking about **two dimensional space**, *two approaches of the real world representation in digital environment* can be distinguished, Vector and Mosaic. As those representations are used in 3D GIS as well it is worth to mention them bellow.

Vector representation

Vector representation consists of **geometric primitives** (points, lines and polygons) which are used for **representation of objects** of interests (such as trees, rivers, forests for nature data or e.g. crossroads, streets and buildings for manmade features).

Point is defined by its X, Y coordinates that determine a location of a described object in the 2D space. A dimension of point geometric primitive is 0, as nothing can be measured inside the point.

Line is defined by coordinates of its beginning and end (X_1, Y_1; X_2, Y_2). A dimension of line equals 1, as a length can be measured. **Polyline** is then defined as an ordered list of lines. Line or polyline represents usually a centerline of a described object[8].

Polygon is then defined as a closed ring of lines (or polylines) and reaches a full dimensionality of 2D space, as an area can be measured. It is worth to mention a special type of polygon defined by exactly three lines – **triangle** – as it is used as construction primitive for triangle based mosaics. Polygon represents an area covered by a described object (a footprint of the object on the Earth's surface).

Mosaic representation

Mosaic composed of cells is used for **representation of continuous phenomenon** (such as terrain shape or ground temperature coverage). Mosaic can be characterized by a shape of its cells (typically triangular, square or hexagonal) or by an irregular or regular division of space. The most used mosaics are regular **grid**[9] with square cells and Triangulated Irregular Network (**TIN**).

Mosaic dimension is defined as 2.5D (see e.g. Slocum et al. (2008)), because its third coordinate (e.g. Z) is represented as a function of planar coordinates X and Y (1).

$$Z = f(X, Y) \tag{1}$$

Using grid mosaic, Z value is stored as a value of a cell and there cannot be two cells with the same planar coordinates X, Y. TIN stores Z values for each triangle vertex; TIN cannot have two triangle vertices with identical X, Y coordinates and different Z coordinate because of its creation by two dimensional constrained Delaunay triangulation as described e.g. in Chew, L. P. (1989) [10]. In any case, 2.5D mosaics represent a **surface** of represented phenomenon.

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[8] Polyline can also represent borders of an object, however that is not a recommended approach and a polygon should be used for such an object.

[9] Grids are also used for all imagery: photogrammetry, earth observation, textures, etc.

[10] Note that from geometrical point of view TIN is constructed as a two-dimensional mesh, see e.g. Bern & Eppstein (1992).

Data structures specific for 3D GIS

In fact, all data structures used in 2D space can be easily adopted for use in 3D space as well. A definition of **point**, **line** and **polygon** (**triangle**) can be extended by adding a third coordinate (Z). Note that a polygon with 4 and more vertices defined in 3D space can easily become a non-planar. Polygons are therefore often filled by triangles to be portrayable[11].

Points are often used in large set, so called **cloud of points** (or point cloud) to represent. Lines have simply the third coordinate added. Such a **3D line** then often represents an **edge** of adjacent **faces** represented as 3D Polygons.

Mosaics (**grid**/**TIN**) can be used directly, as they already have third coordinate defined.

3D vector structures

3D vector structures are used for **representation of objects** of interests from real world ~ analogically to 2D vector structures. But it is important to stress that there exists a difference of digital representation of reality between 2D and 3D space. Geometric primitives (point, line and polygon) can still represent a reference location of a real world object, the object center line or an area the object covers on the Earth's surface. But talking about a representation of full 3D shape of an object of real world, a wireframe, surface (boundary) or volume model come.

A 3D **wireframe model** is an edge or skeletal representation of a real-world object. 3D wireframe models consist of points, lines, arcs, circle, and other curves that define the edges (or also center lines) of objects.[12] As the model does not represent faces of the modelled object, it comes easily to be ambiguous, see more in e.g. Zhengxu (1990).

A model based on representation of both edges and faces of the represented object is called **surface model** but it can be also referenced as a **boundary representation** (B-rep for short), see e.g. Choi (1989). A solid object is represented as a collection of connected surface elements (edges and faces), describing a boundary between solid and non-solid[13]. The boundaries does not necessarily cover the whole object, and often they do not, e.g. a building is represented just by its walls and roofs, but no edges of its foundations are modelled.

A Constructive solid geometry (CSG)[14] is a technique producing **volumetric models** of real world objects. CSG uses well described mathematical solids (such as cuboids, cylinders, prisms, pyramids, spheres, cones and others) and Boolean operators to construct a more complex solid models, Foley (1996). CSG is used in CAD systems, but contemporary 3D GIS packages do not support such a process of volumetric model creation. A usual type of volumetric model in GIS is a **closed surface model**. All edges of a closed surface model are adjacent to exactly two faces. A building modelled by its roofs, walls and foundations is an example of a closed surface model.

It is worth to mention that faces used for representation of an object boundaries are usually modeled as sets of triangles. Such a data structure corresponds to a triangle mesh in 3D (see section below).

3D Mosaics

There are two more types of mosaics which can be used in 3D GIS: **three-dimensional triangle mesh** and **3D grid**. Moreover a **tetrahedron mesh** should be mentioned for a comprehensive overview. But contrariwise to 2D, there is different usage of these data structures, as explained below.

A **Tetrahedron mesh** is a volumetric representation composed of (irregular) tetrahedrons. Tetrahedron mesh is created by a tetrahedralization method, see e.g. Bern & Eppstein (1992) for details. A Mesh of tetrahedrons is not used in 3D GIS directly, but a 3D mesh of triangles, which can be extracted as a surface of a tetrahedragonalized object is used widely.

A **three-dimensional triangle mesh** is a set of consecutive triangles which does not have the Z = f (X, Y) limitation of triangular irregular network (TIN). A 3D triangle mesh can be computed by a full three-dimensional triangulation

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[11] Note that making a triangularization of just a polygon boundary vertices is sometimes not a suitable way as a nonsensical shape can be easily created. Sometimes it makes more sense to fill triangles to the polygon from other data – e.g. such a surface data from TIN (see more in the chapter about visualization).

[12] https://knowledge.autodesk.com/support/autocad/learn-explore/caas/CloudHelp/cloudhelp/2016/ENU/AutoCAD-Core/files/GUID-84E193D7-A18D-4EE2-B978-19E4AFBCAEEC-htm.html

[13] https://en.wikipedia.org/wiki/Boundary_representation

[14] https://en.wikipedia.org/wiki/Constructive_solid_geometry

(tetrahedragonalization) and following extraction of triangles lying on a surface, see e.g. Bern & Eppstein (1992) or later in Golias & Dutton (1997) for particular methods. However a very common source of a 3D mesh of triangles is a CAD model, where 2D triangularization was processed for each particular 2D face of the model.

As follows from precedent paragraph, three-dimensional mesh of triangles is still able to describe just a boundary of phenomenon or an object. However, TIN (or GRID) is used for phenomenon (such as mentioned relief) boundary, three-dimensional triangle meshes are not used for phenomenon boundary representation. But they are heavily **used for representation of object boundaries** in surface model (both non-closed and closed).

As mentioned, 2.5D mosaics can be used to represent a boundary or a level of continuous phenomenon (e.g. TIN used for representation of Earth surface ~ a boundary of Earth mass; grid used for temperature distribution on certain level above ground). But these structures cannot portray a 3D phenomenon (Such as e.g. temperature, noise or indoor navigation spaces) in its complexity. A native data structure for portraying 3D phenomenon is three dimensional grid composed of cells also called **voxels**[15]. At least some contemporary GIS packages[16] can handle a **3D grid** of cells called voxels. 3D grid can be understand as a three dimensional array and it is so far the only data structure capable to handle fully three dimensional phenomenon (such as e.g. temperature, noise or indoor navigation spaces) in GIS.

Usage of data structures in 3D GIS

A three dimensional GIS model of an area of interest typically consists or should consist of:

1. At least one **digital terrain model**, represented by TIN for detailed models or grid for larger areas and when a lower of DTM detail is acceptable.
2. Most of the **geodata** are then **draped on** such a **terrain**, just taking over the third coordinate from the terrain model. It is easy for points. But for lines, there is a need to insert new vertices, when a change in direction does not comes in X, Y plane, but just in Z coordinate. Even more complicated it is for polygons, where a triangulation has to be extracted from DTM and inserted into the polygon area. Otherwise it can lead to lines or polygons diving underneath the terrain.
3. Points can be also represented by a full **3D symbol** from a predefined symbol library (e.g. trees, city furniture, etc.). **Lines and polygons** can be **extruded** to a specified height to be visualized as planes respectively volumes. Points, lines and polygons can of course be also placed over or underneath a DTM by specifying different **base heights**.
4. Using a combination of above mentioned techniques a quite advanced model can be created even if maximally the 2.5 dimensional data structures were used. But a true 3D GIS originates, **when full 3D data structures** are used. It means an incorporation of 3D data structures (usually for models of manmade objects, such as buildings, bridges, etc.). As mentioned contemporary GIS struggles with 3D models design and drawing tools. Therefore 3D models are often created in CAD in a **local coordinate system**, then converted to a data format suitable for 3D GIS and referenced to other geographic database by an **anchor point**, direction of **rotation** and a **scale**.
5. Last but not least – 3D GIS should not resign on spatial data relationship to attribute data typical for GIS in 2D. Many contemporary 3D GIS scene have been created primarily for visualization purposes and there is a lack of **relationship between 3D data and attributes**. Typically a building or even block of buildings is created as one object, without any further segmentation. Attributes can be then related just to the object as a whole, but not to its particular parts. This leads to more generic descriptions in attribute domain and a further analysis is then rationally less detailed precise as well.

PROCESSING AND ANALYSIS IN 3D GIS

3D GIS of course builds on processing and analytical tools of classical GIS. Most of them can be used in three dimensions as well and it is not a matter of this chapter to describe all of them. This chapter focuses on describing specifics of some processes when 3D is taken into account.

[15] http://wiki.gis.com/wiki/index.php/Voxel

[16] See e.g. GRASS GIS: https://grass.osgeo.org/grass64/manuals/raster3dintro.html or https://3d.bk.tudelft.nl/projects/bigvoxels/

Processing of data

Full 3D models of objects of interest are created in CAD and have to be referenced into a geographic database managed in GIS. It means that **not all data is manageable in one software** (GIS). If there is a need of a 3D model update, it has to be done in a CAD and then reimported into GIS – this can cause an inconsistency in data. The only present exception is CityEngine software, which is able to edit 3D models directly in ESRI geodatabase format, where the ordinary geo data can be stored as well.

Data interoperability in among various GIS data formats is quite good for 2D data structures, but not for 3D data structures. Suppose that a data format A is capable to handle both 2D and 3D data structures (e.g. shapefile using point, polyline or polygon; or multipatch). When there is stated that a data format A can be converted to a format B, then such a conversion can mean that only X,Y coordinates are converted, but Z coordinate is partially or completely lost [17].

Classical GIS packages are able to **transform data from one geographic coordinate system to another** usually using a seven-parameter Helmert transformation. As the Helmert transformation is three dimensional, it works well. But a **conversion from orthometric heights to ellipsoidal heights** (and vice versa) by a standalone tool, see e.g. Kotsakis, Christopher. (2008), but implementation to a GIS is still in a development phase[18]. Therefore, currently such a conversion can be done for points but is difficult for lines, polygons or even 3D models.

Analysis of data

Again, many two dimensional analysis still make perfect sense in 3D GIS and many analyses of 2.5D data (such as a distance analysis taking terrain into account) are well interpretable in 2D space, but can be definitely used in 3D GIS as well.

Talking about a pure **3D analytical tools in GIS**, there can be seen an approach analogous to classical two dimensional tools. It means that there can be seen general operations, such as Intersect 3D, Union 3D, Inside 3D, Buffer 3D, etc. and operations supposed to be chained to target a specific geographically focused question, such as e.g. SkyLine, SkyLine Barrier and Skyline Graph. But whether general or targeted operations are constructed as **atomic tools** (input –>operation –> output) whose can be **chained to a process** solving a particular research question ~ following simply the same philosophy as analytical tools in usual GIS.

Any detailed description of particular GIS package would become almost instantly obsolete, because of rapid development in this area. But generally speaking, the most evolved 3D analytical tools can be found is ArcGIS[19].

It is worth to mention that GIS interferes with other domain specific software in 3D domain, such as software for weather and climatic forecast, floods modelling, noise modelling, signal propagation, etc. A current, well proven approach is to **prepare geographic data in GIS**, export them an above domain specific software, **run the analysis externally**, import results back and **visualize results in GIS**. This will probably remain a dominant approach in future for some of mentioned domains (e.g. meteorology). However for other domains, like e.g. a widely used analysis of signal propagation, a GIS based solution can evolve as well[20].

VISUALIZATION OF A 3D SCENE

This chapter focuses on matters related purely to GIS. The chapter is *not going to describe advanced 3D scene visualization techniques* such as shadow modelling, ray-tracing, etc. (as they belong to computer graphics).

Also a **type of display** in not addressed in detail. Just to mention in general, having a 3D scene, it can be displayed on:

- Monitor – then it is perspective visualization. A perception of depth emerges by moving the virtual observer position or line of sight.

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[17] https://gis.stackexchange.com/questions/163711/can-qgis-import-multipatch-geometry-type/163721

[18] See e.g. https://gis.stackexchange.com/questions/244383/changing-the-vertical-height-from-ellipsoid-to-a-local-vertical-crs/244387

[19] http://pro.arcgis.com/en/pro-app/tool-reference/3d-analyst/an-overview-of-the-3d-analyst-toolbox.htm, http://pro.arcgis.com/en/pro-app/tool-reference/3d-analyst/an-overview-of-the-3d-features-toolset.htm

[20] http://www.spatialanalysisonline.com/HTML/viewsheds_and_rf_propagation.htm https://solutions.arcgis.com/telecommunications/help/coverage-maps/

- Monitor using passive or active glasses / 3D monitor – a full stereo perception emerges.
- 3D print / hologram – physical/virtual three-dimensional scene emerges.

See experiments with different types of display e.g. in Kubíček et al. (2017).

Coming to GIS related issues. First of all, there exists solutions **displaying 2.5 dimensional data** and they are commonly called 3D GIS as well even if they do not support full 3D objects.

Next, there are two different **types of coordinate systems** used: a *Cartesian coordinate system*, speaking geographically – a projected coordinate system, e.g. an UTM Zone. Then all coordinates are in the same units (usually meters). More challenging is the other type – a *geographic coordinate system using latitude and longitude* locating both objects and phenomena on Earth globe, but a *metric units for* (ellipsoidal or orthometric) *height* – then different types of units (angular and metrical) are used for different axes. Such a situation is typical for virtual globes.

Talking about cartography, there are **two main approaches** to visualize a 3D scene, **photorealistic versus symbolized**). Photorealistic approach tends to use real world textures and create an impression as close to real world as possible. The other approach, consisting of applying a cartographic symbols on the scene, challenges contemporary cartography, as not all cartographic techniques can be transferred from 2D to 3D. There can be distinguished among techniques able to apply without a change, techniques needs to be adapted and inapplicable techniques, see more about in Hájek, Jedlička & Čada (2016, 2018).

And last but not least major issue is that **3D GIS has to deal with large data in a different way than in 2D**. Two dimensional GIS deals with large amount of data by a concept of scale dependent rendering (also called a scale dependent map) and using pyramiding and generalization techniques. But important thing is that always the whole thematic layer (or even a map) is represented at one level of detail in one view. When zoom in or out, an appropriate level of pyramid is depicted. A different approach is needed in 3D - instead of using one zoom level as a threshold for what and how to visualize, the **observer position and line of sight** have to be taken into account. Then, objects closer to observer have to be presented in more detailed way than objects away, no matter if they are from the same layer or different layers, see the picture below.

DISCUSSION AND CONCULSION

The paper goes through all processes of 3D GIS and points out major differences to 2D implementation of GIS. Main bottlenecks of contemporary 3D GIS can be summarized as follows:

- A big part of software packages so called 3D GIS still **work maximally with 2.5D data** only even when data structures for 3D representation of real world objects and phenomena exists.
- 3D editing tools are still not sufficient – an **editing outside 3D GIS** using CAD is usually performed.
- 3D models created are not structured in detail, therefore **attribute relation to geometry is not detailed** as well.
- Data **interoperability** is sometimes **limited to 2D** data only.
- Conversion tools between **ellipsoidal and orthometric heights** exists mainly for points but no other data structures.
- **3D** scene is sometimes **harder to interpret then 2D** map (see e.g. Popelka & Dolezalova (2016)) it usually makes sense for detailed areas, such as a model of a city for maximum, but it is questionable for wider areas (therefore usually a globe is used when a user zooms out).
- Full **3D analytical tools** just starts to emerge.

As a complete description of 3D GIS would need much more space, the paper sometimes servers as a starting point to further study. There follows a list of themes worth elaborate further but out of scope of the presented paper:

- **Topology in three dimensions** – topological match of 2D geodata and 3D models, topology of 3D models itself.
- Building Information Management (**BIM**) – only a usage of full 3D data structures allows GIS to enter inside the buildings – the same applies for **Indoor maps and navigation**.
- **Smart cities** – GIS has to find its way to present its efficiency of smart city management, starting from an evidence of land ownership (see e.g. in van Oosterom (2013) or Janečka et al. (2018)).

- **Big data** – even if the data in (3D) GIS is usually well structured, there is a large of amount of data processed and specific techniques are needed to communicate the data effectively to the user.
- **Linked data** – it is not a 3D specific issue, but GIS has to have learn how to deal not only with well-structured but also with just semi-structured or even unstructured data, see more e.g. in Čerba (2014) or Čerba et al. (2016).
- **3D printing** – for materializing 3D maps.
- **Time as fourth dimension** – as the nature of world is dynamic, time awareness is essential for any geographic database to its appropriate representation.

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