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Survey of True 3D and Raster Level of Detail Support in GIS Software

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Abstract. Principles of stereoscopic vision have long been used in geographic data processing and visualization. In recent years, a number of mainstream digital devices and systems with stereoscopic capabilities are marketed to public, making *True 3D* visualizations more accessible. This trend may potentially impact how spatial data is visualized in everyday life. In low-bandwidth environments, however, *level of detail (LOD)* management approaches have to be applied for efficient processing of large -*True 3D*- spatial datasets. In order to outline future research needs in True 3D visualizations, this paper presents a survey on current support provided in common *Geographic Information Systems (GIS)*. The survey is designed to document whether the visualization modules of the selected systems a) can display 3D b) can display stereoscopic 3D c) can manage different levels of detail when displaying raster graphics. We document the names of visualization modules and report the types of stereoscopic operations, stereoscopic viewing methods and raster LOD management approaches in surveyed software. The analysis shows that all surveyed GIS support non-stereoscopic or stereoscopic 3D visualizations and a form of raster LOD management. Present raster LOD techniques in the surveyed systems are efficient for level switching when scale changes, however, unlike in other graphics processing software, none of them utilize human visual system inspired approaches. We hope that findings from this study will allow both researchers and practitioners to assess the current state of True 3D and raster LOD management support in widely used *GIS software*.

Keywords: GIS Software Survey, True 3D, 3D Visualization, Stereoscopic Visualization, Level of Detail Management, Geo-Virtual Environments

1. Introduction and background

1.1 Motivation

The availability of *Geographic Information Systems (GISs)* and the amount of spatial data and services increase continually. Visualization of geographic information is a crucial part of many applications developed in such systems or services. This has led *geographic information (GI)* scientists to establish research priorities for geovisualization, considering both the developments in visualization media and the growing amount of, and need for, geo-spatial data [9, 26]. In parallel, the market for True 3D with stereoscopic viewing solutions has been growing [6, 14, 30, 37, 52, 54], which further emphasizes the need for research into stereoscopic concepts and techniques to improve the visualization experience. Within this larger context, the objective of this paper is to assess the state of the art of mainstream GIS software regarding their capabilities in 3D visualization, stereoscopic visualization and raster *Level of Detail (LOD)* management. The findings about each of the GIS software are reported in a series of sections. Additionally, the results are presented in a summarized manner in Table 1, providing the reader with a quick overview.

In the next section we present some definitions which are central to the topic at hand and the remainder of the paper. Subsequently, a brief review of recent visualization approaches in GIS software and services is presented. This is followed by an introductory text on the concept of LOD management for efficient visualizations. In the remainder of the paper the software survey methodology is explained and the results are presented with an integrated discussion. An outlook on planned further research concludes the article.

1.2 Definitions

Since the presented study involves several related but separate disciplines, brief definitions of the most relevant terms (*in italics*) are provided in this section. The term *visualization* expresses forming a mental or computational picture of a scene which is not actually present to the sight [48]. In this paper, when the word visualization is used, it refers to a scene that is displayed using a digital system. *Stereoscopy* can be considered as a visualization (or viewing) method that takes the binocular nature of human vision into account (in its traditional sense, stereoscopy is the practice of using a stereoscope, an optical device that separates left and right images [48]). Combining the two terms, *stereoscopic visualization* describes the concept or process of using stereoscopic principles in an optical or digital environment to create a 3D image.

The term True 3D has traditionally been used for 3D depictions that have three independent coordinate axes [56]. This was used to avoid confusion with 2.5D representations. In GIS*,* 2.5D is used for elevation modeling where altitude is represented as an attribute. In more recent texts, the term True 3D has also been used to describe the visual experience in virtual environments [37, 66]. When used in a virtual reality context, it refers to 3D visualizations that create an immersive experience for the viewers (including stereoscopic displays and holograms) [7, 8, 37, 40]. In True 3D systems, the virtual scenes are perceived in front of, or behind the physical screen, through various (physiological and psychological) depth cues [37]. Throughout this text, we use the term True 3D to refer to configurations where stereoscopic visualization is enabled.

1.3 Visualization in Geographic Information Systems and Services

Since the early days, when GIS started as a government enterprise (i.e., Tomlinson's *Canada Geographic Information System* in 1962 [4]), it has gained wide acceptance also in industry, research and education [4, 27]. A constant trend in producing cheaper hardware with increased performance [41, 46] has led to the development of more powerful GIS software. In the early 1990s, the combination of the Internet and spatial technologies has triggered the development of concepts like virtual globes (e.g., Google Earth, NASA World Wind) and online mapping services (e.g., Google Maps and Microsoft Bing Maps) [27, 53]. GIS software are capable of creating, managing, analyzing and visualizing geo-referenced information, while virtual globes and online mapping services are markedly less powerful in some of those areas [16]. However, they provide many users the possibility of exploring the earth via 2D and 3D visualizations. Experts predict that the recent developments in both GIS and online geographic services will have a similar positive impact on *GIScience* as the personal computer has had on computer science thirty years ago [10, 53].

1.4 Level of Detail Management Approaches

While geographic data and services are becoming widely available, their accessibility may be hindered due to its growing size. Therefore, storing, processing and, more particularly, transmitting it (over a limited bandwidth) are notable problems to be solved. Among several methods that have been developed for efficient visualization of geographic information, an important one (originating from computer graphics) is LOD management. In LOD management a complex object is constructed and stored at different resolutions. For visualization, the most appropriate representation is chosen in real time, in order to optimize the tradeoff between image fidelity and frame rate [45]. In managing the LOD, the software and/or the content provider takes practical and perceptual constraints into account [13].

In vector environments, LOD management methods often involve simplifying complex polygonal meshes, while in raster environments they typically control the resolution of the images in order to strike a balance between computational needs and human perception. The selection of higher or lower resolution representations can depend on several factors including the *distance* of the object from the view-point, the *size* of the object in screen space, the *eccentricity* of the object with respect to the user's gaze, the *velocity* of the object across the user's visual field, the *priority* of the object according to the user's interest [45]. For stereoscopic visualization, the important factor is the *depth of field* where the user's eyes are converging [11, 12, 42]. Since the early 1990s more researchers have turned their efforts towards developing algorithms which maintain the visual appearance as much as possible through respecting afore-mentioned factors [45].

To obtain a set of LODs for raster datasets various techniques make use of *image pyramids* (Fig. 1). For example, *mipmapping* is a heuristic for texture mapping where the rendered LOD of the texture is dependent on the distance between viewer and the object [65]. The mipmaps represent textures using an image pyramid in which each pixel is typically an unweighted average of the neighboring pixels in the next higher resolution level of the pyramid [45].

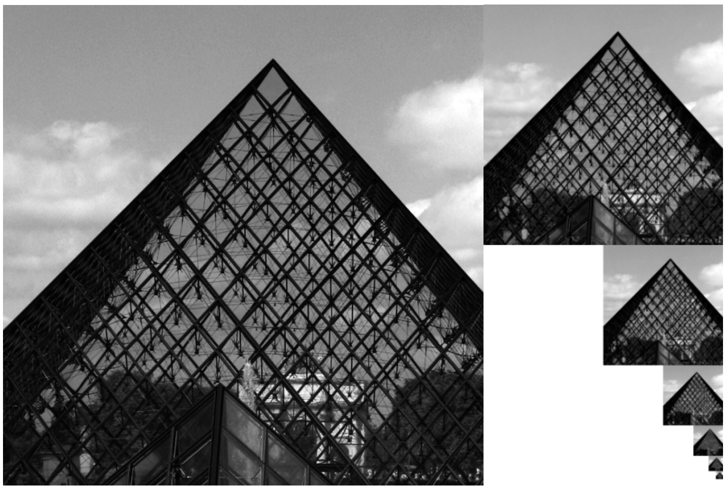

Fig. 1. Example image of the Louvre Pyramid in Paris (left) and 6 levels of detail in the corresponding image pyramid (right).

Another raster LOD management example is the *Multiresolution Seamless Image Database (MrSID)* format [44]. *MrSID* first performs a lossless encoding using wavelet transformation, then provides an optional optimization and finally decodes the image selectively. During encoding, for every input image, multi-resolution zoom levels are created. The decoding process works by running all encoder steps in reverse order and reassembling an image from appropriate zoom levels.

LOD management offers strong image compression and is crucial in many applications. It is also used for displaying large geo-datasets in virtual environments and is especially applied in low bandwidth configurations (real-time web based applications, mobile devices or car navigation systems) [7, 15, 20, 32, 38, 43, 67]. On the other hand, LOD management for stereoscopic 3D has been studied much less than the conventional LOD methods. This is possibly due to its computational complexity and historically smaller market [11, 45]. Documenting the current raster LOD support in GIS software will make it easier to assess the current state of the art and reveal the potential or ease to transfer these and other new LOD management approaches to True 3D geovisualizations.

2. Survey Results

2.1 Method and criteria

To establish the state of the art on any given subject, the most common practice is a literature review. However, approaches may also include expert interviews, questionnaires and in case of technical subjects, documentation of features of the software commonly used in the domain [39, 50]. Especially in technology driven areas such latter methods may reveal more up-to-date information about a research subject than a literature review. Thus, based on a recent publication on GIS software [57] and a market share study [31], we decided to do a survey on following software: *ESRI ArcGIS, Intergraph GeoMedia, ERDAS, Autodesk AutoCAD, Bentley MicroStation, Pitney Bowes MapInfo, Quantum GIS (QGIS)* and *GRASS*. The commercial software in our list seem to share among themselves a substantial part of the market (82%) and are significantly more popular than lower-ranking alternatives [24, 31]. Open source software are typically not included in market share studies, however, in our survey, two commonly known open source software (*QGIS* and *GRASS*) are included to introduce diversity in the study. Note that stand-alone photogrammetry software is often capable of processing and visualizing stereoscopic imagery, too; however, they are not explicitly evaluated in this study.

Modern GIS software is commonly expected to be able to process imagery and encompass all steps of handling 3D geographic information [29]. To test this assumption and to quantify current GIS' capabilities, our survey investigates following specific questions in a systematic evaluation: Does the software support *3D visualization*, if so, is it via an internal (native) or external (third-party) module? The same question is also considered separately for *stereoscopic visualization.* A further step in the software survey is to document *what kind of stereoscopic viewing* the software allows (i.e., active or passive). In geo-virtual environments, stereoscopic viewing requires intense computational interaction with a (dual head) graphics card. Hence, it is also relevant to document which GIS software support stereo-enabled graphics cards. Finally we ask: Given the GIS software supports stereoscopic visualizations, does it have built-in algorithms to compress the data and does it support some form of raster LOD management?

Through documenting whether these features exist or not, an overview can be obtained as to how commonly 3D and stereoscopic visualizations are implemented across the surveyed GIS software. The existence of such support (i.e., the tendency of companies to provide native or external implementations of these features) may serve as an indicator of the interest of the public in using these visualization options (i.e., the demand). If we observe a common trend for GIS software to support specific visualization features, it is supposed that such supply is met by a common corresponding demand.

To answer the survey questions, software manuals, GIS and photogrammetry journals and news resources were analyzed. In some cases, company representatives were contacted via phone or e-mail to obtain more information. In the following sections we document our findings, i.e., detailed information on 3D, stereoscopic and raster LOD management functionality for each software.

2.2 Results

2.2.1 ESRI ArcGIS

ArcGIS 3D Support. *3D Analyst* is the extension of ArcGIS for the analysis and visualization of 3D vector and raster data. It supports all data formats used in ArcGIS, including several image formats, shapefiles, geo-databases, CAD data and *MrSID* data. In addition to these, 3D Analyst supports MultiGen, OpenFlight and 3D Studio MAX formats for realistic representation of 3D features. Beside area, volume, slope, aspect, hillshade and several other calculations, an interactive and seamless navigation through multi-resolution image data is supported. By using ArcGlobe or ArcScene (two applications building on 3D Analyst) it is possible to visualize and analyze geographic information from global and local perspectives. The user can create animations and save them in MPEG, AVI or QuickTime formats. Additional features like distance-dependent drawing and LOD support enhance the user's experience of 3D visualizations. In the ArcGIS family *Raster Pyramids* are the implementation of image pyramids, which are described in the section 1.4. They allow users to visualize different LODs depending on scale. Via 3D Analyst, ArcGIS newly supports so-called *terrain* datasets which are multi-resolution triangulated irregular network (TIN) surfaces stored as a pyramid-like structure [1, 2].

ArcGIS Stereo Support. In the stereo viewing mode of *ArcScene*, it is possible to use anaglyph (requires red/blue or red/green glasses) or shutter glasses (requires a set of signal transmitter hardware), as well as polarized glasses in the so-called *free viewing* mode. Stereoscopic operations are supported with an external module called *Stereo Analyst* (developed by *Leica Geosystems*). Stereo Analyst is capable of collecting and revising spatial features from imagery in a stereoscopic environment. A Component Object Model (COM) application programming interface (API) allows the developers to implement applications that support external photogrammetric project formats.

Stereo Analyst automatically identifies the graphics card in the system. If the graphics card is not stereo-enabled, Stereo Analyst displays stereo images in anaglyph mode. If there exists a graphics card supporting quad-buffered stereo, the scene can be viewed with polarized or shutter glasses in 3D. Stereo Analyst supports several 3D mice for efficient 3D work [58].

2.2.2 Intergraph GeoMedia

GeoMedia 3D Support. In GeoMedia, *TerraExplorer Pro, TerraBuilder and TerraGate* are modules dedicated to visualizing, managing and streaming 3D spatial data [33]. TerraExplorer Pro is developed by *Skyline Software Systems* as a standalone application. The latest release of TerraExplorer 5.1.2 (as of August 2009) has visualization and analysis features including interactive drawing, importing and adding geometric shapes, user defined objects, text and labels on 3D terrain models, measurements for terrain analysis, creating snapshots and creating 3D fly-through animations in AVI format from flight paths. The *Imagery Layer* feature allows viewing *multiple resolution levels* of terrain imagery. It is also used to rectify source image files (e.g., Windows Bitmap (bmp), Tagged Image File Format (tiff), Graphics Interchange Format (gif), Joint Photographic Experts Group (jpeg, jpeg2000), *MrSID* (sid) and ERDAS Imagine (img) formats) to the coordinate system used in TerraExplorer. Additionally, an API is provided for developers to create extensions accessing external data sources [61]. TerraBuilder creates photo-realistic 3D terrain databases using aerial photos, satellite images, terrain information, digital elevation models and vector data. It can support and import a wide range of image formats including gif, jpeg, jpeg2000, tiff, bmp, img, user-defined binary raw, sid and Enhanced Compression Wavelet (ecw). TerraBuilder is able to merge datasets of varying resolutions and sizes. It can apply color adjustments, area selection and clipping operations. Resulting 3D databases can be enhanced with 2D and 3D dynamic or static objects and can be streamed over a network or accessed offline [62].

TerraGate is the application specialized in streaming 3D terrain data over networks to remote TerraExplorer users. It offers an optimized data transfer for low-bandwidth connections and is compatible with TCP/IP and SSL protocols, firewalls and proxy servers, and takes advantage of multi-processor server hardware [63].

On the 2009 GeoMedia international user conference, GeoMedia3D has been announced as a new product that will come to market in 2010. GeoMedia3D will integrate 3D visualization capabilities natively into GeoMedia [36].

GeoMedia Stereo Support. *ImageStation Stereo*, the registered product of *Z/I Imaging* (acquired by Intergraph in 2002 [55]), is the *GIS-based* data collection environment for GeoMedia. ImageStation Stereo is able to capture, display and manipulate 3D photogrammetric and remote sensing data. It uses GeoMedia data servers to access common databases (e.g., Oracle Spatial, SQL Server or ArcSDE). Data collection is handled either interactively or facilitated by automatic attribution. Generated data can then be stored in an open database so that any GIS software can access it. Further, ImageStation Stereo supports compressed and uncompressed 8-bit grayscale and 24-bit rgb, jpeg and tiff formats. It offers dynamic zoom and automatic raster enhancement, interactive feature extraction and geometry validation capabilities as well as infrared shutter or passive stereoscopic viewing [39]. Dynamic zoom capability simulates the continuous optical zoom behavior of a stereo plotter [34, 35]. The integrated *ImagePipe* software enables *stereo roaming*. Intergraph markets this feature as a way of improving visualization performance for quickly navigating through stereo-displayed imagery [34]. ImageStation Stereo supports 3D mice.

2.2.3 Earth Resources Data Analysis System (ERDAS)

ERDAS 3D support. *ERDAS Imagine* is the raster graphics editor and remote sensing solution from ERDAS. Other solutions in photogrammetry and geographic information visualization fields include the *Leica Photogrammetry Suite (LPS)* [25], Imagine Vector, ERDAS Image Compressor, ERDAS Virtual Explorer, ERDAS Imagine Stereo Analyst and *ERDAS Imagine VirtualGIS*. The last mentioned is able to create, analyze, and visualize 3D geographic representations. Users can project aerial or satellite images onto terrain models. They can add vector layers, symbols and 3D objects to the visualizations, create 3D animations and navigate through scenes. Using *Imagine Developer's Toolkit,* developers can implement applications in C and C++. In VirtualGIS the *multi-resolution morphing* feature provides seamless visualization during zooming operations. VirtualGIS supports raster formats (like img, gif, tiff), various DEM formats (from US Geological Survey (USGS), Digital Terrain Elevation Data (DTED), National Geospatial Intelligence Agency (NIMA) and Defense Mapping Agency (DMA)), OpenFlight databases and native DEMs of Imagine's OrthoBASE. In VirtualGIS it is possible to drape 3D raster and vector data. Aerial photography, satellite imagery, scanned maps and thematic images are typical raster data resources for such draping operations. Among vector formats ArcInfo coverages, shapefiles and Open 3D shapefiles are supported [23].

ERDAS Stereo Support. *Stereo Analyst* – a product of Leica Geosystems – is the solution utilized in ERDAS Imagine for data collection, interactive analysis and visualization operations. Stereo Analyst superimposes existing 2D vector layers onto what Leica terms a “Digital Stereo Model”. These models can be created in four different ways: 1) Creating a relative stereo image pair by overlapping, leveling, and projecting corresponding images, 2) With the *Create Stereo Model* tool, which uses internal camera parameters and image information, 3) By using external aerial triangulation results from photogrammetric systems and 4) Via *LPS* which transforms raw data obtained from images to geospatial information for photogrammetric operations such as producing orthophotos, terrain models and extracting 3D features. Stereo Analyst supports anaglyphs, stereo emitters and stereo graphics cards. Image enhancement capabilities of Stereo Analyst include brightness and contrast adjustments, image histogram analysis, stretching and scaling operations. For efficient image processing and visualization *hierarchical pyramids layers* are used. In addition to Stereo Analyst, LPS Stereo is an add-on that can be combined with LPS or PRO600 (introduced in more detail in the section 2.2.5) for geospatial content extraction from stereoscopic images [59]. Stereo Analyst supports 3D mice.

2.2.4 Autodesk AutoCAD

AutoCAD 3D Support. *AutoCAD Map 3D* is the solution of Autodesk built on the AutoCAD platform for creating, analyzing and managing 3D spatial information. Map 3D is able to drape aerial photographs onto topographic data and works with more than 4000 coordinate systems. Survey functionality, map creation, data integration and management, 3D surface creation (via the *Surface Creation* extension) and analysis (elevation, aspect and slope analysis) as well as shading studies and fly-through animations are offered, for example. Map 3D can visualize geographic objects depending on the viewer's zoom level (i.e., LOD management for generalization). Developers can further extend functionality by implementing applications using PHP, Java and .NET APIs provided by Autodesk. Map 3D is able to work with vector and raster data in several formats. Supporting open source Feature Data Object (FDO) technology, Map 3D extends data access for developers and supports ESRI shapefile, Oracle, Microsoft SQL Server, MySQL and ESRI ArcSDE. A large selection of raster formats (bmp, jpeg, jpeg2000, tiff, DEM, Portable Network Graphics (png), sid and ecw) are supported for streaming and visualization of multi-resolution images [3].

AutoCAD Stereo Support. In terms of stereoscopic visualization, Autodesk products employ one native and two external applications. *LandXplorer* is the 3D city modeling software of Autodesk. It can create, analyze and visualize digital city models. With dual head graphics card support, LandXplorer offers stereo viewing of digital models with shutter, polarized or anaglyph glasses. *ELCOVISION 10* (developed by Photo-Mess-Systeme) is one of the two third-party add-ons for Autodesk's products. This close range photogrammetry package has several modes, which enable 2D digital rectification, stereoscopic measurements and stereoscopic visualization via anaglyph or shutter glasses [17]. *Super/Imposition* (from DAT/EM Systems International) is the second external add-on. Super/Imposition is a graphics tool that allows stereo-plotter operators to perform map revisions using digitized objects that are superimposed on stereoscopic models [60]. DAT/EM supports 3D mice.

2.2.5 Bentley MicroStation

MicroStation 3D Support. Bentley Systems offers *Bentley Descartes* as a visualization tool integrated into its MicroStation software. Bentley Descartes can accomplish conversions between raster and vector data formats and between different coordinate systems. Bentley Descartes supports binary, grayscale and 1 to 64-bits color images including, ecw, sid, img, jpeg2000, 1 to 32-bit tiff, rgb, and bmp formats. In addition to its tools which are able to crop, copy, move, merge, scale, mirror and rotate images, Bentley Descartes can create seamless mosaics of scanned aerial photos or raster images. It can also drape images onto digital terrain models (DTMs) or on 3D objects and apply lighting effects. Further, users can create fly-through animations and 3D PDF files as alternative means of visualization. Developers can use Bentley Descartes' API to implement new functionalities [5].

MicroStation Stereo Support. The *Leica PRO600* package (also known as ERDAS PRO600) is the stereoscopic feature collection and visualization tool used in Bentley MicroStation. Leica PRO600 provides a stereo viewing engine, data collection and editing tools as well as a feature definition library. It is closely integrated with LPS. Custom functionalities may be added via Visual Basic macros or C and C++ applications. The PRO600 package supports Leica TopoMouse and other 3D input devices and consists of several add-on modules, including PROCART, PROLPS, PRODTM, TerraModeller and LPS. These add-ons are responsible for cartographic functionalities, linking between modules, creation of workflows for terrain modeling applications, displaying DTMs and photogrammetric operations, respectively. PRO600 supports active and passive stereoscopic viewing [21].

2.2.6 Pitney Bowes MapInfo

MapInfo 3D Support. The *Vertical Mapper* module, integrated within MapInfo Professional, has map creation, analysis and 3D rendering features and mainly works on grid-based continuous spatial datasets. By means of the Grid Translator Pro (GTP) add-on from *Geomatics Systems*, Vertical Mapper can import around 60 raster formats (e.g., bmp, img, gif, jpeg, and Silicon Graphics Image (sgi)) to Vertical Mapper's grid format and export Vertical Mapper grids to standard raster formats. By means of the *Preview Resolution* option the degree of image resolution can be adjusted for the current view. Vertical Mapper features a Software Development Kit (SDK) which allows developers to implement additional functionality [49]. *Encom*, acquired by Pitney Bowes in December 2007, develops custom-built extensions for MapInfo Professional. One of these tools, *Encom Engage 3D pro*, handles 3D vector and raster data analysis and visualizations. To that end, Encom Engage 3D pro performs a number of tasks such as smoothing, clipping and analysis of spatial data, surface creation, application of transparency and lighting effects, creation of color look-up tables, image format conversion and interactive presentation via fly-throughs. As an optional module of the add-on Encom Discover, *Encom Discover 3D* handles both 2D and 3D modeling and visualization, draping raster images onto 3D surfaces and real-time 3D navigation tasks [18, 19].

MapInfo Stereo Support. The *Encom Discover 3D* module supports dual-head graphics cards; therefore anaglyph viewing and full-color 3D stereo projections are provided. For handling 3D navigation, 3D mice are supported [19].

2.2.7 GRASS and Quantum GIS

GRASS and Quantum GIS are open-source projects of the *Open Source Geospatial Foundation* (OSGeo) [47]. Both are two commonly used open-source GIS. Since Quantum GIS uses some GRASS modules, their features are reported in the same section.

Geographic Resources Analysis Support System (GRASS) 3D Support. *GRASS* is designed for management, analysis and visualization of spatial data, image processing, map production and modeling purposes. Users can either work with the graphical user interface (GUI) or a command line interface. There are over 300 core modules in addition to 100 add-on modules implemented in C, C++, Python, UNIX shell, Tcl or other scripting languages. GRASS has 2D and 3D raster and vector processing, visualization and animation modules. The Geospatial Data Abstraction Library (GDAL) is a translator library (licensed by OSGeo) for raster and vector spatial data formats [51]. For example, the *r.in.gdal* module can be used to import a GDAL supported raster file (around 80 formats including tiff, bmp, jpeg, jpeg2000, gif, png, and sid) into a binary raster layer. The *v.in.org* module is used to convert GDAL-compatible vector layers to a GRASS vector layer. The *nviz* animation and visualization module is used to visualize raster and vector data for rendering 3D surfaces and creating fly-through animations in the MPEG-1 video format. nviz has color, lighting and transparency adjustment capabilities and provides control over resolution to improve rendering speed and to manage LOD. The tcl/tk interface is planned to be rewritten so that developers can add more functionality to the nviz module [28].

GRASS Stereo Support. In nviz anaglyph images can be created. Alternatively, *Paraview,* an open-source multiplatform data analysis and visualization application, can be used to render GRASS data in anaglyph mode [28].

Quantum GIS (QGIS). *QGIS* is a GIS under GNU General Public License [51]. QGIS performs common GIS tasks such as editing, analyzing, composing and visualizing spatial data. QGIS allows users to develop customized GIS applications with the QGIS library using C++ or Python. Supported by GDAL, QGIS can handle numerous raster and vector data formats. The GRASS plug-in provides access to GRASS databases and to functionalities such as visualization of GRASS raster and vector layers, digitizing vector layers, editing vector attributes, creating new vector layers and analyzing GRASS 2D and 3D data. QGIS does LOD management by creating and storing lower resolution copies of data in an image pyramid. Depending on the zoom level, the most suitable layer of resolution can be selected from this pyramid. The *Scale dependent rendering* feature allows the user to specify a threshold for minimum and maximum scales at which a layer's visibility is toggled. With the *Map rendering* option, the visibility of a layer can be temporarily suspended. There are sample workflows for QGIS users where 3D spatial data is created in LPS from stereo image pairs and GRASS plug-ins are used for visualization operations [22]. Besides using the Grass modules, QGIS can handle stereoscopic visualization via a 3D Globe plug-in developed by Pirmi Kalberer (www.sourcepole.ch) and Marco Bernasocchi (www.bernawebdesign.ch). This plug-in is expected to become a standard in QGIS version 1.7. The 3D Globe is based on OpenSceneGraph and it supports 3D visualization as well as anaglyph and quad buffered active stereoscopic visualization [64].

2.3 Synopsis

The survey demonstrates that all of the analyzed software provide support for non-stereoscopic as well as stereoscopic 3D visualizations. For non-stereoscopic 3D, Intergraph is supported by the products of Skyline Software Systems, and QGIS makes use of GRASS modules and OpenSceneGraph plug-ins. All other companies provide native non-stereoscopic 3D visualization solutions. In this category, Pitney Bowes provides two solutions: the native Vertical Mapper and the solutions from Encom, which has been acquired by Pitney Bowes. In stereoscopic visualization category, ESRI ArcScene, ERDAS Stereo Analyst and AutoDesk LandXplorer can be listed as native solutions. AutoDesk is also supported by external solutions from ELCOVISION and DAT/EM. Intergraph uses the solutions form Z/I Imaging and Pitney Bowes has support from Encom. ERDAS has a native solution, the Stereo Analyst, which is also used by ESRI. In this category, Bentley and QGIS are supported by external solutions. Bentley uses the P600 from Leica and Super/Imposition from DAT/EM. QGIS uses GRASS modules and OpenSceneGraph plug-ins.

Table 1 collates the results of the software survey. The first column indicates the GIS software. The second column – *3D Support* – reports the name of the corresponding native or external 3D visualization module. The third column – *Stereo Support* – lists the names of the stereoscopic visualization modules. In the fourth column, the respective supported stereoscopic viewing methods are listed as passive and/or active. Column five – *Raster LOD* – shows the supported raster LOD methods in the studied software.

In *3D Support*, 6 software have native 3D visualization solutions (ESRI, ERDAS, AutoDesk, Bentley, Pitney Bowes and Grass) and the remaining 2 utilize external implementations (Intergraph and QGIS). In *Stereo Support*, 3 out of 8 GIS software are complemented by add-on products of the same company. Namely, Stereo Analyst (used by ESRI and ERDAS) and P600 (used by Bentley) are both products of Leica. This may indicate a possible common ground in approaches to, as well as methods in, stereoscopic visualization. As stated in the fourth column, 6 out of 8 software support both active and passive modes for viewing stereo and both open source software support only passive viewing. In *Raster LOD,* each software support multi-resolution raster representations of map layers. Additionally, the multi-resolution data format *MrSID* is supported by all software.

The results show that leading commercial GIS software offer functionality that can handle non-stereoscopic and stereoscopic 3D visualizations, common forms of stereoscopic viewing and basic raster LOD management. However, they do not feature human visual system inspired LOD methods. It is worth noting that all software provide necessary operations to create, edit, and visualize 3D features. Raster and vector formats are supported by all products and many of them allow users to apply conversions between these. Furthermore, all studied GIS software can create fly-through animations and save these in various video formats.

Table 1. Results of the GIS software survey (°: native solution, *: external solution).

	3D Support	**Stereo Support**	**Passive / Active Viewing**	**Raster LOD**
ESRI	ArcGIS 3D Analyst°	ArcScene° and Stereo Analyst*	Anaglyph, polarized / Stereo emitter, shutter glasses	Raster Pyramids, MrSID
Intergraph	TerraBuilder*, TerraExplorer*, TerraGate*	Imagestation Stereo°	Passive system / Infrared emitter, shutter glasses	Imagery Layer, MrSID
ERDAS	ERDAS IMAGINE VirtualGIS°	ERDAS IMAGINE Stereo Analyst°	Anaglyph, polarized / Stereo emitter, shutter glasses	Multi Resolution Morphing, Hierar-chical Pyramid Layers, MrSID
AutoDesk	AutoCAD Map 3D 2010°	LandXplorer°, ELCOVISION10* Super/Imposition*	Anaglyph, polarized / Shutter glasses	Zoom Levels, MrSID
Bentley	Bentley Descartes°	P600* and Super/Imposition*	Anaglyph, polarized / Stereo emitter, shutter glasses	LPS Image Pyramids, MrSID
Pitney Bowes	VerticalMapper°, Encom Engage 3D° and Discov-er 3D°	Encom Discover 3D°	Anaglyph / Full-color 3D stereo projection	Preview Resolution, MrSID
GRASS	nviz module°	ppmtorgb3° and rgb3toppm° commands	Anaglyph / –	LOD, MrSID
QGIS	GRASS modules and OpenScene-Graph plug-ins	GRASS modules and OpenScene-Graph plug-ins	Anaglyph, polarized / Shutter glasses	Scale Dependent Rendering, MrSID

3. Discussion and Conclusions

The presented survey shows that all investigated commonly used GIS software provide non-stereoscopic and stereoscopic 3D visualization support either natively or by integrating a third-party software. The fact that all 8 software provide these services can be interpreted as meeting a demand from consumers, that is, companies clearly invest into either developing or acquiring 3D and/or stereoscopic visualization functionalities. Considering this together with the growing supply of stereo-enabled hardware in the market, makes it seem worthwhile to invest effort in developing more innovative 3D visualization approaches for GIS software and services. Both the demand and the tools are there, the functionality can still be improved upon. We will shortly highlight what we suppose such innovation should be aiming for.

The results of our survey also clearly show that all investigated GIS software support stereoscopic viewing. However, the functionality is implemented to a different degree. While the open-source software GRASS supports only anaglyph (i.e., passive) viewing, all others support active stereoscopic viewing as well. This means they readily communicate with dual head graphics cards that can handle stereoscopic visualization. We interpret this as a positive trend of using efficient graphics processing and (effective) True 3D visualizations in geo-virtual environments.

Current raster LOD implementations in the selected GIS software (e.g., raster pyramids, hierarchical pyramid layers or *MrSID* format) focus on solutions for seamless zooming operations, accounting for *distance* or *size* controlled LOD (as explained in the section 1.4). While all surveyed software support multi-resolution graphics data, they do not include priority type or depth of field LOD management at all. Besides this shortcoming, there is the continuing growth of the GIS user-base, virtual globes and online mapping services and the increased availability of larger datasets. Some virtual globes not only offer 3D visualization but also stereoscopic viewing through a third-party software (e.g., TriDef for Google Earth). This can be seen as a further indication of the increasing interest of both professionals *and* laypersons in True 3D visualizations. However, it is also worth to mention that virtual globes and online mapping services are frequently hindered by bandwidth limitations. Therefore, exploring alternative LOD management techniques may not only be helpful for full-blown desktop GIS but also for overcoming some of the inherent limitations of online 3D geo-visualization services.

We thus identify a need to further improvement of LOD management approaches. We think that by introducing human visual system inspired LOD management methods into existing GIS software and services, the 3D visualization experience could be substantially enhanced. Improvements may include (but are not limited to) extending the use of LOD management models and methods, representing spatial data in a more effective and efficient way and finding solutions that may reduce the complexity of cartographic visualizations.

In 2002, Heipke pointed out that, while modern GIS software should contain modules supporting all stages of handling 3D features, they are rather far away from providing this support [29]. The survey results suggest that today's GIS software have indeed come a long way and are now equipped with modules which can deal with 3D geo-spatial graphics. Additionally, most of the software provide comparable capabilities (i.e., supporting 3D and stereoscopic visualization, supporting dual head graphic cards) in terms of spatial data handling and visualization. How well these modules function in real-world scenarios will be the subject of a follow-up study.

In order to support and complement the information obtained from this software survey we meanwhile launched an online questionnaire (however, analysis has not been finalized at the time of this writing). The main objective of the online questionnaire is to measure the attitudes and opinions of experts working in GIScience towards 3D and stereoscopic visualizations. Early results indicate that a majority of the participants make use of 3D or stereoscopic 3D for analyzing and visualizing geographic information. A detailed analysis from that questionnaire will be included in a follow-up publication.

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