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Three-dimensional interactive maps

Theory and practice

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Certificate of Research

This is to certify that, except where specific reference is made, the work described in this thesis is the result of the candidate. Neither this thesis, nor any part of it, has been presented, or is currently submitted, in candidature for any degree at any other University.

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Abstract

Maps are among the oldest and the most popular forms of graphical communication, which have always been highly regarded for high efficiency of information transfer. Regardless of how efficient two-dimensional maps are, three-dimensional interactive maps offer significant improvements and benefits over their traditional counterparts. While the enabling technologies for three-dimensional (3D) mapping have been ready for some time, and the benefits are significant, one might expect that a wide adoption of three-dimensional maps should already be happening. However, for some reason, the transition to 3D cartography is not happening as quickly and effectively, as would be allowed by the technological and social conditioning.

In this work we discuss three-dimensional interactive maps in depth from both the theoretical and practical perspective, as well as show the benefits for a number of applications, and identify some of the factors that inhibit their popularization. We define 3D maps and three-dimensional cartography, and discuss its relations with the broader discipline of geovisualization. We demonstrate that more 3D cartographic research would benefit users of maps, as well as those of GIS and geovisualization products.

Three-dimensional maps are such a broad subject, and they encompass so many different things, that hard definitions are difficult. That is why we use a technical description and propose a set of functional factors that differentiate, describe and define three-dimensional maps, instead of trying to provide a single narrow definition. We also discuss and validate various cartographic, functional, practical and technical aspects of three-dimensional maps, by a practical exercise of implementation of a 3D mapping platform.

The platform developed, called the 3D Map Viewer, is used to demonstrate the usefulness of 3D maps, and discuss a number of applications where they offer benefits over the existing approaches. By applying our platform to different tasks we also prove that efficient 3D mapping products may be built today, without a need for further technological progress.

We believe that the adoption of 3D cartography would benefit a wide range of users, and that it has a potential to stimulate progress in numerous disciplines of business, life and science. It is our objective to contribute to widespread recognition of three-dimensional maps' usefulness, and to adhere to their continued development and popularization.

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Table of contents

1 Introduction **1**

1.1 Interactive 3D maps 3

1.1.1 Statement of needs 5

1.1.2 Applications 8

1.1.3 Current status 9

1.1.4 Trends and potential 10

1.2 Research outline 12

1.2.1 Objectives 12

1.2.2 Methodology 14

1.2.3 Approach 19

1.3 Organization of the thesis 22

2 Cartography: from prehistoric to digital **25**

2.1 Definition 25

2.2 History before the computer era 27

2.3 Introduction to the basic aspects 30

2.3.1 Geographic coordinates 30

2.3.2 Geodetic systems 33
2.3.3 Map projections 36
2.3.4 Map production process 39
2.3.5 Cartographic presentation 41
2.3.6 Types of map 43
2.4 The emergence of digital cartography 47
2.5 Modern technologies and trends 50
2.5.1 GIS 50
2.5.2 Global Navigation Satellite Systems 54
2.5.3 The Internet 56
2.5.4 Multimedia cartography 58
2.5.5 Digital globes 59
2.5.6 The Geospatial Web 61
2.5.7 Data collection methods 62
2.5.8 Display technologies 69
2.5.9 Geovisualization 71
2.6 Chapter summary 74

3 3D cartography 76

3.1 Definition 78
3.1.1 Cartography versus geovisualization 79
3.1.2 3D versus other branches of cartography . . . 83
3.2 Research background 85
3.2.1 Statement of research needs 86
3.2.2 ICA research agenda for the 21st century . . . 88
3.2.3 Practical studies 93

3.2.4 Input from geovisualization 100

3.3 Chapter summary 105

4 3D maps 107

4.1 Definition 108

4.1.1 Technical description 108

4.1.2 Differentiating factors 112

4.2 Interaction 122

4.2.1 Human-computer interaction 124

4.2.2 User-driven map interaction 126

4.2.3 Ergonomics 132

4.2.4 Map-driven interaction 137

4.2.5 Map intelligence 138

4.3 Remaining cartographic and technical aspects . . . 144

4.3.1 Dimensionality of data 145

4.3.2 Data sources 146

4.3.3 Terrain modelling 150

4.3.4 Data representations 157

4.3.5 View and navigation efficiency 160

4.3.6 User orientation 163

4.3.7 Understanding of a map 166

4.3.8 Map projections 170

4.3.9 Animation 173

4.3.10 Graphical environments 175

4.4 Chapter summary 179

5 3D Map Viewer **181**

5.1 Functional description 182

5.1.1 User interface 183

5.1.2 Navigation and manipulation 186

5.1.3 Data analysis 188

5.1.4 Map editing 189

5.1.5 Map-user interaction 190

5.1.6 Data representation 190

5.1.7 Visual efficiency 192

5.1.8 User and map orientation 193

5.1.9 Animation 195

5.1.10 Remaining cartographic aspects 196

5.2 Technical description 197

5.2.1 Development 197

5.2.2 System architecture 199

5.2.3 Graphical Engine 202

5.2.4 Terrain modelling 203

5.2.5 Data sources and formats 204

5.2.6 Flexibility 205

5.2.7 System requirements 207

5.3 Chapter summary 208

6 Applications **209**

6.1 Maritime safety 210

6.1.1 Problem significance 211

6.1.2 State of the art 212

6.1.3 How 3D maps can make a difference 215
6.1.4 Mapping platform extensions 217
6.1.5 Maritime navigation 224
6.1.6 Traffic monitoring 227
6.1.7 Decision support 229
6.1.8 Sailing directions 231
6.1.9 Professional pilotage 232
6.1.10 Navigation training 234
6.2 Other marine applications 236
6.2.1 Regatta visualization. 236
6.2.2 Offshore planning and simulation 237
6.2.3 Fishery 238
6.2.4 Underwater navigation 239
6.2.5 Marine GIS 241
6.2.6 Hydrographic survey 242
6.3 Land applications 244
6.3.1 City modelling 244
6.3.2 Environmental and urban planning 245
6.3.3 Navigation 248
6.3.4 Command and control 249
6.3.5 Aeronautics 249
6.3.6 Visibility testing 251
6.4 Chapter summary 252

7 Conclusions 257

7.1 Summary 257

7.2 Contribution 259

7.3 Future work 262

Appendix A: Introduction to 3D computer graphics 264

A.1 Scene, object, model 264

A.2 Object representations 265

A.3 Coordinate systems 268

A.4 Camera and view volume 272

A.5 Basic 3D affine transformations 273

A.6 Lights and materials 274

A.7 Textures 275

A.8 Optimization of drawing 276

A.9 Animation 278

A.10 The rendering pipeline 279

A.11 Hardware and software support 280

Bibliography 283

Chapter 1

Introduction

Maps are among the oldest forms of graphical communication, and are the most effective and efficient means for transfer of spatial and geographical information (Kraak, 2001a). Different types of maps were developed independently in different cultures and times. For thousands of years these were used in many aspects of peoples' lives: in navigation, education, trade and the military.

For centuries the evolution of maps was slow. Drawing technologies and materials used to change over tens or hundreds of years. With the evolution of maps so evolved the discipline of map making called cartography. New techniques of effective presentation of geographical information and representation of different sizes of areas – from small to global – were developed.

Important revolutions occurred from time to time, like with the invention of paper, or when Guttenberg invented the printing press in mid-15th century. This resulted in the unprecedented growth of the map production to a scale larger than ever before. Over the years, new map types and map projections, innovative printing methods, and rules of symbology and generalization, as well as the progress in methods of land surveying and in geographical and statistical data representation, led the cartography into the shape it had attained in the mid-twentieth century.

With the invention and popularization of computers, starting from the late 1960's and 1970's, all this dramatically changed. The evolution gained speed that had never been seen before. Changes became more frequent and often revolutionary. Popularization of GIS and personal computers democratized the medium of maps, and reduced the role of trained cartographers (Dorling and Fairbairn, 1997). Maps, which moved from paper into digital format, became more popular than ever, often produced by non-professional people for their private purposes. Emergence of the Internet and World-Wide Web further accelerated the process of evolution. Nowadays, maps of almost any area of the world are accessible online, with a few clicks of a computer mouse. Maps can be shared and developed by on-line communities. These also become multimedia, integrating various types of additional information, from encyclopaedia articles and books to pictures and movies (Cartwright and Peterson, 2007). As cartography expanded into a wider domain of geovisualization, digital maps became tools for spatial reasoning, exploratory data analysis (Tukey, 1977; Andrienko and Andrienko, 1999), and started to be used as interfaces for access to any types of information from underlying databases and GIS systems (Kraak and Ormeling, 2003).

Although the scope and range of changes were truly dramatic and overwhelming, Cartwright and Peterson (2007) noted that digital maps are still not much different from their traditional counterparts.

The evolution continues; new computing, telecommunication and display technologies that will affect mapping are constantly being developed. The discipline of mapping and cartography will inevitably face many changes in the future. However, one of the most promising changes in mapping is happening notably slower then allowed by the technological progress and social conditions. The change which has a potential to be a true revolution in map use is ready to happen on a wide-scale and seems inevitable. The talk is about a widespread popularization of three-dimensional interactive maps.

1.1 Interactive 3D maps

Three-dimensional maps use 3D computer graphics to present geographical information, using perspective representations that, to a certain degree, correspond to the real world. The view presented on a 3D map is more natural, intuitive and easier to understand than its 2D equivalent. 3D maps may, but do not have to, use real-3D data and volumetric objects. Earth surface representation, that incorporates height information, called 2.5D, complemented with 3D symbols, is good enough for many applications (Raper, 1989). 3D maps are interactive by definition. Their usability is very limited without the possibility of interactive manipulation of the presented view, and unhindered setting of the desired perspective. The higher the level of interactivity which is provided, the more useful a 3D map becomes. Interactivity facilitates spatial thinking, and allows some degree of data analysis, without the need for complex algorithms. 3D maps are not meant to be realistic 3D representations of the real world. As in other map types, cartographic rules of abstraction, symbolization and generalization have to be used, to assure efficient transfer of the depicted geographical information, tailored to the purpose, and suitable for the target map user.

However, it is not easy to define what is and what is not a 3D map. As with traditional maps there are different types and categories of geographical presentations that use 3D visualization. A majority of research focuses on the broader subject of application of 3D in geographical visualization, or geovisualization (GV), (MacEachren and Kraak, 2001). Representations used in this discipline range in levels of realism and presented data types. In the geovisualization's understanding, a 3D map may be a realistic reconstruction of a city, or a planned landscape, as in geospatial virtual environments (GeoVEs), (MacEachren et al., 1999b). In GeoVEs 3D visualizations are used, among other things, for urban and landscape planning, and environmental impact assessment. 3D maps may also be connected to underlying databases to provide access to various types of data. They became indispensable as interfaces for many complex systems, such as 3D GIS. 3D maps may also provide 3D representations of thematic or statistical information. Then the third dimension may not be used to depict the terrain topography, but to convey some other types of information.

This work will focus on 3D maps that present topography of terrain (land, or underwater bathymetry) and use a combination of different types of textures and symbols (3D objects and labels, 2D symbols, lines and polygons, text, numbers, points; selectable or not; multimedia and hyperlinks), in accordance with the rules of cartography, to facilitate effective and efficient transfer of presented information. These have been defined in Chapter 4 with the use of four differentiating factors that correspond to the "4-I" factors

(Immersion, Interactivity, Information intensity and Intelligence of objects) proposed by MacEachren et al. (1999a) for geo-virtual environments. Our proposition is adapted to interactive 3D maps and consists of: the use of 3D visualization, application of cartographic presentation rules, high interactivity and map intelligence.

The first factor is rather far from revealing for three-dimensional maps. The second factor – the application of cartographic rules – is necessary for maximization of information transfer efficiency. Interactivity – proposed as the third factor – is a necessity for efficient three-dimensional maps, and a special emphasis is placed on the efficiency and intuition of map interaction and manipulation. Factor number four – map intelligence – may further increase the efficiency of map use, and enable new applications.

1.1.1 Statement of needs

Traditional maps are difficult and expensive to decode, in terms of brain power. The user has to generate a mental model of the presented area, translate symbols and match map features with the observed world. This takes time and effort, which explains why so many people have trouble with the use of maps and find them difficult. Raper (2000) reminds us about representational compromises used in traditional mapping, which often result in – sometimes fatal – mistakes made by map users.

The potential of three-dimensional maps is based on their greater representational flexibility compared with traditional maps, as well as inherent ease of their understanding, and their relatively high intuitiveness. This is a consequence of the way we see the world and how 3D representations appeal to our brains (Van Driel, 1989). According to estimates about 50% of brain neurons are used in the process of human vision. 3D views stimulate more neurons and hence are processed quicker (Musliman et al., 2006). The process of decoding is easier because topographic 3D maps resemble the real world to a greater degree then their traditional 2D counterparts, and are more natural to human brain. This is confirmed by surveys (Schilling et al., 2003). The usefulness of 3D representations is widely acknowledged in the research concerned with GeoVEs (Brown et al., 2002; Kraak, 2002b).

But the strength of 3D maps lies not only in perspective representation that mimics the way humans perceive the world. Another advantage is due to use of 3D symbols, which are much quicker and easier to comprehend than their traditional 2D equivalents. We learn to recognize objects around us from early infancy – cars, houses, trees and animals – small children love naming what they see. The process has been perfected by millions of years of evolution, because prompt recognition of potential dangers was, and still is, crucial for survival. Today it is very fast and reliable. One of the results of this evolutionary spatial training is that a large part of properly designed 3D symbols can be recognized without special training or referring to a legend. This is true for symbols that represent tangible objects or features, which have equivalents in the real world. For these objects recognition can be based on previous life experience of the user. This extends the range of experience-based presentations used in classical cartography, as described by Giertsen and Lucas (1994). What is important is that symbols do not have to be realistic. Simplified and abstracted representations are still easily recognizable. In fact non-photorealistic (NPR) computer graphics is known for its capability to provide vivid, expressive and comprehensive visualizations with strong potential for use in cartography (Durand, 2002; Dollner, 2007). The use of 3D symbols contributes to the increased usefulness of 3D maps also for large regions, where otherwise visualization of terrain topography loses the effect of 3D and becomes visually flat, almost 2D-like.

The time and mental effort required for understanding of 2D maps has severe consequences in areas where time for analysis of the situation is crucial. This is the case for example in navigation of high-speed marine craft, where not only the situation changes quickly, and time available for reaction is limited, but tiredness of navigators further limits their cognitive capabilities. Porathe (2006) describes several cases of high speed vessels crashing into rocks, among them one involving 16 deaths. All these collisions were caused by poor understanding of the situation or temporary loss of orientation by navigators. These incidents prompted that author’s doubts in regard to the usefulness of traditional maps and were a motivation for the experiment in which four different types of map were tested for navigation efficiency (Porathe, 2006). The efficiency has been measured by the average time needed to navigate through a small room depicted on maps, and by the number of mistakes made by 45 diversified participants. The map types in question were: 2D paper, digital 2D north-up, digital 2D with orientation aligned to the direction of motion, and 3D oriented to match the direction, i.e. presenting the user-perspective view. The results showed that participants made almost 5 times less mistakes when using the 3D map, compared to its 2D paper equivalent. The 3D map was also over 3 times less error-prone then the digital 2D north-up map. Results in favour of the 3D map were complemented by the fact that the average time needed to cover the route with its help was significantly shorter, than for any other type, over two times faster than for the paper counterpart. Moreover, users asked to assess ease of understanding and general friendliness of different types of map chose the 3D map as by far the best option. Based on these results, the author argues that 3D maps are not only quicker to understand but also provide improved situation awareness, and have a strong potential in helping to minimize marine accidents (Porathe, 2006).

But the need for 3D maps is not restricted to marine navigation. Their strength is related to their wide range of potential applications.

1.1.2 Applications

3D maps have a wide range of potential applications in diverse disciplines. Better and more accurate understanding of the situation that supports faster and less error-prone decision making is very important in navigation, decision support and disaster management.

The addition of the interaction of the user with the rendered scene, as well as between objects (defined by MacEachren et al. (1999a) as "object intelligence") further extends the usability. In some applications, such as visibility checking, interaction between the user and the map can be used as an equivalent to complex algorithms. Interaction between objects, as well as the map-triggered interaction based on built-in intelligence algorithms, enables better decision support. This may be achieved by application of kinetic spatial data structures, useful for example in marine navigation for collision detection (Gold and Condal, 1995; Goralski and Gold, 2007b). If the chosen structures are locally updatable, as Voronoi-based data structures are, this allows also for real-time visualization of gathered survey data, useful for example in hydrography. Interactive 3D mapping tools can be also used in environmental planning and impact assessment, oil and gas planning and simulation, wind farm and offshore turbine planning, ocean management and geology.

The range of potential applications of three-dimensional maps is obviously wide, and concerns multiple domains, including some which have not been analysed here, because they lay outside the scope of this thesis.

1.1.3 Current status

At present the potential of 3D interactive mapping systems is largely underutilised. These are not used as broadly as they could, and should be. In our opinion this is caused by several factors. One is the relative technical complexity of good quality 3D solutions as compared to 2D counterparts, resulting in longer time and the higher cost of development of such systems. The low level of awareness by map application users, regarding the potential of application and usefulness of 3D interactive systems, translates into a weakness of market pressure for investment into more innovative technologies by established companies. The competition from new producers is not strong enough, as they do not have enough resources and marketing power to break into the mainstream market, and further develop their innovative products. Other factors are higher hardware requirements of 3D systems, and force of habit of cartographers and the older generation of map users, familiar with traditional maps. This is compounded by a lack of 3D data of sufficient quality to allow universal 3D visualization.

In consequence today 3D maps are used mainly in sophisticated geo-visualization systems, such as GeoVEs or as interfaces for 3D GIS. Different types of 3D visualizations are used in advanced systems that are used by geo-information professionals. At large 3D maps are vastly underutilized. Their popularity is far lower than their potential, because the customer market lacks good products from this category. Available 3D-map-based products are far from perfection, in interface, manipulation and quality of presentation. Successful products such as the second edition of the Atlas of Switzerland, which has a 3D module (Sieber and Huber, 2007) are still new and exceptional.

Correcting these imperfections requires more research that would focus specifically on the basic aspects of 3D maps, such as cartographic rules relevant for 3D, instead of on all other areas that surround applications of maps in geovisualization (where research efforts tend to focus at present). Also more efforts in popularization of this innovative means of geographic information transfer, that facilitates spatial thinking, are necessary.

1.1.4 Trends and potential

Despite all these obstacles interactive 3D maps are slowly finding their way into a growing number of applications, and getting more of the attention they deserve. We believe that it is a growing trend, as younger and more demanding generations of map users, used to 3D visualization and the high level of interactivity of computer games, are getting more influence. These people are not only demanding customers, with more knowledge about the capabilities of modern technology and higher expectations, but are also finding jobs in R&D departments of established digital mapping and GIS companies. The progress in computing technologies, with related increase of computing power and graphics capabilities of Personal Computers, already enables wide use of 3D applications on typical PCs. As computers are getting gradually more powerful this will be getting even more evident over time.

The technological progress brings new possibilities, and already enables widespread use of 3D map-based products. More effort is needed from mapping technologies providers, who need to acknowledge the potential of new technologies, and see the incentive to walk an extra mile in order to deliver more innovative products. As we will demonstrate in practice further in this work, there are no technological reasons for keeping 3D maps on the "substitutes' bench" of the mapping technologies.

The obstacles to popularization of 3D maps, outlined in the previous section, suggest that a guide book – summarizing 3D cartographic theory and practice; presenting basis of 3D mapping technologies; analysing functional requirements; and demonstrating technical solutions and the process of development of a 3D mapping platform – would be of great value for improving the situation. Our intention in this work was to provide as much guidance as possible. We do not claim to have all the answers, but wherever answers are missing the effort has been taken to at least ask relevant questions.

The details of research objectives, scope and methodology are discussed in the next section.

1.2 Research outline

This research is dedicated to popularization of 3D maps as effective and efficient tools for transfer of geographical information, and support of spatial thinking and reasoning. The goal is to present 3D maps as promising tools for multiple application areas. Special focus is put on their capability to improve decision making quality in reduced time, and as a consequence to minimize human errors in areas where the quality and time of decisions translates into number of accidents, which are linked with human lives and financial losses.

The popularization effort is based on several elements, including: presentation of the potential of 3D maps; discussion of the development of cartographic rules required for its maximization; definition of 3D maps and 3D cartography; practical demonstration that there are no technological barriers for widespread application of 3D maps; outline of a number of applications; and creation of a practical guide to their development. The objectives and methodology are discussed in detail in the subsequent sections.

1.2.1 Objectives

The broadly stated objective of 3D map popularization can be broken down to a list of several smaller goals:

1. Definition of 3D cartography: analyse the state-of-the-art of 3D mapping and geovisualization in order to define the boundaries, position, shortcomings and further research requirements of 3D cartography
2. Definition of 3D maps: propose and discuss defining factors and properties of 3D maps

3. Core development and practical validation: validate the cartographic principles and proposed defining factors through a process of practical development of a 3D map viewing platform
4. 3D map functional description: gather and use practical knowledge and feedback from test users to discuss functional aspects to maximize usability of 3D mapping products
5. Application development: develop a specialized 3D marine navigation application, based on the developed platform, and validate its usefulness in efficient navigational decision-support and a number of other maritime safety-related applications
6. Practical demonstration: use the developed platform to demonstrate the possibility of successful and immediate development of 3D maps, without the need to wait for further technological or scientific progress
7. Identification of applications: outline and discuss the usability of 3D maps in different application areas, both land and marine

The final objective regards the content of this thesis:

8. Guide book: provide a guidebook on theoretical, technical and practical issues related to the development process of a 3D mapping product

The objectives listed above fall into one of the two categories: they are either theoretical (1, 2, 4 and 7) or practical (3, 5, 6 and 8), and were realised accordingly either in the process of theoretical analysis, which was a part of preparation for writing of this thesis, or in a long and laborious process of practical product development and testing. To be precise the work was done as two parallel, rather than subsequent, streams, which feed into, learnt from, and enriched each other in an iterative process (Figure 1.1).

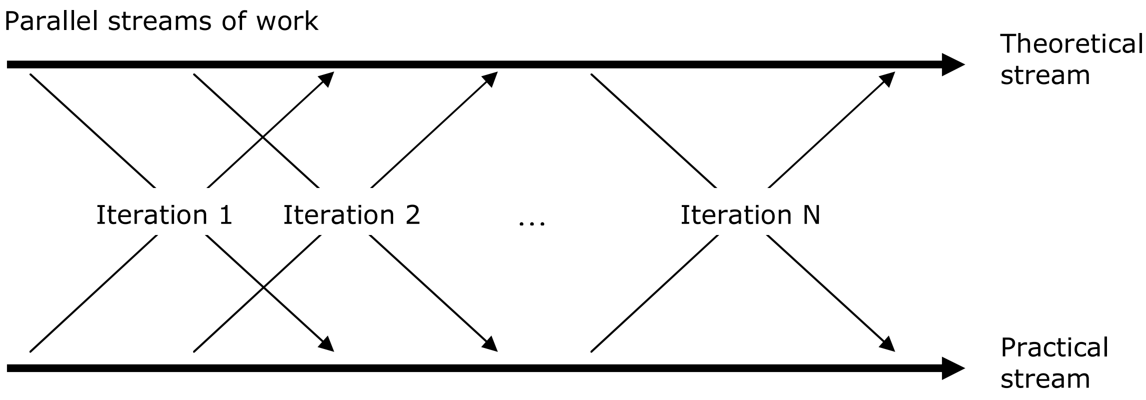

Figure 1.1. Two streams of work iteratively feeding into each other

The results regarding each of the goals are discussed later in the thesis: analysis and definition of 3D cartography is provided in Chapter 3; definition, technical aspects and functional properties of 3D maps – which are based on theoretical study, our practical experience and user feedback – are summarized in Chapter 4; the developed 3D mapping platform is discussed in depth in Chapter 5; the 3D map-based marine navigation aid and other applications, are discussed in chapter 6. The overall summary of the results is provided in Chapter 7. More details about the methodology, referring to the presented list, are provided below.

1.2.2 Methodology

The first goal – the definition of 3D cartography (Chapter 3) – was necessary due to a confusion regarding the place and meaning of 3D cartography in relation to its other branches, and – in particular – to the broader discipline of geovisualization. Theoretical studies of the available literature were used to analyse the differences and to provide the suitable definitions. The subsequent analysis of cartographic aspects that are relevant to 3D maps, and of the required extensions of the cartographic body of knowledge, was especially important due to our conviction that without the application of cartographic rules, 3D maps cannot attain their full potential in efficiency of information transfer. This view is supported among others by Dollner and Kersting (2000) and Meng (2003). A fundamental aspect of this step was the realisation that 3D cartography is generally neglected as a research topic, and existing literature is scarce (Haeberling, 2002). The 3D was not even a separate theme in the ICA Commission on Visualization research agenda for the 21st century (MacEachren and the ICA Commission on Visualization, 1998; MacEachren and Kraak, 2001).

The aim of the second objective – the definition of 3D maps (Chapter 4) – was to provide a set of differentiating factors, based on the existing theory, that allow a clear distinction between 3D cartographic maps and other forms of 3D presentations used in geovisualization. This was based on the analysis of the available literature. Four such factors were proposed including: the use of 3D visualization, employment of cartographic presentation rules, high interactivity and map intelligence. The proposed factors were thoroughly discussed. 3D maps were also defined by a technical description followed by the discussion of the most important aspects of their functionality and design.

The goal number three, core development and practical validation, was based on long and intensive work, performed in two stages. First a multipurpose 3D graphical library – the Graphical Engine – has been implemented using object-oriented programming design. Then this library has been used for the development of the 3D Map Viewer (3DMV) platform. The 3DMV is a relatively simple but well-defined map viewer, capable of displaying a limited number of commercially available data formats (see Section 5.2.5), offering a full global coverage without the need for additional data collection. It facilitates kinetic data structures for object animation and map intelligence. The main focus was placed on high interaction and efficient yet intuitive manipulation, rather than on the realism of visualization. The cartographic principles and the initially collected functional and technical 3D map requirements (which were the main focus of the fourth goal) were evaluated and gradually enhanced in an iterative process, in parallel to the development. The 3DMV is described in Chapter 5, where its functional and technical details are presented.

The aim of the goal number four – 3D map functional description – was the formulation of cartographic and functional recommendations that would maximize usability, and in consequence the opportunity for popularization of 3D maps that adhere to them. It has been achieved by different means: analysis of the state-of-the-art of the relevant research areas and technologies by literature review, conference presentations, meetings, discussions and brain storming sessions with other researchers and professionals from the industry. Links established with institutions such as the Royal Institution of Naval Architects, the University of Plymouth, Shanghai Maritime University and the French Naval Academy have been extensively used. Existing products, including professional marine simulators in Brest and Saint Petersburg, were analysed. Every chance to present the work to potential users during designated meetings or research conferences was taken, followed by a thorough analysis of the feedback. The results were also greatly enhanced and validated in the process of practical development of the 3D Map Viewer platform. The resulting functional description of different aspects of three-dimensional maps is presented in Chapter 4.

The main application of the 3DMV is the subject of the fifth research goal – application development. Maritime navigation has been selected, because 3D maps provide better orientation in the situation, and enable reduction of cognitive load. Since over 90% of marine accidents are related to human errors (Talley et al., 2006) these can contribute to improved safety. 3D navigation software – suitable for real-time visualization on board a ship, as well as for land-based vessel traffic monitoring – have been developed as an extension of the 3DMV (Goralski and Gold, 2007a), in cooperation with the Research Institute of the French Naval Academy (IRENav, Ecole Navale, Brest). The second stage was an assessment of the actual usability of the resulting 3D marine navigational aid. This has been done with involvement of the participants of the meetings held for the purpose of the fourth objective and various new groups of potential users, on dedicated presentations for marine navigators and on multiple other events. Among others, the application has been presented at SeaTechWeek 2008 – the professional marine trade show in Brest. The feedback, which was mostly enthusiastic but also useful as constructive criticism, has been used to further improve the results. Along with the validation of the usefulness of 3D maps for navigation this was also a practical way of verifying the correctness of the requirements list, developed to fulfil goal number five. More details can be found in Chapter 6.

The sixth goal, practical demonstration, is related to the goals number five and seven. It has been fulfilled by successful development of the

3D Map Viewer, and the subsequent development of several applications based on the core platform. The results of the development have been published (Goralski and Gold, 2008) and presented on several research conferences, and further publications are planned. Demonstration of the readiness of 3D technologies for immediate application in 3D mapping is also an important purpose of this thesis, which provides a documentation of several implemented and potential applications in Chapter 6.

The seventh objective – identification of applications – is partially related to the goal number six. Brainstorming sessions, discussions with potential users, researchers and mapping specialists, as well as an extensive literature reviewing have been used to compile a list of potential applications, where 3D mapping could offer significant improvements. The well-defined set of 3DMV's features, including its low hardware requirements, open, elastic and easily-expandable design, use of widely-available 2D data, and intuitive, highly-interactive manipulation mechanisms allowed for quick demonstration in some of the identified directions. Applications other than maritime safety-related, which have already been demonstrated or could potentially be implemented using the 3DMV, are described in Chapter 6.

The last step in fulfilling our ultimate goal of interactive 3D maps popularization was the creation of a guide book to both theoretical and practical aspects of three-dimensional mapping – which also illustrates their extraordinary efficiency and wide usefulness. It has been realised by completion of this thesis.

Before we move further into the thesis it is worth pointing out what is unique in our work. It is explained in the next section, and can be best described in one word – the same which is used as its title – the approach.

1.2.3 Approach

Although most of the research on 3D maps is focused on their applications in modern geovisualization, there are also works focused on use of these for the roles traditionally dominated by paper maps. The biggest chunk comes from the area where 3D maps can offer the most visible progress – marine navigation. Ford (2002) proposed a prototype 3D marine chart which allowed 3D visualization of purpose-prepared models of selected sea regions. Arsenault et al. (2003) presented a similar system for visualization of bathymetry and safe waters. Another example is the previously discussed work of Porathe (2006). However useful and innovative, all of these systems required labour-intensive preparation of data, or offered a limited interactivity, therefore being applicable only as proofs-of-concepts, meant for illustration purposes. Although their value, based on the possibility of attracting attention, and illustrating concepts cannot be disputed, none of these was based on a technology that would allow smooth transition into the real-life use.

There is a research theme that in our opinion is worrying and should be counter-acted. It is the conviction which lingers on among some of the researchers that successful implementation of 3D maps needs to be delayed for various technical reasons. The supporters of this view say that 3D maps require various improvements of existing technologies, data structures, algorithms and availability of sufficient quality 3D data. These and other obstacles to the wider application of 3D technologies were raised among others by the British national mapping office, the Ordnance Survey (Capstick and Heathcote, 2006). There are few examples of can-do attitude, such as presented by Terribilini (1999) who, instead of looking for obstacles, points out that since most available data sets are only in 2D, ways to build 3D models directly from these should be examined.

This can-do approach is also the attitude presented herein, in this work. With full acknowledgement of the existing limitations and potential problems, we decided to examine interactive 3D maps and prove their usefulness from a practical perspective. It has been done by integrating theoretical and practical research, as well as by embracing users' needs in the process of development of a fully-functional, working 3D mapping product. The approach was to actually build a three-dimensional map that would be as close to the market as possible. We focused on all the relevant aspects, including technology, development quality, and usability.

In the process we had to accept some compromises related to the state of the technology, such as the lack of sufficiently robust 3D data structures and algorithms (Zlatanova et al., 2002b; Musliman et al., 2006), and the shortage of good quality, globally-available 3D data. Instead of waiting for the progress we decided to use existing technologies including 3D visualization, interactivity, two-dimensional kinetic spatial data structures and two-dimensional electronic charts. These have been combined with new algorithms into a product which is not only capable of demonstrating the usability of 3D maps, but which can be brought into the hands of real users in a relatively short time.

Apart from demonstrating practical development, our work brings attention to the importance of 3D cartography for the efficiency of 3D map visualization. The speed of developments in the computer mapping technologies and in 3D geovisualization proved too fast for the discipline of cartography to catch up. Today it still struggles to embrace the changes and to realize the need for, and to provide appropriate extensions of, the cartographic theories (Meng, 2003). On the other hand the importance of 3D cartography is neglected due to purely-technological focus of the geovisualization systems' developers, and by the lack of proper education regarding its importance. Bringing 3D cartography to the core of 3D mapping is one of the objectives of our effort. We think that a holistic approach, which integrates theory with practice, adds value to the process, and contributes to the credibility of its results.

Another distinguishing factor of our approach lies in the design of the viewer, which focuses heavily on the efficiency of interaction in its two aspects: 1) user-map interaction (manipulation, navigation and analysis of data); and 2) map-user interaction, based on built-in intelligence. In regard to 1) usual 3D visualization products offer three separate perspective views: plan-view (a view from top, 2D-map-like), model-view (elevated perspective) and world view (eye-level, or street view) (Kraak, 2002b; Lin and Zhu, 2006). The focus on ergonomics of our platform resulted in unification of these three different perspectives into one, intuitive, coherent and integral manipulation system. Regarding the map intelligence 2) Kinetic Voronoi-based data structures were integrated to enable automatic spatial analysis of kinetic map objects, used for example for efficient prediction and communication of navigational dangers.

Our work demonstrates that even a relatively simple and limited interactive 3D map can be useful in various areas, and is a proof that such a map can be produced at low cost, based entirely on the technology and data available today. Our platform manages without the need for purposely-collected 3D data, and offers a global coverage, using only commercially available digital 2D map formats. It works on cheap PC computers, and despite all its limitations has a potential to bring improvements to multiple potential applications. The usefulness of the resulting product, and hence of the 3D maps in general, has been (and still is being) tested in the most practical way, by evaluating the market interest.

We believe that despite the compromises and imperfections of the result, our attitude has a greater potential of attracting attention, provoking thoughts, igniting discussion and promoting the idea of interactive 3D maps, than the strictly theoretical or prototype-quality research conducted before.

1.3 Organization of the thesis

This dissertation covers theoretical and practical aspects of interactive 3D mapping. The first four chapters act as an introduction to the subject, a literature review, and a thorough discussion of the discipline of 3D cartography and 3D maps. These chapters form a core of the theoretical contribution of the thesis. Subsequent chapters provide practical descriptions of the development work performed, followed by a discussion of potential and existing applications of the 3D Map Viewer built as its result, and of three-dimensional maps in general. The thesis is concluded with an evaluation of the research outcomes and original contribution, and a discussion of future work.

Chapter 2 provides background to the discipline of cartography, and shows its evolution from the ancient to modern times. Basic aspects of the traditional cartography are discussed, along the most important technologies used in the contemporary digital mapping.

Chapter 3 is focused on 3D cartography. The need for 3D cartographic research is documented; definition of 3D cartography is provided through the discussion of its relative position to other branches of cartography and to geovisualization; and the background literature is reviewed.

Chapter 4 is oriented more specifically on interactive three-dimensional maps. These are defined through a set of theory-based differentiating factors, and through a technical description. Important cartographic and technical aspects of 3D maps are discussed in depth from both the theoretical and practical perspectives.

Chapter 5 describes the software package developed as the result of this work, and used for validation of research hypotheses – the 3D Map Viewer (3DMV) platform. The system is described from the functional perspective (which corresponds to the findings presented in the theoretical part), as well as from the technical design angle.

Chapter 6 discusses a number of applications of interactive three-dimensional maps. These are presented in the three main categories: maritime safety, general marine, and land-related. Benefits and necessary extensions of the basic 3D mapping platform are discussed for each of the applications.

Chapter 7 concludes the thesis with a short summary of research outcomes, as well as a discussion of its original contribution and of future work.

Appendix A provides a short introduction to 3D computer graphics, in aspects relevant to the design and implementation of 3D mapping products.

Chapter 2

Cartography: from prehistoric to digital

This chapter is an introduction to the discipline of cartography. We discuss its origins and definition, as well as the evolution of the traditional cartography over the ages. This is followed by a discussion of new trends and technical developments that transformed maps from paper into digital format, and which are shaping cartography nowadays. For a more detailed study of the discipline and its different aspects please refer to Dorling and Fairbairn (1997), Kraak and Ormeling (2003) or Ehrenberg (2005).

2.1 Definition

Cartography is the discipline dedicated to study and practice on production of maps. The term is derived from ancient Greek, where *chartis* means map and *graphein* is write. The expertise of cartographers involves the knowledge of visual design – to make the map as readable as possible – as well as the technology, materials and drawing techniques of map production. According to the president of the International Cartographic Associations (ICA) Rystedt (2000) it is one of the oldest disciplines, which dates back to first maps, created several thousands years ago.

It is not easy to provide a suitable definition of cartography. The understanding of its role, scope and definitions based on these, have changed over time. D'Ignazio (2004) compiled a list of 42 definitions of the discipline, while the lexicographical report by Andrews (1996) informs about 321 different definitions of the world 'map' found in dictionaries, encyclopaedias, textbooks, monographs, journals and glossaries. Edson (1979) cited the following definition as the one used by the ICA: "Cartography is the totality of scientific, technical and artistic activities aiming at the production of maps and related presentations on the basis of data (field measurements, aerial photographs, satellite imagery, statistical material, etc.) collected by other disciplines. Further, cartography includes the study of maps as scientific documents as well as their use. In this sense, cartography is limited to "Cartography proper", i.e., to data presentation up to the reproduction and printing of maps and charts: it will be understood that in the practical application of this definition, the gathering of primary data, field surveying and photogrammetry are excluded as are surveys carried out by other disciplines such as geology, statistics, demography, etc."

This understanding has changed to include the underlying technologies in the late 1980s, when a debate on the definition of cartography was held by the ICA. As Visvalingam (1989) pointed out "if cartography is concerned with the making and use of maps, then it is not just concerned with visual products: it is equally concerned with the processes of mapping, from data collection, transformation and simplification through to symbolism and with map reading, analysis and interpretation.”

Traditionally cartography has been concerned with two-dimensional representations of the three-dimensional surface of the Earth. Flat surfaces of different materials were used for this purpose. In ancient times these were typically clay tablets and parchment, which at some point have been replaced with paper.

In recent decades cartography moved into the digital world, where maps are presented interactively on computer screens. This required modifications and extensions of its concepts and rules, which were successfully introduced and accepted (Kraak, 2002a). This proved that the discipline is able to adapt to the requirements of the modern world. Unfortunately this does not apply to three-dimensional interactive maps, where cartographic research is scarce and rules virtually non-existent (Meng, 2003).

The next section presents a history of traditional cartography, until it got caught by the wave of computer revolution. The emergence of digital cartography and related technologies are introduced in Sections 2.4 and 2.5. Three-dimensional cartography is discussed in Chapter 3.

2.2 History before the computer era

It is impossible to tell precisely when the first map was created. Some scholars believe that the first known example of a map is a cave wall drawing found at the Neolithic site of Çatal Höyük, which dates back as far as eight thousand years to around 6200 BC. According to one of the hypothesis it represents a plan of the village (Mellaart, 1966; Harley and Woodward, 1987). However other researchers argue that it was rather a work of art, depicting a leopard's spots, not a map (Meece, 2006). Whatever the truth is regarding the Çatal Höyük map, there are no doubts regarding the maps produced in Babylonia on clay tablets, dating back as far as 3800 BC. The first known map of the world, of which copies have not survived, has been described in books II and IV of "Histories" by Herodotus. It was created by Anaximander of Miletus (Robinson, 1968) around 550 BC.

Throughout the ages maps have been used to graphically represent space, from plans of buildings, villages or the whole countries, to the known world and the stars in the sky. These were used for many purposes; travel, trade, the military, education, navigation and planning. Their use constantly grew and technologies developed in parallel in most known cultures. Over time and with the advances of technology, maps became more portable and precise. The oldest maps were drawn on cave walls, then on stones, clay tablets, cloth, wood, papyrus, parchment, leather and finally on paper. Advancements included the knowledge of symbols, drawing techniques (use of colours), geographical coordinates, projections and printing.

It is not our intention, nor is it possible, to provide the complete history of maps in this thesis. The most important milestones in the history of cartography and mapping, subjectively chosen by us, are presented in the following list:

- Circa 240 BC: Calculation of the diameter of the Earth by Eratosthenes in Libya
- Around 105 AD: Invention of paper by Tsai Lun in China

- About 150 AD: Invention of projections and geographical coordinates by Claudius Ptolemy in Alexandria
- Mid 15th century (around 1450): Invention of the moveable type printing press by Johann Gutenberg in Germany
- 1556: Development of a method to fix positions and to survey land using compass-bearing and distance by Niccolo Fontana Tartaglia in Italy (Tartaglia, 1556)
- 1569: Invention of cylindrical projection for portraying the globe on flat maps by Gerardus Mercator in Belgium (Mercator, 1569)
- 1701: Possibly the first contour map (showing curves of equal value) created by Edmond Halley in England (Halley, 1701)
- 1752: Introduction of a notation which gives a name and address to every possible point in 3D space (x, y, z) by Leonhard Euler in Switzerland (Euler, 1752)
- 1782: First topographical map created by Marcellin du Carla-Boniface in France
- 1801: The first large-scale geological map of England and Wales, setting the pattern for geological cartography and founding stratigraphic geology created by William Smith in England (Winchester, 2001)
- 1809: The method of determining an orbit from at least three observations presented by Johann Carl Friedrich Gauss in Germany (Gauss, 1809)
- Mid-1940s: A range of computing machines developed. These included Colossus, Harvard Mark I and ENIAC (Electronic Numerical Integrator and Computer) – the first general-purpose electronic computer (Goldstine, 1972) announced in 1946 in

USA. ENIAC was the first high-speed Turing-complete, digital computer capable of being reprogrammed to solve a full range of computing problems (Shurkin, 1996)

- 1967: Comprehensive theory of graphical symbols and modes of graphics representation was created by Jacques Bertin in France (Bertin, 1967; English edition 1983)

Because of the importance and a high frequency of changes brought by the computer revolution, the list presented above does not include the advancements related to computing technologies. The above list is just a subjective selection of the most important milestones. For an excellent and much more detailed summary of the history of cartography please refer to Robinson et al. (1995, pp21-38) or Friendly and Denis (2001).

2.3 Introduction to the basic aspects

This section introduces several basic aspects which are fundamental for both the traditional and modern cartography. One of the most important concepts universally used in almost all types of maps, concerns inclusion of information regarding geographical locations of the portrayed areas and features. It is done using geographic coordinates.

2.3.1 Geographic coordinates

In the *spherical coordinate system* (Figure 2.1), every point P (x, y, z) in Cartesian space, can be expressed as a set of three coordinates (r, θ, φ), where:

$r \geq 0$ is the distance from the origin to a given point P (radius of the sphere);

$0 \leq \theta \leq \pi$ is the angle between the positive z-axis and the line crossing both the origin and P;

$0 \leq \varphi < 2\pi$ is the angle between the positive x-axis and the line from the origin to the P projected onto the XY-plane;

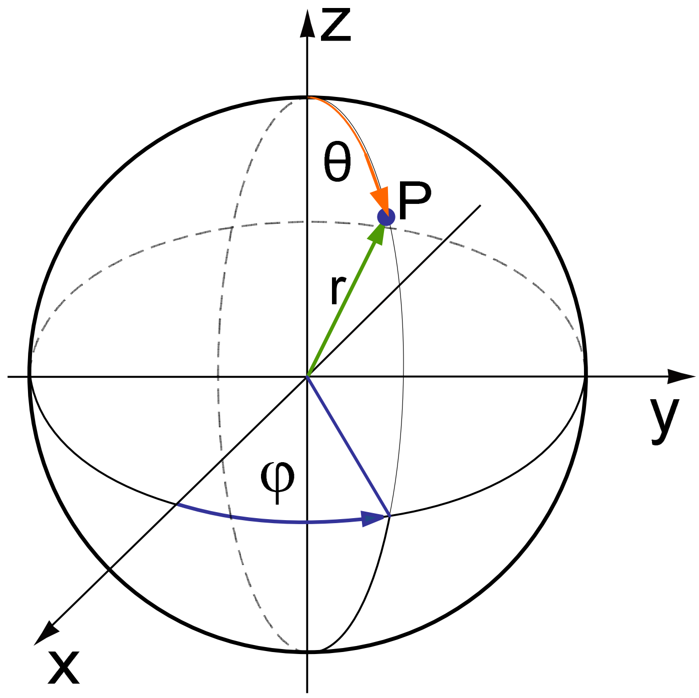

Figure 2.1. Spherical coordinate system

Cartesian coordinates may be retrieved using the following equations:

$x = r \sin\theta \cos\varphi$

$y = r \sin\theta \sin\varphi$

$z = r \cos\theta$

An alternative version of the spherical coordinate system is used in geography and cartography. As the radius of the Earth is known, two coordinates are enough to describe any position on the surface of the Earth. These *geographical coordinates* are called *latitude* and *longitude*.

Latitude (φ or Lat.) is the equivalent of θ in the spherical coordinate system, and is the angle between the line from the centre of the sphere and the point on the Earth's surface, and the equatorial plane (Robinson et al., 1995, p46). Lines joining points of the same latitude form concentric circles on the surface of the Earth. These are called *parallels*. The values of latitude change in the range of -90° ≤ φ ≤ 90°, which is expressed as 90° S ≤ φ ≤ 90° N. The South Pole has the latitude of 90° S, and the North Pole is 90° N. The *equator* – parallel of the 0° latitude – divides the globe into the northern and southern hemispheres (Figure 2.2).

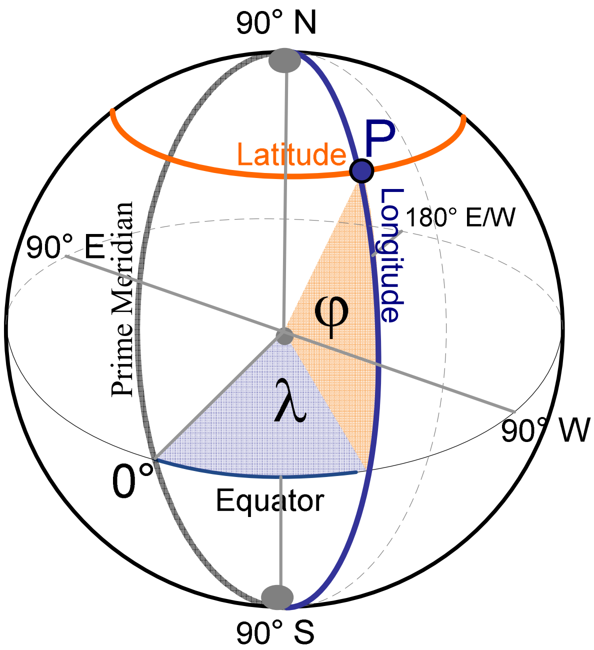

Figure 2.2. Geographic coordinate system

Longitude (λ or Long.) is the angle east or west of a reference *meridian* between the two geographical poles to another meridian that passes through a point P (Robinson et al., 1995, p48). All meridians are halves of great circles, and are not parallel. They converge at the North and South poles.

The meridian passing through Greenwich (UK) has been selected as the international zero-longitude reference line called the *Prime Meridian*. It divides the globe into the eastern and western hemispheres. Longitudes have a range of 180° E ≤ λ ≤ 180° W. The antipodal meridian of Greenwich is both 180° W and 180° E.

There are several formats for denoting geographical coordinates, always using the same latitude, longitude order. The most popular is the notation: degrees°minutes'seconds" N/S, degrees°minutes'seconds" W/E, for example for Warsaw, the capital of Poland, it is 52°15'0" N, 21°0'0" E.

2.3.2 Geodetic systems

In the previous section equations for the calculation of Cartesian coordinates of a point P (x, y, z) located on the surface of a sphere, expressed in spherical coordinates, were given. However, in the case of geographical coordinates for locations on the surface of the Earth, this and converse operations are not so trivial. This is caused by the fact that the Earth is not a sphere, and it can be approximated as a sphere only with a very limited precision. A *biaxial ellipsoid* provides a better approximation of the unique shape of our planet, known as *geoid*.

In the process of conversion between the geographical coordinates and the real positions on the Earth's surface, or vice-versa, a *geodetic system* that provides a local point of reference for geodetic measurements, or a global reference *datum* for the Earth's shape, has to be used. Geodetic systems, known also as *geodetic data* or *datums,* are used in geodesy, navigation, land surveying and remote sensing, by cartographers, in satellite navigation systems, GIS and digital maps.

Geodetic datums (Robinson et al., 1995, pp44-46) were traditionally used by land surveyors to provide a reference point for their measurements. These comprise of *horizontal* and *vertical data*. A horizontal datum is used to establish the horizontal position of a point on the surface of the Earth. There are hundreds of local horizontal data, usually using convenient local reference points, used around the globe.

A vertical datum is used to provide a reference for measurements of altitudes. There are different types of vertical data, for example tidal based on sea levels, or geodetic. Commonly, elevations are expressed in height above sea level – this is a widely used tidal datum, where zero-level is calculated as an average sea level. Geodetic vertical datums take some specific zero point, and compute elevations based on the geodetic model, without further reference to sea levels.

Examples of different datums are:

- NAD83, the North American Datum or its older version NAD27
- OSGB36, of the Ordnance Survey of Great Britain
- ED50, the European Datum

- HK80, the Hong Kong Datum
- JGD2000, the Japanese Geodetic Datum (replacement of the formerly used Tokyo Datum)

National mapping agencies around the word still use different datums. This causes problems with unique determination of true positions of locations expressed in geographical coordinates, calculated using different data. The precision can vary and the same location computed using one datum can be hundreds of metres shifted from its equivalent calculated using another. This is called a *datum shift*. To determine the real position of a geographic location the knowledge of the datum used for its calculation is necessary.

Although conversions between different datums are possible, with advances in air and sea transport, navigation systems and aeronautics, there was a need for a global reference system, allowing precise and unified determination of geographic locations everywhere around the globe. To answer this need the World Geodetic System (WGS) has been created. The work on WGS started in 1950s and resulted in its first version WGS 60. Since then it has been revised several times (WGS 66, WGS 72) and the latest version is WGS 84, used in modern digital maps and satellite navigation systems.

WGS 84 is comprised of a standard coordinate frame for the Earth, a reference surface for altitude data (known as the datum or reference ellipsoid), and a geoid defining the nominal sea level for the whole planet. The latest revision of the WGS 84 was introduced in 2004, and this will remain in use until 2010.

More about different datums used in surveying, GIS and remote sensing can be found in the book by Iliffe (2007).

2.3.3 Map projections

In the previous sections we spoke about geographic coordinates and the process of conversion between these and the Cartesian coordinates. In this discussion we spoke about three-dimensional space. However, traditional 2D maps are produced on two-dimensional surfaces. This introduces additional complications to the process of map production.

In order to produce a map of any area of the Earth on a flat piece of paper, it has to be projected from its geoidal surface to a flat two-dimensional plane. Such processes are called *map projections* and can be depicted as translation from geographical coordinates expressed as latitudes and longitudes to the two-dimensional coordinate space of a map. This can be done in a number of different ways. However, it is impossible to do that in a way that does not introduce significant distortions.

There are many different types of map projections, and different types have different properties. Some projections preserve the original scale of distances, others represent angles correctly, and others preserve areas. A correct representation of one of these properties excludes a correct representation of the other two. There are also many projections which do not preserve any of the mentioned properties, but compromise all of them to instead focus on aesthetical representation of the areas. Most projections have one or two *lines* or *points of true scale*, or *zero-distortion*.

Projections that preserve distances are called *equidistant* (Robinson et al., 1995, p66). Despite their name even equidistant projections can represent the scale of distances correctly in only one direction. It is also important to note that the distance is not scaled correctly everywhere on the map. Equidistant projections are used for portraying large areas, such as maps of the world, as they result in aesthetically pleasing shapes of the portrayed areas. Examples of projections from this group include *equidistant cylindrical*, *azimuthal equidistant* (Robinson et al., 1995, p83) and the *conic equidistant* (Robinson et al., 1995, p85).

Projections of another type preserve the angles. These are called *conformal* (Robinson et al., 1995, pp74-79). An example of a conformal projection is the *Mercator* projection (Robinson et al., 1995, p76), widely used in navigation, where correct representation of bearings and angular measurements are important. Conformal projections preserve shapes over small areas, but the scale is distorted away from the line or point of the true scale. This causes areas distant from the zero-distortion lines or points on maps of large areas to be grotesquely exaggerated. Hence this type of projections is not appropriate for maps of large areas, such as maps of the world.

The third main type of projections preserves the true proportions of the Earth's areas. Projections from this group are called *equal-area* or *equivalent* (Robinson et al., 1995, pp78-80). These are used for comparison purposes or in statistical mapping. The areas are represented correctly for the price of distortions of scale. This causes some shapes on equivalent maps of the world to be squashed and have unsatisfactory outlines. An example of an equal-area projection is the *Mollweide's elliptical* projection (Robinson et al., 1995, p80).

Apart from being equidistant, conformal or equivalent, projections can have different further parameters, used to adjust them to the requirements of a map appearance. These customization parameters include the *aspect*, *centring* and *area of coverage*.

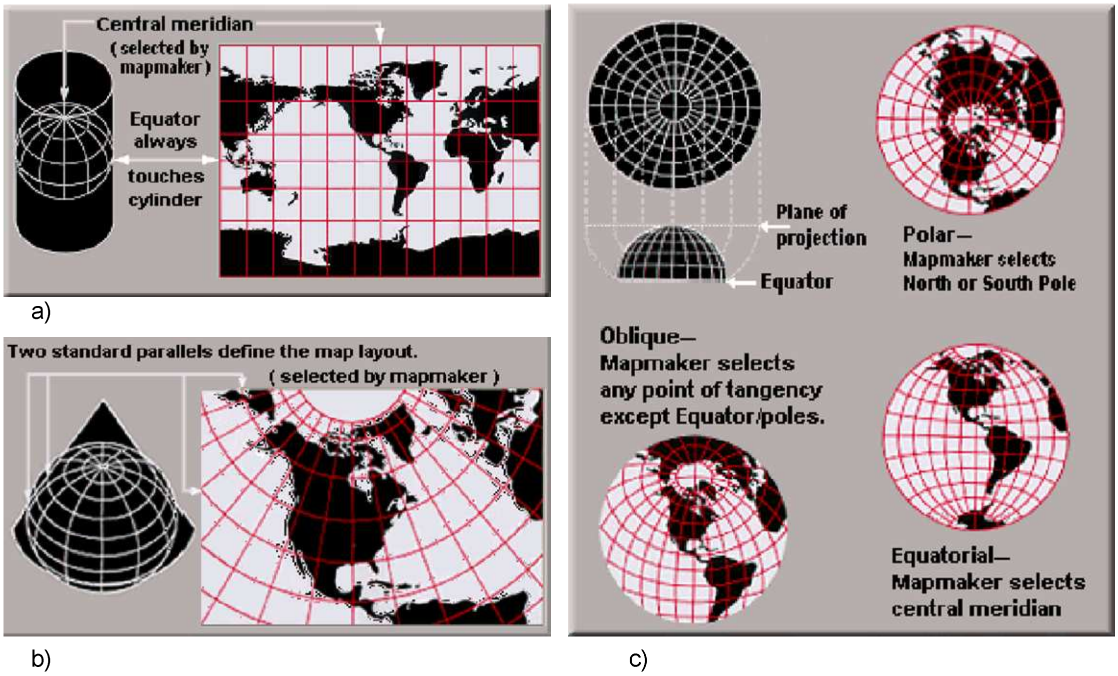

Figure 2.3. Map projections: a) Miller cylindrical, b) Albers equal-area conic, c) azimuthal (U.S. Geological Survey)

Some of the projections can be explained easily visually, as they are equivalent to casting a shadow on a screen. These projections – called *perspective* projections – are named from the geometrical shapes of the surfaces that a sphere representing Earth is projected to. This concept is illustrated in Figure 2.3, an example of three basic perspective projection types: *cylindrical* (Robinson et al., 1995, p84), *conical* (Robinson et al., 1995, p85) and *azimuthal* (Robinson et al., 1995, p83).

There are a number of other perspective projections using different shapes, concepts and ideas, such as various *pseudoconic* and *pseudocylindrical* projections. It is worth noting, however, that projections are not limited to perspective projections, and can be calculated in different ways, by means of different mathematical equations. The equations vary in approach and complexity, and the resulting projections vary in their properties and visual appearance.

A proper projection should always be chosen for the particular purpose and application of the map to be produced (Robinson et al., 1995, pp69-70; Campbell, 1991, pp28-30). For a comprehensive summary of map projections please refer to the excellent book by Snyder (1997).

2.3.4 Map production process

The process of map production, described among others by Kraak and Ormeling (2003), broadly speaking involves data collection, cartographic design and map compilation, followed by printing or display. Each of the first two steps can be performed in different ways, may vary with the purpose, and involves several other activities. Let us have a little bit more detailed look at these.

<u>Data collection</u>

Data collection (Cromley, 1992, pp127-174) was traditionally performed by a cartographer, often for the purpose of a specific map. With progress in geography and cartography a separate occupation of specialized land-surveyors emerged, and the process of topographical data collection became independent from map production. With the advance of new types of maps more types of data, like statistical data, started to be used.

Nowadays data are collected independently from map production, and a once-collected data set can be used to produce many different maps. Data are stored almost exclusively in digital form. Their range is very broad, including topographic data, information about existing objects, administrative boundaries, satellite photographs, socio-economic statistical data, geophysical and environmental data and digitized or scanned maps. Many formats are used to store the data, including various vector and raster files, text, image and multimedia, statistical, geophysical and environmental files (Robinson et al., 1995, pp113-198).

Data are collected using terrestrial surveys (land-surveying), remote sensing, interpretation of aerial photographs (photogrammetry), satellite and airborne sensors and scanners, digitization of existing maps, and from various statistical and environmental surveys (Campbell, 1991, pp77-111).

Cartographic design

Once the data are available a map can be designed (Kraak and Ormeling, 2003, pp120-131) and compiled (Spiess, 2002). The process traditionally involves a cartographer, who is responsible for selection of the data, choice of the appropriate map type, area covered, scale, map projection, design of a graphical representation that would best fit the purpose, and the final drawing of the map (Robinson et al., 1995, pp313-446).

Today the process of map design is often automated and some steps may be performed by computers (Campbell, 1991, pp251-280). For example some aspects of generalization may be performed automatically for the selected map scale and given print or display surface area. This is best seen on digital maps, where the final result is often displayed directly from an underlying database. Traditionally a once-designed map could not be changed. It could be printed and distributed, or displayed on a computer screen as a static image. In digital maps, design and display are linked, and dynamic. This allows the introduction of map customisation functions to the user. In most digital systems the scale or the area of a map can be altered. More advanced ones allow a choice from a range of information to be covered, customisation of symbols used for display or even the possibility to change the map projection. Automatic adaptation to the user and the usage context is also possible.

Despite the automation and all other changes brought by digital technology, the role of a cartographer is still important. Algorithms used at every step of map production still have to be designed by a human, with skilful use of the knowledge and application of the rules of cartographic presentation.

2.3.5 Cartographic presentation

The design of a map involves application of the rules of cartographic presentation. This concerns several steps and aspects, known also as cartographic variables (Bertin, 1967), including selection of the most appropriate representation form, map scale, projection, data to present, as well as the application of the rules of abstraction: selection of symbols and generalization of data. This is done based on the intended map purpose and on the knowledge of the needs of its prospective users.

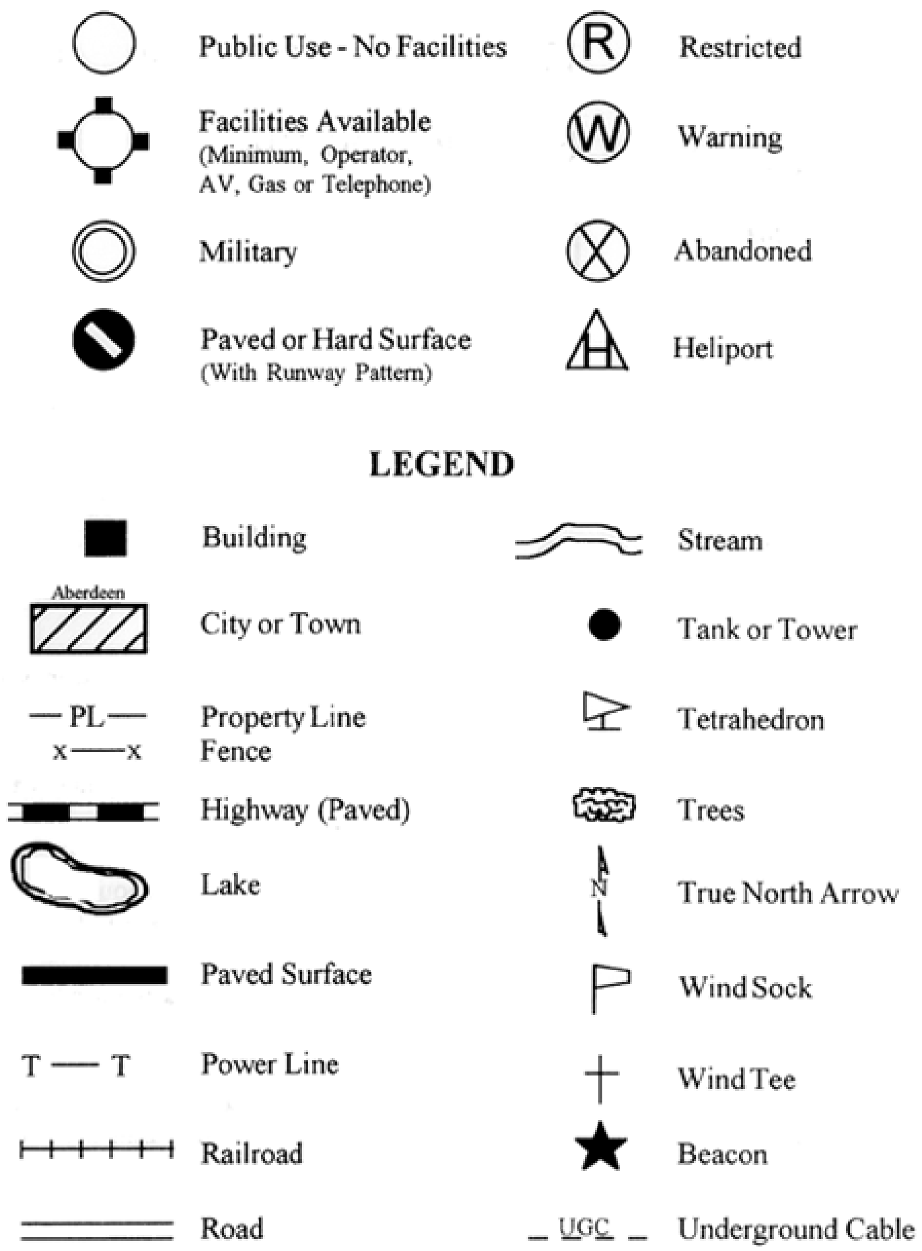

Figure 2.4. Aeronautical chart symbols (NASAO)

An important aspect is the application of symbolisation – the choice of appropriate symbols, to convey the geospatial information of the map (Campbell, 1991, pp203-207). Various shapes, patterns and colours may be used along with text. As an example, Figure 2.4 presents a list of symbols recommended by the US National Association of State Aviation Officials (NASAO), for use on aeronautical charts.

Another important step is the process of generalization (Robinson et al., 1995, pp449-472; Cromley, 1992, pp175-226; Brassel and Weibel, 2002). Its necessity is due to the fact that usually the amount of data available for the given area is greater than the possibility of their physical placement on a limited surface of the map. Generalization is the process of reduction of the amount of detail on a map, in a meaningful way. This involves classification and simplification of data. The process is necessary to assure the map's readability, and to make sure that the most important and relevant details are preserved, and that these are clearly visible (for example by avoiding symbol and text overlaps).

2.2.6 Types of map

There are many types of map. These vary according to the information covered and graphical means used to convey it. The two basic map categories are defined by their inclusion or omission of the landform features.

Topographic Maps

Topographic maps show the natural and man-made features of an area. These are usually prepared for relatively small areas and present information in detail. Topographic maps are prepared from original surveys and aerial photographs, and use contour lines or other methods to represent the relief.

Planimetric Maps

Unlike topographic maps, planimetric maps make no attempt to show varying elevations. They are drawn as though the Earth's surface was a plane.

Apart from these basic categories of map presentations, there are many different types of map specialized for particular purposes. The most popular types are discussed below. Most of these are usually created using planimetric presentation forms, although for city plans and road maps topography may also be included. Navigational charts always include topography, which is an essential factor for spatial orientation of navigators who use them.

Thematic Maps

Thematic maps are used to provide information on a single subject, for example rainfall, soil types, or population density. The area shown on a map is usually simplified, often to just an outline, and the special information is conveyed by different graphical means, such as colours, gradients, shapes or patterns.

Political / administrative maps

Political maps indicate state and national boundaries, as well as capital and major cities. Administrative maps (Figure 2.5) present administrative boundaries of regions within a country, with their names and main cities.

Figure 2.5. Administrative map of Poland (European Commission)

Cadastral maps

Cadastral maps show the boundaries and ownership of land parcels, sometimes with additional information, for example unique parcels' identification numbers, existing structures, adjoining street names, etc.

Climate maps

Climate maps show the areas of different climate zones.

City plans

City plans are used to enable orientation within a city, with its street structure and names, and location of important landmarks and objects. Sometimes they also contain information about public transport. Often used by tourists and residents of big cities, these can be useful to drivers and pedestrians alike.

Road maps

Maps of road networks are provided as a reference for drivers. Road maps often have additional marks, labels and symbols to provide extra information, for example indicating types and identification numbers of the roads, values of distances, speed limits, names of the cities, as well as locations of gas stations and other points of interest.

Charts

Charts are maps used in sea and air navigation. These are specifically designed for navigational operations such as plotting a vessel's course, presentation of navigational signs, orientation based on landmarks, measuring of distances and angles.

Globes

A special type of a map is a globe – a small scale model of the Earth with a map draped over its surface. A globe is the most accurate way to represent the Earth's surface, as it presents all the distances, angles and volumes without, or with a relatively small distortion. However, the big disadvantage of traditional globes is their limited scale. Even a very large globe can present a very limited range of information in a scale that is very small compared to the Earth's size. This limitation has been overcome by the new generation of digital globes, which are discussed in Section 2.5.5.

2.4 The emergence of digital cartography

The invention of computers was the beginning of a new era in many disciplines. This is also true for cartography, which benefited greatly from new means of data collection, maintenance, processing and analysis, as well as computer map design, visualization and printing technologies.

The full list of computing-related inventions that contributed to the developments in modern cartography would be very lengthy and difficult to compile. It would concern a wide range of technologies from many disciplines. However, a few areas of the greatest significance can be pointed out, including:

- The development of a variety of highly interactive computer systems
- New paradigms of direct manipulation for visual data analysis
- New methods for visualizing high-dimensional data
- New graphical techniques for discrete and categorical data
- The application of visualization methods to an ever-expanding array of substantive problems and data structures

This should be complemented with a list of advancements in theory and technology. On a general level such a list should include:

- Large-scale software engineering
- Extensions of statistical modelling to wider domains
- Increased computer processing speed and capacity, allowing computationally intensive methods and access to massive data sets

An important outcome of the technological progress was the emergence of digital maps which offer more than their static, pre-designed, non-updateable and non-changeable predecessors. Computer maps are no longer designed once for a particular type of a user by a cartographer, but generated on-the-fly from the previously prepared underlying data, using pre-programmed algorithms. This enables them to be easily updateable, and allows for provision of the customization of the display and selection of the information for display by a user. This replaces part of the role traditionally done by a cartographer, who still should be involved in, and whose knowledge is important for, the design of automated underlying mechanisms.

Current trends in cartography tend to increase the importance of the user in data gathering, presentation and in user-map interaction. Maps are accessible through the Internet in web-browsers, like Google Maps (Figure 2.6) or as stand-alone interactive applications that use data streaming (for example Google Earth, Microsoft Virtual Earth). The display can be customized by the user, and both these types offer some extent of interactivity.

Web-based maps typically allow a limited range of usual operations, such as panning and zooming. The stand-alone applications offer much better interactivity, allowing the user to easily navigate through the scene and to select any convenient viewpoint. Both the web-based and stand-alone maps can be enhanced with hyper-links that point to different resources regarding the area, or with representations of geographical objects located within it. This content is often user-generated and can have the form of text, wiki entries, geo-tagged photographs from popular sites such as Flickr, book references, sounds, images and video clips. Such maps that follow the paradigms of multimedia cartography (Cartwright and Peterson, 2007) are called hyper-maps.

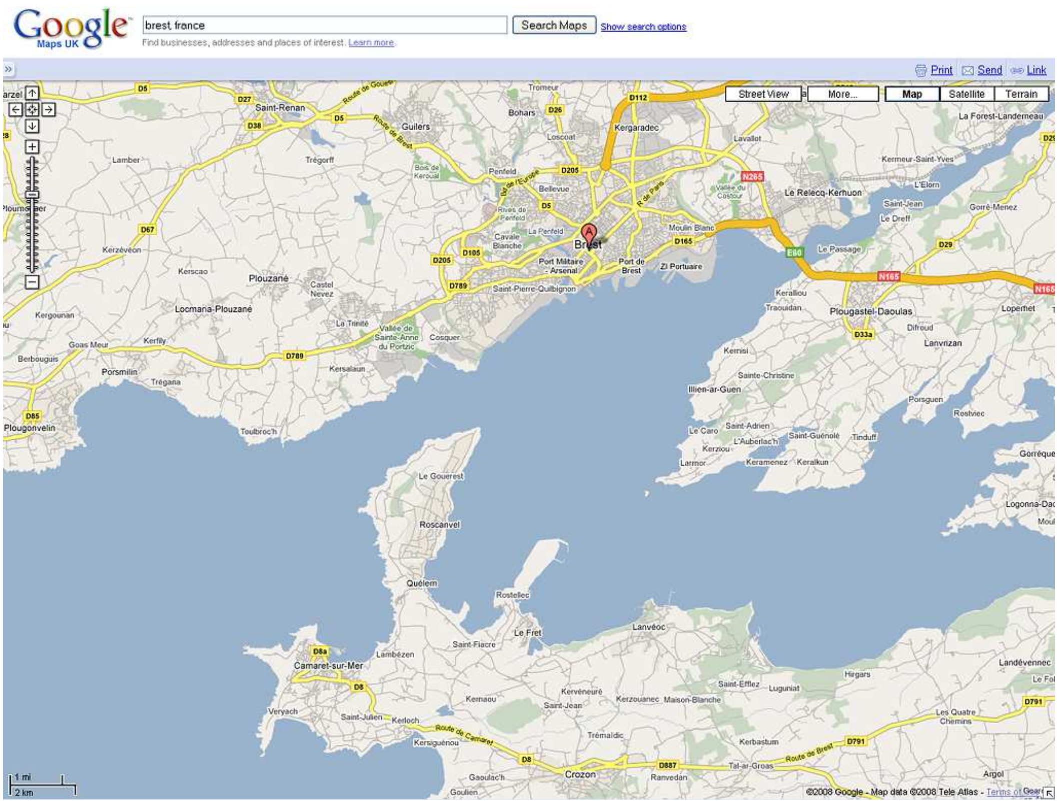

Figure 2.6. Google Maps – an example of a web-based map application, displaying the area around Brest, France

The emergence, development and popularization of computers and computing technologies had and still have an immense influence on modern mapping and cartography. In fact the discipline ceased to evolve slowly as it has had throughout the previous ages. The process of computerization of cartography can legitimately be called a revolution, as changes truly revolutionary in nature happened simultaneously on multiple levels.

Introduction of Geographical Information Systems (GIS) and digital maps made mapping technologies more widespread and powerful than ever before. Digitization democratized the medium, limited the importance of cartographers, and shifted the importance and control towards users. Dorling and Fairbairn (1997) noted that in the preceding decade more maps had been drawn, than in the whole of human history before. Digital maps are easier to design, access, and print than their traditional counterparts, and are easily updateable. Introduction of Global Navigation Satellite Systems, such as GPS, completely changed navigation in the air, at sea and on the ground, and prompted the development of many new applications and services. Popularization of the Internet, as well as of mobile devices and communication technologies has made maps easily accessible and ubiquitous (Hrebicek J. and Konecny M., 2007). Over time these are becoming more and more multimedia and interactive. Awareness of the potential of the 3D mapping technologies is also gradually growing, and recent years have seen a greater increase in their applications.

2.5 Modern technologies and trends

This section provides a background to the technologies, developments and trends that have revolutionized cartography and shaped the ways people use maps today.

2.5.1 GIS

Geographical Information Systems are computer systems designed for the collection, storage, manipulation, analysis and display of geospatial data. These were introduced in the mid nineteen-sixties, almost simultaneously in several places for different applications. The earliest major implementation – the Canadian Geographical

Information System (CGIS) – was designed for agriculture management by the Canadian government (Tomlinson, 1987). Other early applications were developed for land surveying in Australia, local governments in the UK and for utility and natural resources management in the USA. The initial phase of GIS development turned into a quick demand-led growth in the late 1980s (Ottens, 1991).

GIS were commercial products whose emergence was purely technology-driven, and these were heavily criticized by geographers and cartographers. The criticism was caused by the perceived triviality of applications and answers produced by GIS combined with their high price, hardware requirements, poor design and slow algorithms, combined with the lack or high price of data, and difficulty of use. This slowly changed with technological improvements, the growing number of applications and the emergence of Geographical Information Science (Goodchild, 1992). Geographical Information Science or GISc developed a multidisciplinary discussion on concepts of space with psychology, cognitive science, philosophy, linguistics and computer science. GIS-related research involves also visualization, data analysis and data structures, computer graphics, statistics, and computational geometry.

Because GIS were developed for many different purposes, several different definitions exist. They can be divided into two groups: those focused on the technology, and those looking from an organizational perspective. An example from the first group was formulated by Dangermond (1992): *'GIS is an organized collection of computer hardware, software, and geographic data designed to efficiently capture, store, update, manipulate, and display all forms of geographically referenced information'*. An example of the second category is that of Cowen (1988): '*GIS is a decision support system involving the interaction of geospatially referenced data in a problem-solving environment*'.

One of the most important functions of GIS is their ability to combine multiple formats of data from many sources, which enables extensive analysis not possible before. Different data sets are stored in separate layers. GIS help to answer questions such as how to best route emergency vehicles to a place of an accident, where is the area with the highest crime rates, what relations exist between different areas and data sets. Today GIS has so many varieties and applications that it is impossible to summarize them all. Some example applications are presented on the following list:

- Environmental impact assessment and planning
- Urban and infrastructure planning
- Disaster and crisis management
- Natural resources management
- Asset management
- Oceanography
- Coastal geography
- Monitoring of Environment
- Socio-economical studies
- Census statistics
- Cadastral surveys
- Archaeology
- Criminology

- Logistics

Development of GIS was the main cause of the widespread digitization of maps. One of the first applications was to automate the process of map production (Rhind and Coppock, 1991), which decreased the role and importance of trained cartographers, but resulted in popularization of maps as a medium. GIS proponents like to emphasize that these democratized the medium, changed the way people perceive the world and made them more spatially aware (Dorling and Fairbairn, 1997).

GIS were predecessors of modern digital maps, and there still exists some kind of ambiguity and confusion as to what could be called a GIS and what is merely a digital map. In fact GIS and digital maps overlap and interpenetrate each other to some extent. Many digital maps allow some operations typical to GIS, like querying information about objects or measuring distances, while GIS use digital maps as their interfaces for displaying data (Kraak and Ormeling, 2003, pp1-3). Some types of digital maps, like Electronic Chart Display Information Systems (ECDIS) used for maritime navigation, are classified as rightful members of the GIS family (Ward et al., 1999). Some simple systems considered as GIS are not much more than extended digital maps. The differentiation can be based on the observation that GIS in general have higher capabilities of importing, managing, modifying and performing spatial analysis on different types of data. Maps are generally simpler and their main purpose is efficient visualization of geospatial information. But it is hard to deny that both discussed groups have much in common.

Since their initial development GIS have followed a path of immense innovation. Requirements from disciplines such as oceanography, atmosphere and climate studies, geology and human geography prompted research on new types of GIS, capable of working with kinetic and multidimensional data, or maintaining spatio-temporal information (Raper, 2000). The immense success of GIS is a proof of the need for efficient and interactive geovisualization.

2.5.2 Global Navigation Satellite Systems

Global Navigation Satellite System (GNSS) is the generic term for satellite navigation systems that provide geo-spatial positioning with global coverage. GNSS uses a network of satellites that transmit microwave signals containing messages that indicate their positions and message sending times (Leick, 1995, pp68-72; El-Rabbany, 2006, pp13-16). This enables small electronic receivers to calculate their location (longitude, latitude and altitude) based on the combination of signals received from several satellites. Calculation is based on the distances measured to each of the satellites, based on the transit times for the received messages, and geometric trilateration combining these with locations of the satellites (Leick, 1995, pp4-5; El-Rabbany, 2006, pp8-10). In theory three satellites are required to determine the receiver’s position. In practice, due to clock time errors, at least four are necessary.

Currently the only fully functional GNSS is the Global Positioning System (GPS, or NAVSTAR-GPS) developed by the United States Department of Defense (Hofmann-Wellenhof et al., 2001). The system was originally developed for military use, but in recognition of its usefulness for civil applications it was made freely available for civilian use. It uses a constellation of between 24 and 32 Medium Earth Orbit satellites (Leick, 1995, pp60-62; El-Rabbany, 2006, pp6-7), portrayed in Figure 2.7.

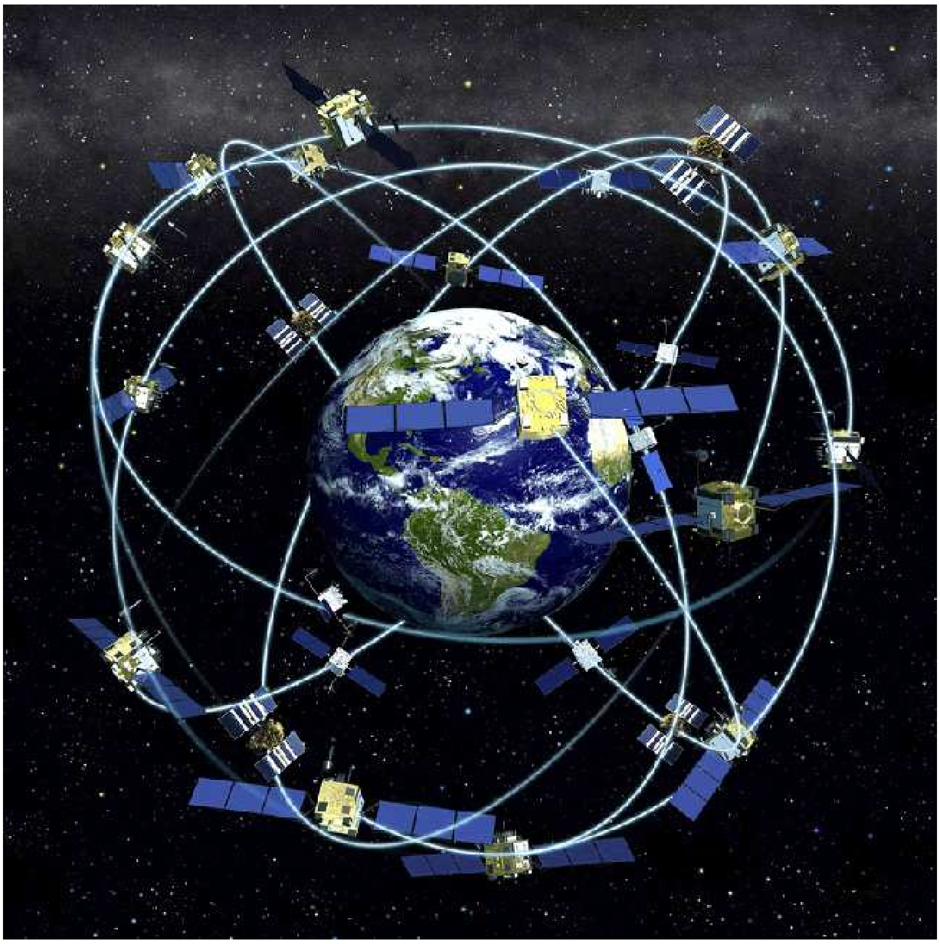

Figure 2.7. The constellation of NAVSTAR-GPS satellites (NOAA)

Other systems are still in development. These include the Russian GLONASS (El-Rabbany, 2006, pp163-167), the upcoming European Galileo global satellite navigation system (El-Rabbany, 2006, pp167-170), the regional Chinese Beidou navigation system (El-Rabbany, 2006, pp170-172), the Japanese QZSS (El-Rabbany, 2006, pp172-173), IRNSS of India, and DORIS of France.

GNSS have a broad range of applications, both military, such as target tracking and missile guidance, and civilian. Civilian applications include:

- Navigation – GPS is widely used for car, air and marine navigation
- Search and rescue – to locate those waiting for help
- Tracking – used for truck fleet management, in shipping, for anti-theft car systems, etc
- Data collection – surveying for map creation and GIS systems
- Transfer and synchronization of time
- Multiple other scientific applications, such as in geodesy

Recent wide-scale introduction of GPS receivers integrated with mobile phones has prompted the development of new applications, such as personal navigation and location services. Personal navigation systems are a new generation of portable satellite navigation systems, adapted to the needs of pedestrians. These allow quick determination of location and orientation in the user's proximity, determination of the closest points of interest, and finding of the optimal walking paths. Location services allow tracking of other users' positions. Applications range from personal, such as indication of a user's position on a social networking site, or automatic detection of friends who are located nearby, to more serious, such as the determination of the locations of emergency number callers.

2.5.3 The Internet

The Internet is a global network that connects computers from all over the world, allowing for transmission of data. It was created initially for scientific and military purposes. The ARPANET (Advanced Research Projects Agency Network) started in 1969 (Denning, 1989). It was the world's first operational packet switching network, and is widely acknowledged as the predecessor of the Internet. The early Internet was used mainly by computer experts, engineers, scientists, and librarians. It was very difficult to use and slow. Over the years it has become faster and more intuitive, as new protocols such as the TCP/IP and services such as chat, email and World Wide Web (WWW) were developed. Since its creation the Internet has been constantly growing and gaining popularity.

Today it is used by approximately 1.5 billion people in every country of the world. In the developed countries it is virtually ubiquitous and can be accessed even in remote areas using mobile telephone networks. It has changed almost every aspect of our lives, providing easy access to information, effective means for communication, and a convenient platform for collaboration.

Emergence of the Internet had a large impact on cartography and mapping (Peterson, 2007). It became an efficient means for distribution of maps, and allowed new forms of mapping activities, such as sharing of maps, collaborative mapping among online communities, and participatory GIS (PGIS). PGIS use online interfaces to allow access to geospatial data and are aimed at increasing public participation in environmental and planning decisions (Rouse et al., 2007).

The Internet allows on-demand access to maps of different types for any area of interest, without the need to purchase and carry stacks of paper maps just in case they should be needed. Online maps can be displayed on computers, or on mobile devices such as mobile phones. In practice, that means that anyone with access to the mobile Internet is carrying multiple maps of the whole world in his pocket. Combined with technologies such as GPS, this ubiquity of maps allows a multitude of innovative services, such as real-time tracking of the location of a pet, a child, or a person with Alzheimer's disease.

An important event in opening digital mapping for the mainstream Internet users was the introduction of free mapping platforms in 2005 by Google, Yahoo and Microsoft. Along with their mapping applications free APIs were provided to allow integration with external applications, services and data sources. This allowed users to integrate their own layers of data within widely-accessible and highly popular mapping platforms.

2.5.4 Multimedia cartography

Developments in multimedia allowed integration of different types of data within maps. These include animations, movie clips, sound files, photographs, drawings and text that can be provided as additional information regarding map regions or objects. These enhancements of digital maps were prompted in large part by the same reasons as the ones behind the development of three-dimensional maps – the users' need for more efficient and intuitive visualization of geographical data, with more information depth and better interactivity (Cartwright and Peterson, 2007).

Following the analogy to the World Wide Web, hyperlinks were introduced to digital maps. These active, clickable areas allow access to different files (multimedia) stored locally or on the Internet, or a quick reference to different maps, for example to detailed city plans, or to maps of a larger scale. Multimedia hyper-maps have become interfaces to larger sets of data, accumulated within their geographically-referenced interfaces.

Both the terms multimedia cartography and hyper-maps refer to stand-alone offline maps and online web maps alike. In offline maps hyperlinks point to multimedia stored locally while online maps allow access to a much broader range of information accessible via the Geospatial Web (described in Section 2.5.6).

2.5.5 Digital globes

Digital globes are the implementation and expansion of the idea of the traditional globes. These are digital maps that use a spherical shape to represent the surface of the Earth. Unlike their traditional counterparts, digital globes allow for inclusion of precise map data at various and dynamically-changeable scales. Their advantages over flat maps are twofold: 1) the digital globes do not require the use of map projections that always introduce distortions, and 2) they enable continuous navigation within the whole globe, preserving the feeling of its integrity. This is very useful for tasks which require a global perspective, and is used for example in teaching geography. Depending on the application they may have disadvantages, for example they are not suitable for representation of the themes without the global data coverage, or of local phenomena. Riedl (2007) discusses the ‘globe-worthiness’ of map themes, and provides a set of criteria to determine if a theme is suitable for display on a globe.

Digital globes are based on 3D models and use animation, interactivity and 3D visualization mechanisms (Riedl, 2007). Their popularity can be demonstrated by the fact that almost every electronic atlas uses a virtual hyperglobe as part of the interface. Examples of digital globes are Google Earth (Google, Figure 2.8), World Wind (NASA) and Virtual Earth (Microsoft).

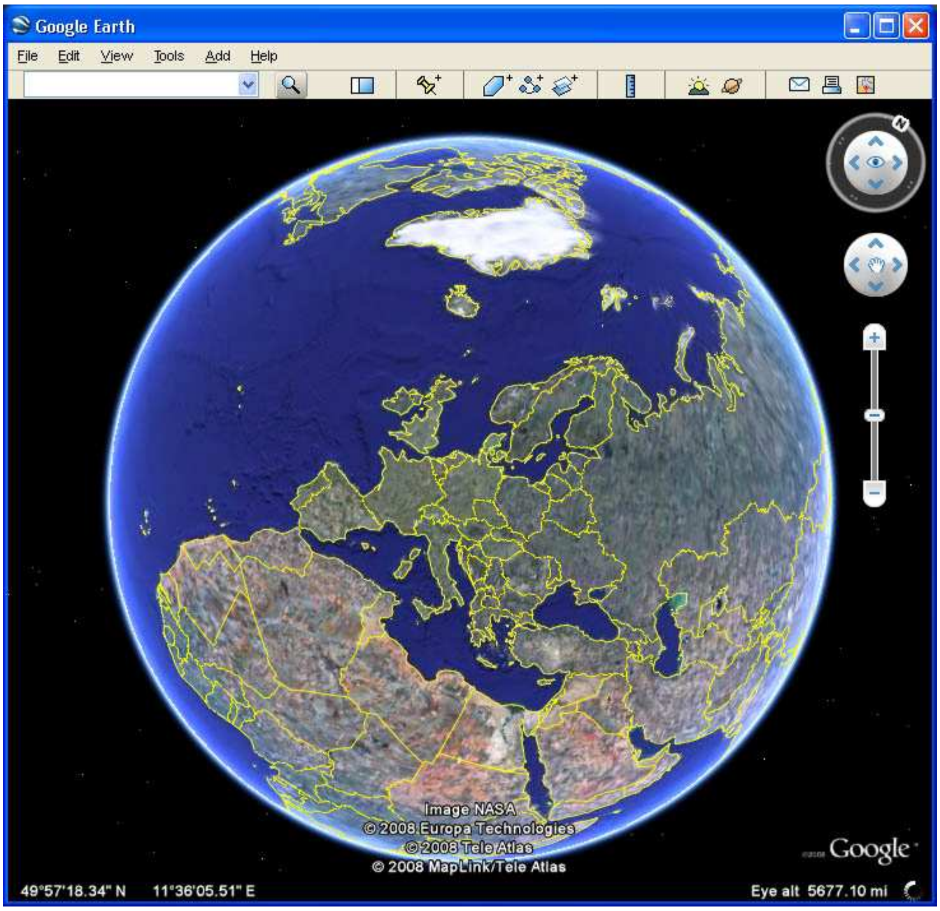

Figure 2.8. GoogleEarth – an example of a digital globe

Google Earth has started a strong trend of transition from offline virtual hyperglobes to online environment, where data are streamed via the Internet instead of being stored on a local drive. This allows for provision of much greater detail of always up-to-date data, as information is requested on-the-fly only when it is needed, for the currently displayed region at a desired scale. For example the size of the whole Google Earth database exceeds (as of early 2009) 70 TB (terabytes), which is the equivalent of over 15251 DVD-ROMs of standard 4.7 GB size.

The most popular digital globes follow the principles of multimedia and web cartography, and use the Geospatial Web to enhance their capability of information gathering. For example Google Earth supports the display of several categories of hyperlinks and files. These can be either geo-referenced multimedia files that refer to the portrayed area, for example photographs from popular internet photography sites such as Flickr, or references related to geographical objects, such as Wikipedia entries and excerpts from books referring to places, monuments or historical events. This creates a great platform for learning about different places and events from the geographical perspective.

2.5.6 The Geospatial Web

The advent of the Internet, the introduction of satellite navigation systems, the developments in multimedia cartography and the creation of web-based mapping platforms contributed to the emergence of the so-called Geospatial Web (Scharl, 2007).

The Internet provided the platform in which spatial data can be searched for and easily transferred to mapping applications. Popularization of GPS-enabled mobile phones enabled innovative location-based services, such as sharing information about a user's location with his friends on-line, or detecting friends who are located within a defined distance. Web-based mapping platforms that use multimedia concepts, such as Google Maps and Google Earth, have gathered large user communities who are allowed to share their own data. All this constitutes the Geospatial Web – a new environment that consists of users, social mapping services and the underlying technology (Scharl, 2007).

The underlying technical part of the Geospatial Web is based on several components: hardware, such as servers that host databases and power web-applications; networking technology, including hardware and protocols from low-level, such as the TCP/IP, to high-level, such as web services; different types of software (server-side, middleware and stand-alone applications for mobile devices and PCs); standards and protocols that allow querying and linking web search results by location; and data exchange formats such as the Geospatial Markup Language (GML), described by Lake and Farley as "a Lingua Franca for the Geospatial Web" (Lake and Farley, 2007).

2.5.7 Data collection methods

The technological progress brought about significant changes to techniques, methods and approaches used at all stages of the map production process – not excluding those used in the collection of data. Traditionally that was a responsibility of land surveyors – trained professionals who measured a given area of land, using local points of reference and local measurement techniques such as measuring tapes, optical instruments, and triangulation methods (among other techniques), in a slow and costly manual process. With the advent of aeronautics and photography another method – called *photogrammetry* – emerged, in which photographs of land taken during aeroplane flights are used as a source of data, allowing for faster and more precise production of maps of larger areas. Over the time new techniques and technologies, within the new discipline of *remote sensing*, were developed, including the use of stereographic photographs (*stereographic photogrammetry*), different types of *radars* and *airborne lasers*, which – mounted onboard planes or satellites – allow for the efficient collection of data of large areas. GNSS and global datums are used instead of the traditional methods and local reference points for determination of positions, and the measurements usually include terrain's altitude. Similar progress have been observed in hydrography – where GPS replaced triangulation methods, reference *beacons*, and *dead reckoning* used for geo-positioning – while modern *echo-sounders* and *side scanners* replaced *lead lines* in measurements of depth and reconstruction of bathymetry.

Most of modern data collection methods fall within the discipline of remote sensing (including its sub-discipline – photogrammetry), but there are also other methods such as mobile mapping, new trends such as collaborative mapping, and legacy methods such as the digitization of paper maps, that should also be mentioned. The most important disciplines, methods, trends and techniques used within them are discussed below. More information about the practical use of the data collection methods and technologies in the context of 3D mapping can be found in Section 4.3.2.

<u>Remote sensing</u>

Remote sensing is an acquisition of information about an object from a distance, without a physical contact with it. In the context of mapping this usually means surveying of the terrain surface and the reconstruction of different geographical objects that are placed on it from the air. Different sensor technologies and platforms for the carriage of the sensing instruments may be used for that purpose.

Remote sensing methods are divided into two groups: passive and active. Passive methods use sensors which detect natural radiation (radiometers) or lighting emitted or reflected by the observed object – the example of this is photogrammetry which uses the light reflected from the terrain's surface. Active methods emit energy in order to scan the distant object, and these include radar, laser and sonar scanning. For the purpose of mapping the sensors are usually mounted onboard airplanes or on satellites. The most popular methods, apart from photogrammetry which is discussed in the dedicated section below, include airborne interferometric synthetic aperture radar (IFSAR), airborne light detection and ranging (LIDAR), or airborne laser terrain mapping (ALTM).

Photogrammetry

American Society for Photogrammetry and Remote Sensing (ASPRS) defines photogrammetry as "the art, science, and technology of obtaining reliable information about physical objects and the environment, through processes of recording, measuring, and interpreting images and patterns of electromagnetic radiant energy and other phenomena"[1]. In simple words it is a discipline concerned with determining physical features of objects (terrain topography and geographical objects in the context of mapping) from photographic images. The simplest example is a measurement of distances from an

[1] http://www.asprs.org/society/about.html

aerial photograph for which the scale is known. More advanced techniques use stereography and geometric methods such as triangulation to determine 3D coordinates of points within the measured area.

Different wavelengths of the light spectrum (for example infrared) and different types of radiation can be used for the purpose, for example to avoid the interference caused by atmospheric phenomena such as clouds. Photogrammetric methods can be combined with other techniques from the discipline of remote sensing to allow the determination of 3D coordinates from single images (as opposed to pairs of stereographic images), or to improve the quality of the resulting data.

Aerial images have a special use in 3D terrain visualisations and 3D mapping, where they are often imposed on surfaces of terrain models, or on grids of points collected from aerial scanning, to create realistic visualisations of the portrayed areas.

Mobile mapping

Mobile mapping is a data collection technique where a mobile platform fitted with sensors is used for mapping. The platform can be a land vehicle, a vessel or an aircraft. It is fitted with mapping sensors, which are known from remote sensing and can range from digital cameras to radars (for example IFSAR) and lasers (airborne LiDAR), and navigational sensors which provide the information about the platform's position and sensors orientation (Li, 1997). The emergence of the GPS played a major role in the development of this mapping technique, and it is a primary source of the positioning information for the platforms. Additional sensors, such as inertial trackers, gyroscopes, or vehicle wheel sensors are used for the provision of the information regarding the orientation of the sensors. The availability of the sensor orientation parameters significantly simplifies the computational algorithms required for the post-processing of the collected data and contributes to a better quality of the final results. The integration of the mapping and navigational sensor data allows for the direct extraction of the spatial information of the mapped objects (Li, 1997).

Mobile mapping is a flexible method which, depending on the type of the platform and sensors used, allows for efficient mapping of areas of different sizes, at different scales, and with different levels of quality.

Terrestrial mapping

Terrestrial mapping is a higher quality, but slower and more costly method, which is suitable for smaller areas, where very precise measurements are required, or where airborne techniques do not offer a viable solution. Example applications include the reconstruction of buildings, highway engineering and high-resolution topography mapping. Terrestrial laser scanning (TLS) is usually used, but other remote sensing technologies and techniques can be also applied or combined with it.

Terrestrial laser scanning is capable of providing high resolution and accuracy results, however the downside is that the volumes of data produced are very large, and these are only disconnected clouds of surface points, without any information on topology or spatial connectivity between them. The reconstruction of actual mapped objects from such clouds of points is often a complex and difficult process.

Paper map digitization

Over the years a large number of paper maps and charts have been produced, sometimes at great costs. In order to be able to use this data in the digital era such maps have to be digitized.

The process is not simple and far from being efficient – it is laborious and mostly manual (semi-manual at best), and it is difficult to control the quality. The map has to be scanned first, and then different features, such as points, lines, polygons, objects, symbols, labels, values, contour lines, and so on, have to be replicated in the digital format. Automatic algorithms allow for the detection of some of the features in the scanned image, but they are far from being perfect, and almost always require a lengthy process of difficult and error-prone semi-manual post-processing.

Map digitization has a lot of limitations and downsides, including the time and manual effort that it takes, and the fact that the quality and resolution of the digitized data are always limited by the quality of the original map (and this quality is sometimes further degraded in the conversion process). However, in some cases it may be the most suitable option, for example when no viable alternative exists, or when the quality is appropriate for the purpose, while it is cheaper than performing the collection process anew.

Collaborative mapping

Collaborative mapping is a relatively recent trend, which have been enabled by the developments of the Internet and of web mapping platforms, in which map data are collected, and maps are created, not by the mapping professionals working for corporate or governmental bodies, but by the private enthusiasts. The usual objectives of collaborative mapping projects are to enhance the information about the mapped area and to avoid the restrictions that apply to the commercially-available data sources, even if the quality of data cannot be fully assured. Different data sources and collection techniques can be mixed in this approach, including data contributed by corporate and governmental bodies, cycling or trekking routes collected with the use of GPS-enabled mobile phones, or even manual insertion and editing of the points of interest based on the local knowledge of a contributing individual.

The most successful and widely known example of a collaborative mapping project is the OpenStreetMap (OSM)[2], which started in 2004 and as of late 2009 had over 200,000 contributors sharing the objective of creating a free and editable map of the world. However, some commercial mapping platforms, for example Google Maps, also allow for collaborative mapping activities, such as the creation and editing of user-generated overlay data, to take advantage of this growing trend.

[2] http://www.openstreetmap.org/

2.5.8 Display technologies

Digital maps can be presented using different display technologies. Possibilities range from the most simple, such as the traditional computer screens and projectors, to more advanced technologies that produce stereoscopic illusion of 3D and immerse the user.

3D graphics displayed on flat screens is based on the use of perspective to produce a limited effect of 3D-like views. Stereoscopic 3D systems render images which can be perceived by our brains as if they were really observed in three-dimensional space. Such systems render the picture separately for each eye, introducing some perspective shift, similar to the shift between the real-world images seen by each of our eyes.

The signal of two separate images can be directed to eyes using different technological solutions. One possibility is to project two images on a special screen using different polarisation (vertical or horizontal) of each image, and special glasses with correspondingly oriented polarisation filters, to separate the images that are produced for different eyes.

A more advanced solution is used in Virtual Reality (VR), where two small screens mounted in a VR helmet (or VR glasses) display modified views for each of the eyes. VR offers the highest level of immersion, where the user can experience an illusion of being completely immersed in a different, virtual world. Some VR systems allow interaction with the generated model, such as walking or flying through it, or even interaction with objects within the virtual world, using special manipulation devices, such as VR gloves (Figure 2.9).

Figure 2.9. Virtual Reality display and interaction system, comprised of a VR helmet and gloves (NASA)

Another interesting approach to geographic information display is known as Augmented Reality (AR). AR is used to enhance the view of the real world and combines it with additional information displayed on the screen. AR systems can use a combination of a camera and a screen to either completely replace the real view with its digitally enhanced version, or use translucent surfaces, for example of a glasses worn by a user, to dynamically superimpose additional information. Augmented Reality is a very promising technology for supporting navigation, for example in tourism (Schmalstieg and Reitmayr, 2006).

An example of slightly less immersive class of systems are Cave Automatic Virtual Environment systems (CAVE), which do not produce a stereoscopic illusion of 3D, but instead immerse a user by displaying the model on several screens that surround him.

Although VR systems are still complex and expensive, and hence used mainly for professional applications, systems that produce an illusion of immersion and 3D depth perception are already getting into the mainstream of consumer electronics. 3D television is becoming popular with a growing number of receivers being sold and enthusiastic projections for future sales.

3D television uses a similar concept to immersive systems based on image polarisation: it displays a slightly different view of the content for the left and right eye, in successive images that switch every second frame, using special glasses that can rapidly switch each lens from clear to opaque in sync with the TV images. Similar progress is seen in computer displays used in gaming, for example NVIDIA presented its stereoscopic 3D graphics solution '3D Vision' at the Consumer Electronics Show (CES) in 2009.

We expect that the progress in consumer 3D technologies may be an important factor that will facilitate popularization and strengthen the appeal of 3D mapping.

2.5.9 Geovisualization

Geographical visualization, or geovisualization, is a discipline that provides theory, methods and tools for visual exploration, analysis, synthesis and presentation of geospatial data. It is a multidisciplinary science, which is based on the integration of visualization in scientific computing, cartography, image analysis, information visualization, exploratory data analysis and GIS (MacEachren and Kraak, 2001).

Geovisualization (GV) extends the traditional concepts of mapping and cartography, to embrace new possibilities and applications enabled by technological progress. When the term is used in the context of mapping, it refers exclusively to digital, interactive and dynamic maps – different types of which are extensively used in GV's applications. But horizons of geovisualization are wider than just those concerning the use of maps. GV provides interfaces for visualization, analysis and exploration of any type of information that contains geographical aspects. It can be used for presentation at any abstraction level, from abstract representation of non-tangible, statistical or thematic data (Kraak, 2003; Krisp and Fronzek, 2003); to realistic visualization that mimics the real or simulated world with different levels of realism – used for example in environmental, landscape or urban planning (Bishop and Lange, 2005); to photo-realistic reconstruction of existing cities – as in geospatial virtual environments (MacEachren et al., 1999b; Kibria et al., 2008). To maximise the efficiency of data presentation geovisualization systems often use advanced display technologies, such as immersive and VR systems presented in the previous section (Fisher and Unwin, 2002). The design of effective and ergonomic human-computer interfaces is another important aspect. Because a large part of geovisualization concerns efficient display, analysis and manipulation of underlying data, it is an important subject in modern GIS (Kraak and Ormeling, 2003). The interfaces that enable data presentation and access are often based on maps.

Because it is concerned with presentation of geo-referenced data, and involves extensive use of maps, geovisualization may be perceived as an extension and a natural path of the evolution of cartography (Kraak, 2002a). MacEachren calls it "cartography for the 21st century" (MacEachren and the ICA Commission on Visualization, 1998). Some practitioners of the discipline of cartography prefer the new name 'geovisualization', and see the old world 'cartography' as outdated and provoking negative perception (Kraak, 2002a). This resulted in confusion regarding the meaning, scope and boundaries, as well as mutual relationships of cartography and geovisualization. From the progress seen to date it seems that GV is driven almost exclusively by technological progress, and lacks the appropriate research background to support the tasks traditionally bound to cartography (Meng, 2003). Products available on the market offer extensive 3D visualization, but often focus only on photo-realism, and neglect the efficiency of presentation of information, which is the essence of cartography.

In our opinion geovisualization and 3D cartography are separate disciplines, although both are interrelated. At present there is an evident lack of appreciation of the rules of cartography in geovisualization, and although in many aspects geovisualization involves the use of 3D maps, its emphasis is different. The interests of geovisualization are not focused primarily on, nor limited to, the efficiency of information presentation. These are wider, and concern support of spatial thinking and reasoning, exploratory data analysis, GIS data structures and algorithms, as much as the use of maps.

The discussion of the roles and boundaries of cartography and geovisualization is presented in detail in Chapter 3, where we also argue that geovisualization, among other disciplines, would benefit from the development and application of cartographic rules for 3D presentations. Three-dimensional cartography, neglected and almost non-existent today, requires and deserves more research interest, for the benefit of itself, and of 3D mapping products – including those used in geovisualization – as well as of 3D map producers and users.

2.6 Chapter summary

In this chapter an introduction to various aspects of cartography has been provided. This discipline of science has been first defined, then the history of its developments over the ages has been outlined, followed with the introduction to the related aspects such as geographic coordinate and geodetic systems, map projections, map production process, cartographic presentation and map types.

Then the changes brought by the computer revolution and the emergence of digital cartography have been discussed, followed by the discussion of modern technologies and trends that shape cartography nowadays, such as Geographic Information Systems, Global Navigation Satellite Systems, the emergence of Internet and multimedia cartography, digital globes, Geospatial Web, modern data collection methods and display technologies.

At the end a brief introduction of the discipline of geographical visualization (GV) and an initial comparison of GV with 3D cartography have been attempted, in order to introduce the reader to the subject of 3D cartography discussed in more depth in the next chapter.

Chapter 3

3D cartography

For centuries thousands of practitioners of the discipline of cartography developed a broad range of techniques, procedures and rules that allow efficient presentation and conveyance of information using the medium of maps. The popularization of computers and the introduction of digital maps demanded the expansion of the existing body of cartographic knowledge, and the introduction of numerous new rules and presentation techniques (Kraak, 2002a). The changes affected the whole process of map production, from the collection of data, through their processing, design of maps, and content distribution (Dorling and Fairbairn, 1997). Multiple new never-heard-of-before concepts had to be embraced.

Instead of preparing a defined map design that would then be printed and distributed in a form of cast-in-stone hard copies, cartographers had to get used to designs that are dynamic and easily customizable. Digital maps allow the user to perform tasks traditionally done by a cartographer (Dorling and Fairbairn, 1997), such as selection of data that interests him, or alteration of their presentation. Processes that were previously performed once for a particular map by its creator – such as generalization and symbolization – had to be implemented in the form of computer algorithms capable of performing them repeatedly and dynamically on a user's demand, or as an automatic response to the usage context. Emergence of the Internet, and the subsequent introduction of the concept of the Geospatial Web as a medium for distribution of data, allowed the creation of multimedia (Cartwright and Peterson, 2007) and web cartography (Rouse et al., 2007), where maps can be fitted with hyperlinks to other sources of data. Another change was that maps ceased to be static, and allowed the presentation of time-dependant (temporal) data, real or simulated, and incorporation of movies and non-temporal animations (Kraak, 2003).

All these changes stimulated the transformation of the discipline, which in order to survive had to evolve and adjust to the new demands. Extension of classical cartographic rules and variables (Bertin, 1967) proved necessary. Kraak (2002a) discusses some of these new cartographic variables, introduced to meet the requirements of the multimedia cartography, concluding that by now these have become widely accepted by cartographers. The process of adaptation of the discipline to the demands of the digital era, as far as 2D representations are concerned, can be recognized as successful. Although 2D digital cartography is condemned to keep evolving with the ever-changing technology, it is advancing and in line with the state-of-the-art.

But technological progress brought also another change, which as of yet has not been fully embraced by cartography. 3D graphics, initially used almost exclusively for games and entertainment found its way first into scientific visualization (McCormick et al., 1987), and later into geovisualization. 3D maps are now widely used as interfaces to 3D GIS and for visual data exploration in geo-virtual environments (Germs et al., 1999). But these visualizations have little in common with cartography, as they are purely technology-driven, and lack underlying rules of efficient data presentation (Meng, 2003). This calls for creation, or further development, of a new branch of cartography, focused on three-dimensional forms of map presentation. 3D cartography would provide the rules necessary to achieve the full potential of 3D maps, and support their popularization in different applications.

Before we move to the review of the existing 3D cartographic literature, let us first focus on a definition of the new discipline, and discuss its position in relation to geovisualization and to the other branches of cartography.

3.1 Definition

A reasonable attempt to provide a suitable definition of 3D cartography seems to be through the use of analogy to the definitions of general cartography, discussed in Chapter 2. However, the analogy should not be too simple, as the influence of modern technological trends, and the specifics of digital forms of map distribution, presentation and access should also be taken into consideration. When these are taken into account, the definition may be formulated as something close to the following: "3D cartography is the totality of scientific, technical and artistic knowledge and activities, concerning the complete lifecycle of 3D maps, including: the collection of data, the process of production and distribution, the underlying technologies and algorithms, as well as the forms of use and applications."

The trouble with this definition is that it relies on, and hereby requires, a precise definition of the subject of the 3D cartographic interest, i.e. of 3D maps. And these are such a broad subject, and have so many different forms and aspects, that providing a precise definition is difficult. Let us then leave the definition of 3D maps until Chapter 4, and focus now on the discussion of the relations of 3D cartography with geovisualization and with the general cartography. This is followed by the review of existing literature, in which numerous cartographic aspects are discussed from the perspective, and within the context, of 3D mapping. The discussion of boundaries, role and scope of geovisualization (GV) versus these of cartography seems an especially confusing and challenging subject, so let us tackle it first.

3.1.1 Cartography versus geovisualization

Compared to cartography, geovisualization is a relatively new discipline, which concerns various forms of representing geo-referenced data. It is a modern and innovative discipline, rooted deeply in computer technologies, whose emergence was enabled by technological progress.

Most cartographers see geovisualization as an extension and continuation of cartography: MacEachren calls GV "the Cartography of the 21st century" (MacEachren and the ICA Commission on Visualization, 1998). This view is also supported by Kraak and Ormeling (2003). However, it can be noted that the emergence of geovisualization marginalized the meaning and importance of cartography. As mentioned by Kraak (2002a) some cartographers do not like the new term used for what in their view is a natural extension of their domain, and should still be called cartography. They see geovisualization as a natural evolution of cartography, which has adapted to new technologies and needs. To the contrary, Kraak himself sees the old word limiting and provoking a prejudiced, restricted and outdated view of the discipline (Kraak, 2002a). The popularity of geovisualization led even to the emergence of voices willing to assign digital maps to it, and to restrict the use of the term 'cartography' exclusively to traditional 2D paper maps (Krisp, 2006, pp21).

But did geovisualization really live up to its promises? And does it offer a true alternative to cartography? In our opinion both answers are at least partially negative. The trouble is with geovisualization's purpose and scope, which are different, wider and less focused, from those of cartography.

It is easy to observe the fact that geovisualization is a much broader discipline. It involves all kinds of geo-referenced data visualization, including interfaces for GIS, statistical data analysis and exploration, and a number of more or less graphically realistic visualization types. Most of these do not use cartographic concepts of abstraction and symbolism, but blindly aim to mimic the appearance of the real or simulated world. The focus of cartography traditionally was different. Its main aim was the efficient presentation of geo-referenced information. This involves application of the rules of cartographic presentation: abstraction, symbolization, generalization. Most people would agree that there is a significant difference between an air photo of an area and a specially designed map of it. In general, a map should be more efficient in transferring the information regarding spatial features selected by a cartographer than an orthophoto. The same can be said regarding the difference between some forms of 3D photorealistic geovisualization and 3D maps. In our opinion cartography should be kept as a separate discipline, and should provide the research and rules which are missing in geovisualization. Both disciplines are closely interrelated, and both have something to learn from the other. Technical developments in 3D visualization and interaction methods may benefit 3D cartographic maps, while cartographic rules may have a positive impact on the quality of GV products.

The problem with a precise definition of the boundaries between the two disciplines lies in the difficulty of finding definite differentiating factors. Both disciplines use maps, but with a different focus. Geovisualization is concerned with digital maps, which are often used as interfaces to other underlying data. These are often presented with a high level of photorealism. But even from this perspective the boundary is fuzzy, as maps used in geovisualization can be presented with various level of realism: ranging from photo-realistic visualizations, used for planning and visual impact assessment; through simplified views used in 3D city (City GIS) models; to purely symbolic representations. Moreover both the maps in the pure cartographic sense and those used within GV are not restricted to tangible objects, and can present different types of thematic and non-tangible information.

This leads us to the conclusion that it is impossible to give precise definitions of both disciplines' scopes and boundaries. These do overlap, and the positions of the boundaries are fuzzy. Different people may have different views regarding the exact position of the boundaries, and the extent of the overlap.

A definition may be simpler if cartography is discussed in terms of two separate branches: the traditional that concerns paper maps; and the digital. These do overlap, as a large part of the rules and techniques applies to traditional and digital maps alike. At the same time each of these has a large body of knowledge that is not relevant to the other branch.

The overlap of traditional cartography with GV is rather small. Traditional maps are not relevant to geovisualization – as they do not share the technological platform which forms the essence of GV – but a subset of traditional rules which apply to digital cartography could be also applied to, and benefit, geovisualization. The interrelations with GV are much stronger for the digital branch of cartography. A large part of new rules, technologies and cartographic variables developed within digital cartography applies, or could be applied, to geovisualization. Looking from the perspective of maps, the boundary between a digital map and a geovisualization system is equally difficult to define. Digital maps benefit from technological progress attained by researchers in geovisualization, and can use GV's advanced display technologies. Computer maps are often used as data interfaces in geovisualization. Even if intended for use outside of GV, they are not limited to any specific set of functions, and, with the availability of the Geospatial Web, can provide access to almost any type of data.

This discussion is summarized in Figure 3.1, which presents our understanding of the relations between the traditional and digital cartography, and geovisualization. It should be noted once more, that the actual boundaries cannot be precisely defined, and that other researchers may perceive them differently. Therefore the figure should not be treated as a precise definition, but rather as a general illustration.

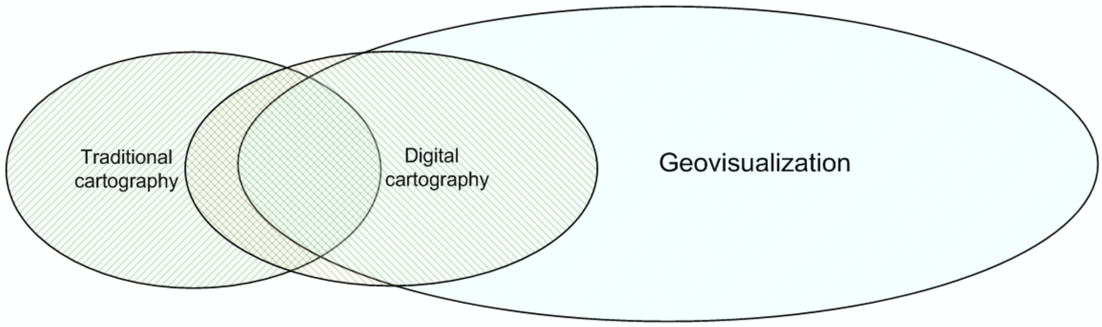

Figure 3.1. Relations between the traditional cartography, digital cartography, and geovisualization

3.1.2 3D versus other branches of cartography

Three-dimensional representations are not entirely new to cartography. Some of these have been known and used for some time. Examples are terrain relief maps made of wood or plaster (Dorling and Fairbairn, 1997, pp112-113), or static perspective views printed on paper. These form a small part of the discipline, as they never got really popular, perhaps due to their inherited limitations. This static 3D subset of traditional cartography is out of the scope of this work, and will not be discussed.

The emergence of three-dimensional computer graphics and interactive manipulation techniques enabled real progress in, and significantly increased the potential of, 3D mapping. Three-dimensional interactive mapping, as we may call it, is entirely the sub-domain of digital cartography. It overlaps with the traditional cartography, with regard to a selection of traditional cartographic rules which have a direct application, or need only a moderate modification, in 3D.

In relation to 2D maps, both paper and digital, three-dimensional maps have some specific properties that differentiate them. The gap is smaller between three- and two-dimensional digital maps, as 3D maps may partially use the same display algorithms, interaction methods and data access technologies which are used in 2D digital cartography. 3D maps have much less in common with traditional paper maps. They do share some of the cartographic rules known in traditional cartography, but what sets them apart is the use of 3D perspective views and interactivity. Paper maps are static and do not allow any level of interactivity. For the reasons of the inherent limitations of static perspective views, such as distortion of distances, and the existence of hidden regions, interactivity is a must for efficient 3D maps. They would be useless without it, and as such cannot be successfully used on paper, apart from some limited applications.

The relation of three-dimensional interactive cartography, with its two-dimensional digital sister, is much closer. Digital maps of both categories come in different flavours that vary with the technological solutions applied, but share a large part of the same technological platform. For example both these types can be accessed via the web or may be presented in the form of standalone applications; and both types of standalone applications may store data locally, or access it through the Geospatial Web. The only real differentiating factors are: the type of visualization used; and the level of interaction provided – which is required to be greater in the case of 3D presentations. Our understanding of the relative positions, and overlaps, of the digital, traditional, and interactive 3D cartography, is illustrated in Figure 3.2.

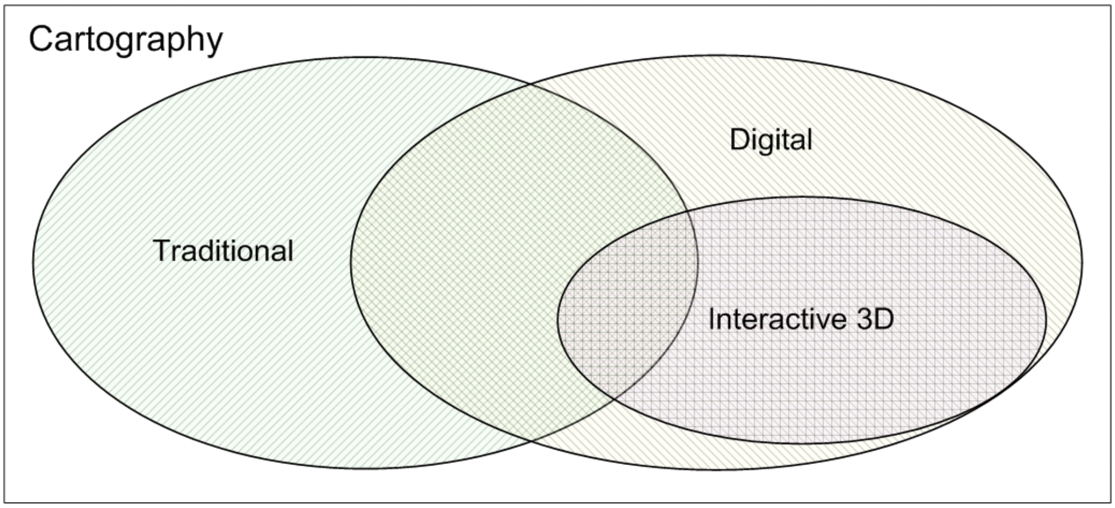

Figure 3.2. Relations between different branches of cartography

3.2 Research background

There exists a limited research background in the discipline of 3D cartography. A lot of research has been done in different types of 3D geovisualization, such as visual interfaces to 3D GIS (Zlatanova et al., 2002a), landscape planning and visual impact assessment (Bors-boom-van Beurden et al., 2006; Pettit et al., 2006) or 3D cities (Haala et al., 1997; Takase et al., 2003). A fair amount of research comes from the use of 3D charts in marine navigation (Ford, 2002; Gold and Goralski, 2007). But the aspects concerned with cartographic rules of efficient 3D map design have hardly been discussed (Haeberling, 2002). According to Meng (2003) "The development of cartographic theories and methods lags far behind the technical evolutions." In the face of this absence of a satisfactory 3D cartographic research body, it seems appropriate to start our literature review from the statement of needs for more theoretical research in this domain.

3.2.1 Statement of research needs

We said before that two-dimensional digital cartography managed to catch up with the technological progress and is evolving in line with it. Unfortunately things are completely different in the case of 3D. Rapid and constant development in the areas of geographical visualization, 3D GIS, 3D modelling of cities and landscapes, urban planning and visual data analysis and exploration, have not been matched with the corresponding developments of 3D cartographic rules.

Haeberling (1999) notices the lack of cartographic rules and theories that would support development of 3D maps as efficient tools for transfer of information. The lack of cartographic principles was listed by him as among the three main problems related to 3D cartography, the other two being ignorance of user needs, and neglect of symbolization and legend. Meng sees a negative impact of the underdevelopment of 3D cartography for the quality of resulting systems and the discipline of cartography itself. "Although new technologies help to make the cartographic practice work better, they do not necessarily yield better products and more usable systems. In the long run, the lack of theories and methods that should guide cartographic processes may cause the degradation of the scientific value of cartography" (Meng, 2003, p2). According to Dollner and Kersting (2000) such rules are required to take advantage of interactivity, intelligence, and different representation styles of 3D maps, and to assure efficient presentation of data. Haeberling (2002) notices that: “unfortunately, for map makers today, cartographic theory and principles about 3D map design are almost nonexistent,” adding that the rules and guidelines for the creation of 3D maps should be formulated, to “give cartographers additional stimuli to generate informative and useful representations, ultimately benefitting the user.”

It is also our conviction that the lack of such rules negatively affects multiple applications within the broad discipline of geovisualization. This is bad for all stakeholders: GV is developing slower and is not as effective as it could be, given the technological and market potential; the customers pay for, and the end-users receive, less-effective and poorly-designed products; and the role of cartographers and cartography is minimized and even seen as obsolete. In addition, the word ‘cartography’ starts to be seen as old-fashioned and causing a prejudiced attitude of the users, who tend to link it exclusively to traditional maps. Hence it is often abandoned even by cartographers who prefer to use the new term ‘geovisualization’ instead (Kraak, 2002a). Although it does not really matter which name should be used, the problem that cartography is facing today is the diminishing awareness of the need for cartographical knowledge among mapping software producers and its users. This poses a serious threat to the discipline. It could be imagined that if cartography cannot cope with the technological progress it may be further marginalized and restricted to traditional paper maps (Krisp, 2006, p21). This is a classical loose-loose situation that would harm all of the interested parties.

However late it may seem, it is still not too late to start developing cartographical rules for 3D mapping. Little has been done in this area so far (Angsusser and Kumke, 2001), and the task is difficult, possibly even more complex than the one faced by cartographers upon the introduction of digital 2D maps. This is further complicated by the limited access to flexible 3D mapping products that could serve as platforms for cartographical experiments. And there are plenty of mapping-related aspects that are unique and new, or completely changed, with the introduction of 3D. Some old rules of cartography will remain valid also in 3D. Other will be applicable to a limited degree. But multiple rules applicable to 2D maps will turn out to be useless with the addition of the third dimension. On top of that, there will be requirements to establish numerous completely new techniques, variables, rules and technological guidelines for the aspects that are unique to the new generation of maps.

The new aspects that are unique to 3D – and hence were never discussed by the traditional cartography – may be seen as especially difficult, and the whole task as daunting. But the discipline and its practitioners proved their capability to adapt, and we believe that they will be able to successfully extend and defend their discipline once again. This is necessary to enrich the potential of 3D mapping and of geovisualization. It has to be done for the benefit of cartographers and of their discipline, as well as for the 3D map producers and users.

3.2.2 ICA research agenda for the 21st century

At the end of 1990s MacEachren and the ICA Commission on Visualization announced a new cartographic research agenda for the 21st century (MacEachren and the ICA Commission on Visualization, 1998). It has been revised in the paper by MacEachren and Kraak (2001), which discussed a list of aspects that require further cartographic research focus, in order to use the full potential of technological development, and to advance the discipline of cartographic visualization to keep up with its pace. The research themes were categorized into four major categories: 1) representation; 2) interface design; 3) database-visualization links (visualization-computing integration); and 4) cognitive aspects of visualization tool use. Each of the main categories has been discussed more deeply in one of a series of publications, in a special edition of the Journal of Cartography and Geographic Information Science: 1) "Representation and its relationship with cartographic visualization: a research agenda" (Fairbairn et al., 2001); 2) "Geospatial Information Visualization User Interface Issues" (Cartwright et al.,2001); 3) "The Integration of Geographic Visualization with Knowledge Discovery in Databases and Geocomputation" (Gahegan et al., 2001); and 4) "Cognitive and Usability Issues in Geovisualization" (Slocum et al., 2001).

The representation theme 1) focused on: a) extending the object of geographic representation to embrace space time phenomena and processes, representation of data reliability and visualization of algorithms used to process spatial data, data structures and query processes; and b) extending the forms of representation. Under this theme it has been stated that "research is needed to determine how to integrate methods for dynamic manipulation into GV tools, and to integrate VR technology with geographic data principles and geographic representation," as well as that "in addition to research on the technical problems of using new technology to best advantage, research is also needed to consider the implications of new representation forms" (MacEachren and the ICA Commission on Visualization, 1998, p4). MacEachren and Kraak (2001, p4) clarify it further: "Advances in methods and technologies are blurring the lines among maps and other forms of visual representation and pushing the bounds of "map" as a concept toward both more realistic and more abstract depiction. As a result, there are a variety of unanswered questions about the attributes and implications of maps." The representation agenda team focused on visual representation as it relates to five issues: semiotics and meaning (how visual depictions relate to underlying meaning), data (how visual depiction relates to interpretations and structures imposed as data are collected and organized), map use (how visual depiction relates to desired uses), map users (how visual depiction relates to human-computer interaction), and technology (how visual depictions can/should take advantage of technological advances)."

The interface design process 2) was recognized as "fundamental to using the geospatial visualization tool effectively" (MacEachren and Kraak, 2001, p6). Four central interface themes identified were: "interfaces and representations of geography, interaction (particularly navigation, access and manipulation), universal access, and practical implementation of interfaces using new technologies" (MacEachren and Kraak, 2001, p6). In part relating to virtual environments (which in large part is an equivalent term for advanced 3D maps) it has been said that: "Although virtual environments are expected to facilitate understanding of complex geospatial information, most VEs are hard to use because there is a mismatch between the visually realistic 3D character of the environment and the tools currently provided for navigating through that environment or changing its parameters" (MacEachren and Kraak, 2001, p6).

The need for research in the database-visualization theme 3) is prompted by increasing volumes of available geospatial data sets, which can be efficiently analysed using visual means offered by interactive 3D maps. The theme is oriented around the issues of integration of GIS with geovisualization; GV in the context of spatial data mining; as well as the extension of concepts of generalization a) from 2D to 3D, and b) to embrace generalization of hyperlink networks (MacEachren and the ICA Commission on Visualization, 1998, p6).

MacEachren and the ICA Commission on Visualization (1998, p4) note that: “The promise of visualization is based on an assumption that human vision and cognition has powerful information synthesis and pattern seeking capabilities that can effectively complement the raw information processing power of digital computers.” They observe that the need for research on cognitive aspects of visualization tool use 4) is necessary because: “Harnessing this power of vision, however, requires developing a more complete understanding of spatial cognition and perception of visual displays. While we have a solid base of knowledge about perception and cognition as it relates to static paper maps, we know much less about the cognitive and perceptual issues associated with 3D and dynamic displays” (MacEachren and the ICA Commission on Visualization, 1998, p6). The topics identified in this theme include: cognitive aspects of dynamic representation, i.e. the role of animations in the human understanding process, with implications of its various parameters such as number of frames per seconds, smoothness of transition between subsequent frames, differences between temporal and non-temporal animations, and methods for retaining orientation within the scene; 3D representations and virtuality, including understanding the cognitive implications of different levels of realism, mental linking of two- and three-dimensional representations, and integration between sonic and visual information; cognitive aspects of interaction with human interfaces and displays; cognitive aspects of navigation in the hypermedia link networks; differentiation between different groups and individual users; testing and understanding the influence of geovisualization methods on the scientific processes and their efficiency; and the role of visualization in decision-making, including understanding how GV tools affect the decision process and its outcomes, implications of different components of such tools for the process and its results, and the effects of data reliability visualization (MacEachren and the ICA Commission on Visualization, 1998, pp6-7). Slocum et al. (2001, pp11-12) adds the "collaborative geovisualization" to the list of topics.

Generally the papers that constitute the agenda consider aspects related to 3D maps exclusively in the context of geospatial virtual environments (GeoVEs). Although 3D maps *per se* do not seem to be a major theme for the research agenda, its authors do ask some questions that are of relevance to them. However, the questions and aspects related to 3D representations are dispersed within the different research themes, and there is not a single theme or a summary focused specifically on 3D. The quality and efficiency of 3D representations is not even mentioned. It may be justified by the fact that the ICA Commission on Visualization's approach gives a more general, broader perspective of research challenges, of which 3D maps are just a minor element; and that some discussed aspects of GeoVEs regarding representation, interfaces, databases and cognition relate more or less directly to 3D maps anyway. Research advances in these aspects will without any doubt also benefit 3D maps.

However, in our opinion, the efficiency of 3D cartographic presentation is such an important subject in its own right that it deserves a more focused and comprehensive analysis, and it is a pity that a specific theme in the ICA agenda has not been dedicated to it. Moreover, it is really disappointing that no publication dedicated specifically to problems of 3D representations has been published since. Lack of specific focus on 3D, and too broad a perspective with low level-of-detail, may mean that some relevant research aspects have been omitted, or have been discussed in too abstract a form to provide guidance applicable to real problems. More worryingly, despite a remarkable achievement of summarizing a vast quantity of aspects that require cartographic research, which the agenda undoubtedly was, most of the aspects that relate to 3D maps have not been pursued further. Over a decade after the publication of the agenda a majority of the questions identified in it remains largely unanswered.

3.2.3 Practical studies

As there is a lack of serious cartographic discussion relating to 3D cartography, most of the publications dedicated to the subject (which is unfortunately true also for our work) are written by computer 3D map developers, interested in practical development. Very few publications are written by trained cartographers focusing on the theoretical side of 3D mapping. It leads to the following observations: 1) these works are usually limited, biased towards the practical development problems and solutions, and lacking general cartographic knowledge. This means also that some of the potentially important aspects may not be covered at all, as they would need a bigger picture to be noticed and understood; on the other hand publications written by cartographers without practical development experience may be too abstract and not suitable for the practical development needs; 2) The demand for cartographic research regarding 3D existed for some time, and was expressed by multiple 3D maps designers. However, it seems not to be heard, as the responses from cartographic professionals are still rare; 3) In the light of the above it seems that the best answer may be provided by a joint research effort from both the communities of cartographers, and mapping product developers.

Let us now discuss publications resulting from practical studies and development efforts. Terribilini (1999) discusses the development of interactive vector-based topographic 3D maps, with focus on cartographic symbolisation in space, not on a realistic landscape rendering. The subject is presented as a process of map transition from two- to three-dimensions. Terribilini uses the difficulty of understanding of 2D maps as an argument towards more widespread use of 3D presentations, with use of more real-world-like symbols portrayed with certain level of abstraction. In this understanding a 3D map, or a cartographic three-dimensional model, is a three-dimensional abstract description (generalization) of one or more aspects of the real world. Terribilini provides a list of requirements for different parts of a 3D mapping viewer. The cartographic model (CM) has to: be able to cope with large volumes of data; use a vector data structure, which is more data volume-efficient than a raster data structure and allows easier and more versatile computational analysis; and has to be multi-resolution, which means that each element contained in the map must be represented with adequate graphic variables (shape, orientation, colour, *et cetera*) depending on the local scale, and requires the support of different levels-of-detail

(LODs). The author also stresses the fact that most available data sets are two-dimensional, and that it is hence worth a special effort to enable production of 3D models directly from 2D data. The requirements towards 3D terrain models are the following: 1) the use of adaptive triangulation structures, such as Triangle Irregular Networks (TIN) which are capable of efficiently storing and presenting details with resolutions that vary over the surface; 2) the possibility of progressive refinements, which means more detailed presentation of some areas, while maintaining the continuity between adjacent triangles. The Delaunay triangulation (DT) is recommended as the most suitable choice, for its desirable property of generation of triangle sets that are as equilateral as possible, which is important for avoidance of long and thin triangles that cause undesirable effects in visualization. Requirements concerning the visualization system that renders the cartographic model are the following: 1) Support for multi-resolution representations, with automatic selection of a suitable level-of-detail depending on the distance to the viewer; 2) Support for multi-viewport representations, i.e. the possibility to display the model from different points of view; 3) Real-time visualization (fly-in), that allows the user to select the best viewing position, without losing the understanding of the scene; 4) High rendering quality; 5) Interactivity. Terribilini argues that a visualization system for cartographic application must be interactive to allow the user to perform queries and obtain additional information about map objects; 6) Capability to import and overlay external data. Modelling of map elements as 3D symbols is another research focus of the author, who states that no theoretic works on symbolization in 3D had been published. Another aspect is symbol generalization, for which an automatic process is planned. The idea is to eliminate the details of a map element’s representation which can not be noticed by the human perception system. The presented list of requirements and research interests was the basis for the research project concerning the development of a prototype viewing system by Terribilini.

Haeberling (1999), in the previously cited paper in which he notices the lack of cartographic rules and theories, discusses the problem of symbolization. He states that the issue is highly complex, and that traditional 2D cartographic principles cannot be used for 3D maps, while the use of perspective views introduces new aspects such as flexibility of design, visibility and spatial arrangements. In the cited work Haeberling did not distinguish between static perspective views of land sections and interactive computer maps. His work was focused mostly on the first category, which includes 3D maps printed in journals and books, used for tourism and education, or for illustration of scientific results. Nevertheless, his observation that 3D maps are mostly designed using subjective preferences, and not the cartographic theory, is also true for interactive 3D maps. According to the author, cartographic principles could be used when choosing the favourite perspective for a landscape section, determining the general layout, adjusting colour tables, arranging point and line symbols and positioning text elements, and "are an indispensible basis for creating not only impressive, but also useful topographic 3D-maps." He called for more cognitive and user studies to supplement development of "a broad set of cartographic principles for topographic 3D-maps" (Haeberling, 1999).

Dollner and Kersting (2000) present an architecture design of a 3D mapping toolkit, in which different map elements are categorized into different groups of abstract building blocks. They distinguish three main categories of map primitives: 1) visual objects; which are accompanied by 2) structural building blocks, used to organize the hierarchy of map content; and 3) behavioural elements, responsible for map dynamics and user interaction. Visual objects include: landmarks – 2D or 3D symbols that represent geographical objects; labels – textual descriptions that automatically orient towards the direction of view; texture layers; and LOD groups – that select appropriate representation of an object, based on the distance to the camera. Visual symbols can be imported to the system, which also provides a built-in shape library. Structural objects are categories and groups, used for map object classification. Behavioural objects include event-callback tables, which define system responses to device or time-based events, and constraints used to limit interaction or manipulation. The system also supports multi-resolution terrain models, with texture trees for support of variable terrain resolutions, and temporal animations with texture sequences that change over time. The viewer is customizable using a simple scripting language.

In another work, Dollner and Hinrichs (2000) present more technical details of the same toolkit, focusing on the design of a hybrid multi-resolution terrain model, which uses a combination of geometrical information with texture layers. Texture trees are used to accommodate multiple resolutions of textures, which can be organized in multiple layers, and combined using high-level operations such as blending and masking. The hybrid terrain model is based on the concept of approximation trees, which allows storing terrain in different topologic formats (for example a coarse grid geometry supplemented locally with more-detailed TIN patches), together with multi-resolution texture layers; and real-time rendering of an appropriate level-of-detail, where selection depends on distance to the observer and the screen size. The use of high-resolution textures, in combination with lower-density terrain geometries, produces good visual results, while improving the rendering efficiency due to the minimized polygon count.

A later work by Kersting and Dollner (2002) discusses interactive 3D visualization of vector data in GIS. The authors recommend a texture-based approach for visualization of 2D vector data in 3D, and technical details of this approach are discussed. The advantage of the approach is based on its ability to display 2D data such as lines, polygons, symbols and text labels on the surface of terrain, with precise matching and good quality. The same multi-texture and approximation tree mechanisms, described previously, are used.

The publication of Haeberling (2002) provides a systematic evaluation of important graphic aspects of 3D perspective views. The author starts with a short classification of 3D cartographic representations, dividing them into two main categories: 3D perspective representations that are presented on two-dimensional media; and "true 3D representations that can only be visualized interactively using special equipment." The author focuses on the first category, but most of his points regarding cartographic "graphic aspects" are applicable also to our area of interest, which is the second class of 3D interactive representations. Haeberling notes that although 3D perspective views possess cartographic characteristics, they should be considered map-related representations, not maps in a classical sense. This corresponds with our definition, which points out that static views have a limited use, due to characteristics of perspective presentation including distortion and visibility issues, and hence only interactive 3D representations free of these limitations truly deserve the name "3D maps." The author divides the process of design of 3D perspective views into three steps: 1) data modelling; 2) symbolization; and 3) visualization. He then moves on to discussion of important "graphic aspects" related to each of these steps, adding that all of these require further cartographic research.

The aspects discussed for 1) (data modelling) include map object aggregation, initial simplification of objects' shapes, positioning and semantic concerns. Positioning concerns include decision on whether the objects should be placed according to their geographical positions, or in relative reference to each other. Semantic considerations are related to appropriate classification of objects, and to mapping their spatio-temporal dependencies in the database (Haeberling, 2002). The difference between static perspective views and interactive 3D maps, that needs to be noted here, is that for that latter category the positioning concerns would be considered in a later stage of the map creation process – during the map rendering on-the-fly – when appropriate cartographic techniques would be applied to the previously-modelled data.

2) Graphic aspects of symbolization include: position, shape, size, colours and brightness, textures and patterns, orientation, special graphic aspects, object animations and movements, and orientation features. Positioning refers to the presentation of positioning information, which apart from object placement within the map can be described numerically. Referring to the non-trivial problem of vertical placement the author notes that: "In the future, all geo-data must also contain absolute or relative height position for 3D representation purposes" (Haeberling, 2002). The graphic aspects of shape include the degree of abstraction, generalization and homogeneity within the 3D scene. Size refers to proportions of

objects, and vertical exaggeration of terrain. Good design of map aesthetics, including colours and brightness, is mentioned as an essential prerequisite. Textures and patterns refer to terrain and other map objects, and these can be created procedurally or by draping raster images. Orientation is said to be of little importance to the 3D map design process, due to the large capabilities of computer systems for applying it automatically during the rendering process. Special aspects include the application of transparency, and the adjustment of style and thickness of lines. Object animations and movements refer to the possibility of application of objects' characteristics that can change with time or upon users' actions – such as modification of sizes and shapes, object movement, and animation of the camera position to enable fly- or walk-throughs. Orientation features include labels, geographical coordinates and scale information.

3) Aspects of the visualization process include the choice of an appropriate projection; a decision on the level-of-detail for the model; settings of the camera (static or moving, position and geometry); application of lighting and illumination (types, directions, geometry and positions of light sources); shading and shadows – which together with lighting have a strong influence on landscape cognition; as well as atmospheric and environmental effects – that enable more natural perception of a 3D map.

3.2.4 Input from geovisualization

We said before that theoretical research in, and development of rules for, 3D cartography would also benefit other disciplines that use 3D maps, such geovisualization. It has also been said that both disciplines can learn from each other. In the situation of the deficit of systematic research in 3D cartography, it is worthwhile to take a look at what has been done in relevant areas of geovisualization. A large amount of GV research has been done, and some of its aspects – such as the technical side of 3D map design – are of high applicability and importance to 3D mapping.

However, before we move into the analysis of geovisualization know-how, is necessary to remember that findings in geovisualization will not replace a properly focused research in cartography. The lack of a harmonised and coordinated approach to 3D cartography, as a specific interest theme, results in the fragmentation of research efforts, and of the resulting knowledge. That means that some 3D maps aspects, mostly these relevant to different applications of GeoVEs, enjoyed a significant progress, while others, with less relevance to GV, have been barely touched. This fragmented literature can be a good source of guidance to specific development aspects, but it lacks the big picture, and does not necessarily lead to a comprehensive and satisfactory improvement of the quality of resulting products.

Publications that are of relevance to 3D representations come from different areas of geovisualization, GIS and geospatial virtual environments. Giertsen and Lucas (1994) discuss 3D maps in a context of 3D visualization for 2D GIS. They provide a conceptual framework describing relationships between 2D GIS and 3D visualization. The main points of their work are: 1) that different user groups have different requirements regarding the presentation styles and techniques; 2) that while traditional cartographic techniques of abstract representation require the use of a legend as a reference key, 3D representations are by nature easier to understand.

Depending on the techniques used, 3D symbols are categorized either as experience-based or realistic representations, which have a lower or no need for a legend, respectively. The authors distinguish four categories of 3D presentation techniques for 2D data: 1) procedural visualizations, that can produce 3D representations of map objects which vary on the level of abstraction or realism, and generally are ranked among experience-based presentations; 2) planar visualizations, in which 2D data are mapped onto one 3D planar surface, creating a single perspective view; 3) height-field visualizations, used for creation of 3D terrain surface models with simple shading and symbolic objects imposed on the surface. This category of presentations is also considered to be experience-based; 4) volume visualizations, used for presentation of real-3D (volumetric) data. Typical means used for abstract presentation of these include shaded isosurfaces and shaded volumetric contour regions. The authors conclude that tools to present data in many different presentation styles are required, and that there is no need to wait for 3D GIS and three-dimensional data to be widely available, before introducing 3D visualization. They argue that many 3D visualization techniques may be applied directly to 2D GIS data.

Other interesting works include an attempt by Zlatanova and Bandrova (1998) to analyze user requirements for 3D GIS, where they discussed such themes as the presentation of objects, resolution, relationships, realism, and graphical user interface. Works by Kada (2002), Meng and Forberg (2006), and Glander and Dollner (2008) provide a detailed conceptual and technical discussion of the subject of building generalization, which is an important aspect for 3D virtual cities and urban modelling – that in a limited range applies also to 3D maps. Paar and Clasen (2007) present approaches to representation of vegetation in 3D, mostly from a perspective of land planning. Dollner (2007) discusses the advantages of, and different approaches to, non-photorealistic 3D representations, pointing out that: "Photorealistic computer graphics does not provide optimal solutions for vivid, expressive, and comprehensible visualizations. In particular it does not provide optimal means for visual abstraction and, thus, for cartographic visualizations" (Dollner, 2007, pp230-231). MacEachren et al. (2005) and Appleton et al. (2004) discuss the problem of representation of uncertainty of data in 3D visualizations. Burton et al. (2008) present a case study of using semi-immersive VR to determine and communicate the visual impact of wind farm planning. The authors discuss different technical aspects involved in such an exercise, and make recommendations based on the feedback from a study of the focus group involved in testing of the proposed solution. They found two important functional requirements, which seem relevant to 3D maps in general: 1) "A compass or location map would allow easier orientation within the virtual model. Ad hoc changes in observer position require a high degree of spatial awareness within the virtual model"; 2) "The ability to switch between alternative terrain drapes, such as an intervisibility map or Ordnance Survey map, was considered important" (Burton et al., 2008, p313).

The problem of rendering vector data on 3D terrain models attracted a large amount of research interest, which is in line with the importance of the problem for 3D GIS and exploratory data analysis. Kersting and Dollner (2002) propose a texture-based approach. Schneider et al. (2005) present a hybrid technique, based on the merging of the texture-based and the geometry-based approaches. Schilling et al. (2007) discuss both of the above approaches, with a focus on web-based 3D map services. Chenguang et al. (2008)

propose an alternative solution, based on the theory of stencil shadow volumes. The authors claim that, unlike the previously mentioned approaches, this screen-space algorithm offers a pixel-level precision, does not suffer from aliasing artefacts (typical for texture-based techniques), and works robustly independent of the complexity of the terrain data set.

As said earlier, the works discussed above, however useful for the particular aspects which they discuss, are not a substitute for a systematic discussion of 3D representations, backed with cartographic research. The selection of topics for which detailed publications are available leads to the conclusion that today's cartographic developments are driven mostly by business, and not by scientific needs. Research efforts are secondary to the demands of technology and market products. On one hand it is good, because this means that the knowledge of the discipline is close to the real-life applications and utilized by a wide audience of market products' users. On the other hand, lots of these technological developments are made without proper background research. It is often the case that progress in technology comes first, and related research tries to catch up only afterwards. This leads to the situation where progress and knowledge are fragmented and incoherent. The absence of research coordination, one which would stem from the understanding of the big picture, has a negative overall impact on the quality of 3D maps, and of geovisualization products that rely on them.

The development of maps without a guidance of underlying cartographic theories may be compared to constructing buildings without firm foundations, or designing architectural works without proper mathematical computations of weight distribution, material strengths and tensions. And although the consequences of that situation in 3D cartography are far less severe than in construction, and luckily no bridge will fall down because of it, in our view it inhibits the quality, usability and the overall potential of 3D mapping products.

From our experience it also makes the life of mapping product developers more difficult. In our work on the development of the 3D Map Viewer platform we were often confronted with the lack of proper scientific knowledge, and in result we often felt like trying to navigate in a dense fog without any guidance. In many development aspects we, as well as other developers of 3D mapping products, had to make decisions based on subjective judgments, intuition, or by pure guessing.

Before we move to the description of practical aspects of our research, let us further discuss all the relevant aspects of interactive 3D maps. In the next chapter we provide our definition of cartographic three-dimensional maps, followed by a discussion of their different theoretical and practical aspects. We also present a list of recommendations for a successful 3D mapping product, which have been used, validated and refined in the development of the 3D Map Viewer.

3.3 Chapter summary

In this chapter the field of 3D cartography has been thoroughly discussed. The chapter starts with an attempt to provide a suitable definition of 3D cartography. This is done in three ways: 1) as a descriptive definition constructed using an analogy to widely known and accepted definitions of traditional cartography; 2) by discussing the similarities, differences and interrelations of cartography and geovisualization; and 3) by defining the boundaries of 3D cartography within, and by discussing its relationships with different branches of, the larger discipline of cartography. This first part of the chapter is mostly our own work (unless a specific reference is made), and is a part of what we propose as the new and original contribution of this thesis.

This is followed with a review of the existing literature on the subject, which, unfortunately, is scarce. The input from the existing sources, such as the ICA research agenda for the 21st century, as well as theoretical and practical studies from 3D cartography and from the related disciplines, is discussed. A statement of need for more research in 3D cartography is formulated and repeated throughout the review.

The attempt to define 3D cartography in the way that traditional cartography is usually defined was concluded with an observation that a suitable definition of the subject of interest of the discipline, i.e. of 3D maps itself, has to exist first.

In the next chapter 3D maps are defined, and various cartographic and technical aspects related to them are discussed in depth.

Chapter 4

3D maps

In the previous chapter the need for the development of a new branch of cartography, dedicated specifically to interactive three-dimensional presentations, has been discussed. The 3D cartography has been defined, and the unfortunately slim body of existing literature has been discussed. Relations with other disciplines, and related sources that 3D cartography could draw from, were also presented.

This chapter is dedicated to a more practical, and technical, description of the core subject of the 3D cartographic interest: 3D maps. As not all forms of geographic 3D presentation are maps in the cartographic sense, we start off with our definition of what we consider a three-dimensional map. This is followed by a discussion of different forms of interaction, and a review of various cartographic and technical aspects relating to 3D maps. These are based partially on the existing literature, and, in the other part, on the practical experience of the implementation of our 3D mapping platform. Requirements for successful three-dimensional mapping products are discussed in the relevant places.

4.1 Definition

Defining precisely what a 3D map is may be compared to choosing just one of over three hundred definitions for their two-dimensional counterparts. 3D maps are such a wide subject, and encompass so many different things, that hard definitions are difficult to provide. They may have various forms and properties, are used in different applications, and may be based on different technical solutions. Opinions about what is, and what is not, a 3D map, may vary among different people. For that reason, it is even more important to declare what we consider to be a 3D map for the purpose of this thesis. This is done in two ways: firstly by a technical/functional description; and secondly by a discussion of a suitable set of differentiating/defining factors.

4.1.1 Technical description

Before we move into the technical/functional discussion, we need to make an important remark. As stated earlier, we are not interested in static perspective views, or physical terrain models, but only in interactive computer presentations. Moreover, our interest is focused on maps which present topography of terrain. We do not discuss 3D representations that use the third dimension to present statistical data or variables, instead of the relief.

Maps which are the subject of our focus use 3D terrain models, as the basis for the display of different geo-referenced data. In these maps information can be presented in multiple (selectable) layers using different representational forms, and these may contain both tangible and non-tangible objects. Moreover, three-dimensional maps may represent existing real-world, as well as simulated data. The maps discussed here may have different interfaces, and offer various interaction, control and navigation tools. They may be static, or allow temporal animations. Different technical solutions may be used, and different sources of data may be supported.

A 3D terrain model – called a Digital Terrain Model (DTM) – is used as a point of reference. It can be a simple representation of the terrain surface, called a 2.5D representation, or a full-3D volumetric description. Map objects (data) can be placed on the surface, or in some relation to it, for example underground or above the surface. The surface provides a reference point for geographical location, as well as for the elevation of data. The DTM may be shaded in different ways, for example to represent terrain elevation with different shades of colours. Textures, such as orthophotographs or scanned maps, may be superimposed on the terrain's surface.

Map objects can be two-dimensional: polygons, lines, points, symbols, numbers or text labels drawn on the terrain surface; or three-dimensional. 3D objects may be drawn using different representation forms (see Section A.2), both based on surfaces and volumetric. These may be presented with different levels of realism, or be purely symbolic. In the second case map objects of defined types, or with defined properties, may be represented with a predefined set of 3D symbols. A three-dimensional symbol may represent a single occurrence of a data point, or aggregate several points. It may also be used to represent a polygon, for example with a single occurrence of the symbol located in the polygon's centre, or with the symbol displayed repeatedly to cover the specified area. The forms of data presentation are restricted only by the technical capabilities, and by imagination of map designers.

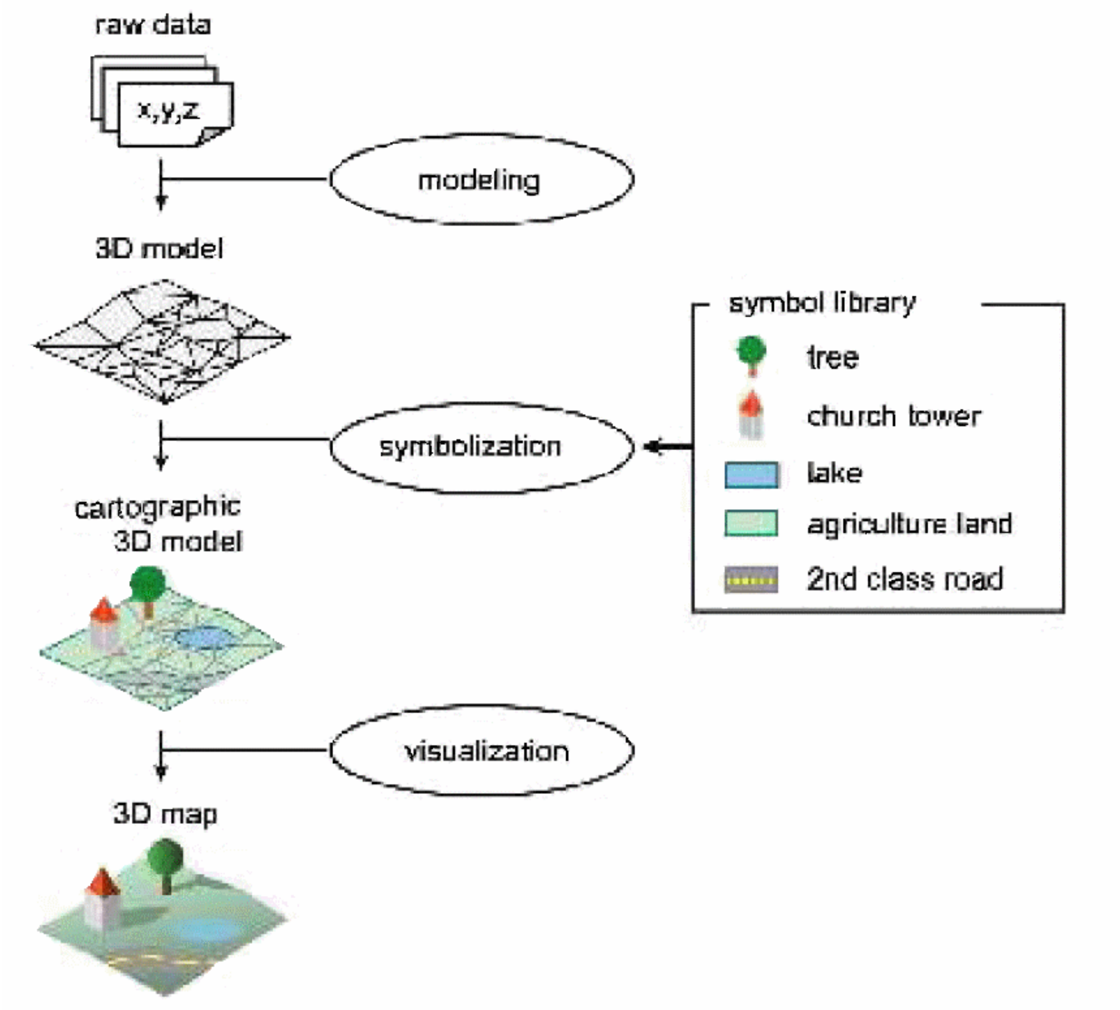

Figure 4.1. Schematic design process for 3D maps (Terribilini, 2001)

A 3D map, as for every digital map, is composed of a database that stores the cartographic model, and the visualization system that renders it upon a request. According to Kraak (2001b, p9) "the cartographic visualisation process is considered to be the translation or conversion of geospatial data from a database into map-like products." Visualization is not a simple drawing, but has to consider the intended map purpose and needs of a user. In the words of Kraak and Ormeling (2003) the process is based on a question "how do I say what to whom, and is it effective?" Usually, a map displayed on a computer screen (or on other display device) has to be redrawn at a constant frame rate, or upon each refresh request from the control mechanism. The visualization system has to be able to draw the map efficiently, from any selected perspective.

Figure 4.1 presents a schematic process of 3D map construction, as described by Terribilini (2001). The shading of the terrain and the application of textures and symbols on its surface represent the cartographic symbolization part of the 3D map design (or rendering) process. In order to assure the efficiency of information portrayal and optimal balance of presentation quality, data readability, and rendering performance, the visualization system has to include different cartographic algorithms. Generalization, multi-representation of objects (level-of-detail, dynamic exaggeration), and multi-resolution of terrain – when appropriate – should be included.

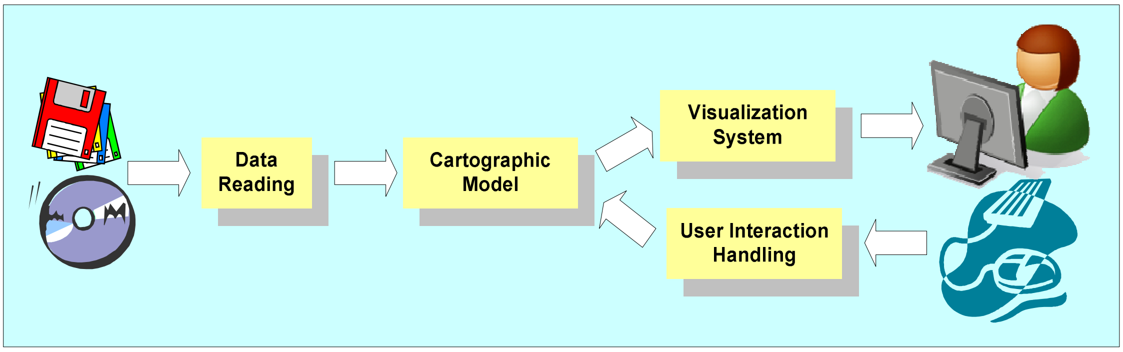

Figure 4.2. Main components of a 3D map system

The cartographic model and visualization system have to be accompanied by at least two other modules to compose a usable digital map viewer. On the data input side, a module responsible for reading the data into the cartographic model is necessary. It may work in just one direction, or both ways, to allow saving modifications made by the user. It needs to be compatible with at least one known format of map data. On the other end, a human-computer interaction module is required, to permit the user to manipulate the view (navigate the map), and interact with the data (query map objects, apply data analysis tools, *et cetera*). A simplified diagram of the complete digital map system is presented in Figure 4.2.

4.1.2 Differentiating factors

Another way to define 3D maps is through identification and description of their differentiating factors, i.e. of the properties that, when combined, make them unique and distinguishable. Each of such factors, on its own, may not be sufficient to define what a 3D map is. But a combination should be clear enough to make a distinction.

During our work we determined, and would hereby like to propose, four properties which seem to fulfil the requirements described above. In our opinion, the four main defining factors of 3D maps of are: 1) the use of 3D visualization; 2) cartographic rules – a focus on efficiency of information transfer and the use of cartographic presentation to achieve it; 3) high interactivity; and 4) map intelligence – the use of intelligent algorithms to increase the efficiency of the intended map use, and support its user.

As stated above, the differentiating factors which we propose are useful only when combined, as each of these considered individually is not unique to 3D maps. 3D visualization is heavily used in geovisualization; cartographic rules are the basis of 2D cartography, both traditional and digital; different levels of interaction are required in many types of digital map; and intelligence may be applied to all types of digital representation. It is the combination of the first three factors that seems a good enough indicator of what a 3D map is; while the fourth factor is somewhat optional – the extent to which it is required depends on the purpose and the intended application of a particular map.

The factors we propose correspond partially to the "4-I" factors (Immersion, Interactivity, Information intensity and Intelligence of objects) proposed by MacEachren et al. (1999a) for the definition of geo-virtual environments (GeoVEs). The analogy seems well justified, as our understanding of 3D maps overlaps in a large part with the definition of GeoVEs provided by MacEachren and his team, in the same way as 3D cartography overlaps with geovisualization. Similarly to our work, which focuses on the superiority of 3D maps for multiple applications, MacEachren et al. (1999a) were juxtaposing GeoVEs with traditional 2D or static 3D perspective cartographic presentations.. The "4-I" model proposed by them was an extension of the previously known "three-I" framework for VR, introduced by Heim (1998). Heim's model included only Immersion, Interactivity and Information intensity, and has been extended with the fourth factor (Intelligence of objects) by MacEachren et al. to adapt it for GeoVEs.

In our proposition: Immersion is replaced, or rather realized with the use of, 3D visualization; Information intensity is replaced with cartographic rules, i.e. information efficiency; and Intelligence of objects is extended to all forms of map intelligence. The only factor which remains largely unchanged is Interactivity.

Let us now briefly discuss each of the proposed factors, including their meaning and importance, as a rationale for our selection.

3D visualization

In Chapter 1 we discussed the superiority of interactive 3D presentations over their 2D counterparts, in terms of speed and efficiency of information transfer. We provided scientific justification (Van Driel, 1989; Musliman et al., 2006), and examples, where application of such presentations can contribute to better understanding of portrayed situations, facilitate quicker and more reliable decisions, and in effect minimise collisions and increase human safety (Porathe, 2006). In the words of Kraak “the availability of a three-dimensional world that can be queried, analysed and viewed would improve insight and is likely to result in better decisions” (Kraak, 2006, p86). Moreover, and equally importantly, 3D views were perceived as more friendly and efficient by the users (Schilling et al., 2003).

Although in general 3D maps require a high level of interactivity to compensate for their inherent limitations (the distortion of perspective and existence of hidden regions), we would like to provide another example, which illustrates that even static 3D perspective views share some of the advantages described previously. In the study conducted by Schobesberger and Patterson (2008) in the Zion National Park (USA) with participation of mountain activities enthusiasts, above half of the users assessed perspective views, used as trailhead maps, as more informative than traditional orthogonal maps. The difference was much more significantly in favour of 3D representations among the younger group of participants, and among women. What is interesting, visitors who did not speak English as their native language (and hence could have problems with reading textual information on a 2D map) preferred 3D maps. In general 3D maps allowed hikers more precise identification of their positions, and were rated as more accurate by experienced hikers. Results also suggest that the two map types had slightly different strengths in cartographic communication: 3D maps were better for understanding of distances, topography and environment, while readers of 2D maps could better recall the places' names. It is especially worth noting that 3D maps attracted more readers than 2D maps, and on average were viewed for a few seconds longer. How much of that may be attributed to their relative novelty remains unanswered.

More tests are required, but this may be an indication that 3D maps are not only efficient solutions for quick and reliable transfer of information, and good tools for support of spatial reasoning, but that these also attract attention and may be used as a practical means for immersing the users.

Use of cartographic rules

In our view 3D maps, as well as traditional maps, are created with a primal focus on efficiency of information transfer. It is our opinion that they must use cartographic knowledge to achieve it. We strongly disagree with the view expressed by Wood in his polemic essay "Cartography is Dead (Thank God!)" (Wood, 2003), or with the classification presented by Krisp (2006, p21), who proposes restricting cartography to traditional paper maps. We see a strong role for cartographers in the development of efficient 3D mapping rules and techniques.

As discussed previously (in Chapter 3) there is a lack of cartographic rules and techniques for 3D. Some of the old methods can be directly applied to new, three-dimensional interactive forms of cartographic presentations. Some will require modifications and extensions for use in 3D. Above that, there will be numerous aspects that are unique to 3D, and require approaches and techniques different than these used for 2D digital maps (Haeberling, 1999). But the same basic concepts which are at the core of traditional maps will still be central to 3D cartography. These include efficient abstraction, generalization, and the use of symbolism, as opposed to photo-realism. This is clearly a different focus than we can observe in GV, where photorealistic 3D presentations are commonly used. The aim to maximize visual communication efficiency requires shifting the balance from photorealism to an abstracted and symbolic approach.

It is not to say that any photorealism should be ruled out. 3D maps need a balanced approach to the issue, as some elements of photorealism may be beneficial for some applications. Effects such as light and weather conditions may improve the factor of immersion, without a negative impact on the efficiency of information transfer. In fact sometimes they may benefit it. It is, however, important to remember what the aim of a presentation is, and to make sure that excessive photorealism is not compromising the map’s readability or limiting its interactivity. The level of accompanying effects that improve realism, such as the rendering of reconstructed building facades, vegetation or the simulation of weather conditions, need to be adjusted to the intended purpose and the user requirements for a specific map viewer.

In general photo-realism is not an efficient means of information transfer, and it reduces interactivity. In most cases simplified, easily recognizable symbols, that represent different classes (categories) of objects, may be used instead with less technical complexity and better results for information efficiency. This is supported in academic publications. In an on-line evaluation study of different types of mountain maps, respondents selected a 3D symbolic view over both a topographic map and an orthophoto draped over the terrain model as their preference for the efficiency of recognition of map objects (Petrovic and Masera, 2005). Kraak states that: "an important characteristic of maps is the fact that they represent selections from reality in an abstract way. Especially for presentation purposes, maps that look 'empty' might even work better than maps with an overloaded view" (Kraak, 2006, p86).

Symbolism is also acknowledged by the International Cartographic Association (ICA) as one of the defining properties of maps. The current strategic plan of the ICA defines a map as: "A symbolised representation of a geographical reality, representing selected features and characteristics, resulting from the creative effort of its author's execution of choices, and is designed for use when spatial relationships are of primary relevance" (Kraak, 2006, p82).

Interactivity

There is a good reason why traditional maps are presented in two-dimensional top birds-eye view (orthogonal perspective), rather than using static 3D perspective views. Static perspective views are not suitable to cover a large area, as they emphasize the sections which are closer to the selected view-point, and make access to information regarding more distant areas difficult or impossible. They also distort sizes and angles, and make measuring distances impossible. Provision of just one static perspective view for a larger area makes little or no sense.

It all changes, however, with the introduction of interaction and dynamics. Only maps which are not static and allow easy interaction and change of the viewpoint can fully leverage the benefits of a 3D perspective presentation. According to Kraak (2006, p86) "three-dimensional displays require an interactive viewing environment that allows one to view the objects from any direction to avoid obstruction and allow the query of all objects in the representation."

Interaction is important not only for the need to overcome 3D presentations' limits, but also to increase 3D maps' efficiency and usability, and to allow wider applications. An important role of 3D maps is support of spatial thinking and decision making. Gold, discussing a decision support system for forestry planning, points out that for decision systems in general "it is necessary that the interaction be simple and rapid, permitting the suggestion of several 'what-if' queries in a short time period, while the manager is actively engrossed in assessing a particular problem" (Gold, 1993, p797). Fairbairn et al. (2001) point out that the process of visualization requires high levels of interactivity. Comparing to their 2D digital counterparts, 3D maps by their nature require higher levels of interactivity, and hence their development has to be focused more heavily on design of ergonomic, efficient and intuitive manipulation mechanisms. This is also another argument for the use of a symbolic, rather than a realistic, approach, whenever the realism is not necessary for the efficient usage in a particular application. Realism negatively impacts the level of interaction available in a 3D visualization, and increases rendering times (Appleton et al., 2002). Advanced photo-realistic systems do not work in real-time, and do not allow direct manipulation or model alteration. A pre-programmed view or a flythrough may take hours, or even days, to render (Berry, 2009, p152). This is in contradiction to the characteristics of modern mapping products provided by Kraak, who stated that "new mapping environments can be characterised by two keywords: interaction and dynamics" (Kraak, 2002a, p324).

Our experience suggests that it is a *sine qua non* that the user has to be able to freely manoeuvre through the map and rapidly change to any viewpoint of his choice, to make a 3D map fully usable. In this light the term '3D map' can be used as a synonym for 'interactive 3D map', as 3D maps are interactive by nature. Hence, whenever we use the term '3D map', its interactivity is implied. In this aspect our definition is different from the traditional approach in the cartographic literature, which speaks about 3D maps mainly in the context of static views, which are classified as perspective pictorial maps together with block diagrams, schematic maps and oblique regional views (Robinson et al., 1995). It is also different from the definition provided by Haeberling, who described a topographic 3D map as a "cartographic representation of a landscape section in a perspective view, combined with topographic information that is defined in a legend" without distinguishing between "printed maps and screen maps for computer applications" Haeberling (1999). Interaction is a broad and important aspect, and is discussed in detail in Section 4.2.

Intelligence

Intelligence is our fourth and final differentiating factor. It is an extension of the concept behind the 4^{th} I-factor proposed by MacEachren et al. (1999a). The original concept is focused around, and restricted to, the use of semi-intelligent objects, and semi-autonomous agents, to assist the user of a GV viewer. Our proposition refers to all possible approaches to map intelligence, including intelligence of objects, as well as different possible uses of underlying data structures, and algorithms, that can improve the efficiency of map presentation, and of the map use in any selected application.

The possibilities regarding the use of intelligent algorithms in mapping are wide, and depend mainly on the area of application, available technology, and inventiveness of mapping product designers. The level of intelligence may vary from relatively simple algorithms to elaborate underlying Artificial Intelligence (AI) mechanisms.

Map intelligence is the basis for map-driven interaction, where the map ignites communication with the user, to inform him about some important facts, events or predictions. This may be crucial for avoidance of dangers in real-time navigation, or useful to support the decision-making process. The idea and its technical fundamentals are described in more detail in Sections 4.2.4 and 4.2.5.

Another aspect of map intelligence is the awareness of the context in which it is being used, and the implementation of mechanisms that allow for the appropriate adaptation of the presentation. In short the presentation can be adjusted to the different characteristics of the user, purpose, device and surroundings (Nivala and Sarjakoski, 2003).

User aspects include his knowledge, experience and expertise level, which may be used for customization of the interface and the available functionalities; his cultural and social background, which may determine the language, format of numbers, dates, and symbols to be used; and his special needs such as disability that affects the use of the interface, or view perception (for example colour-blindness). Special algorithms for analysis of the user's action patterns and browsing history can be implemented to facilitate automatic recognition of some of his characteristics.

Purpose of use can affect the required map behaviour or usage mode, for example the presentation and navigation-support behaviour of a satellite navigation map would be expected to be different for in-car than for a pedestrian use. The device factors focus on adaptation of the map to the device on which it is being used. Different aspects can be considered, such as screen resolution, available human interface devices, availability of a satellite positioning device, or graphical rendering capabilities.

Factors that concern surroundings include external conditions in which the map is being used, such as the time of the day, season and weather, but are not limited to these. Different types of sensors can be used and creatively applied. For example a marine chart could behave differently at stops and at different cruising speeds, or automatically apply the view stabilization when a gyroscope detects strong waves. Typically, navigational aids adjust the displayed area and view to the location and orientation.

4.2 Interaction

It was previously stated that 3D maps cannot realize their full potential without support for interactivity, and a freedom of viewpoint selection. Research on static 3D perspective views, used in mountain cartography, provides some evidence to support this view. Respondents of the on-line questionnaire performed by Petrovic and Masera (2005) were asked to choose the most usable type of a mountain map for several tasks, including measurements of distance, height difference and pointing to the North. Given a selection of different types of the same static perspective view, and a traditional 2D orthogonal topographic map, they selected 2D map the most often. The main complaints in regard to the static perspective views voiced by the pool participants included the distortion, which made performing measurements impossible, and the lack of visibility of some parts of the area. The problems mentioned above are inherent to static perspective views.

The research discussed above may be seen as a practical confirmation of the work of Haeberling (1999), who summarized the drawbacks of static 3D maps in the following list: 1) the inability to interpret the geometry of the topographic 3D map, due to the perspective view; 2) the impossibility of distance measurements due to variable scale; 3) the obstruction of visibility of some of regions and objects. Haeberling was looking for cartographic theories as a way of minimizing drawbacks related to static 3D maps. While generally supporting his view, we think that a large part of the remedy is in providing 3D maps with interactivity. This seems not to be an isolated view (Gold et al., 2004; Kraak, 2006; Jobst and Germanchis, 2007). The ability to select different observers' locations or, better, to freely navigate through the scene, removes the problem of hidden areas, while measurement problems may be tackled by the provision of dedicated interactive measurements tools.

These are just two examples of different forms of interaction that can be built into a digital 3D map. Navigation within or manipulation of the entire scene; interactive measurements and analysis tools, which can be performed as *ad hoc* computations or based on spatial data structures; interaction with map objects, such as selection, querying and editing; and interaction with the map interface, to control its functions and settings; are all examples of user-driven interaction.

Another category is map-driven interaction, which is prompted by the intelligence built into the map and its objects. Examples of these can be alerts displayed to the user of a digital navigational chart upon detection of a possibility of a collision; or warnings raised by a car satellite navigation system in the proximity of a speed-camera. This category of interaction is based on internal map mechanisms that control interaction between different objects defined in its cartographic model. As in the case of data analysis tools, these can be supported either by real-time computations, or by dedicated data structures that maintain spatial relationships inside the map model.

The importance of interactive techniques in mapping has been gaining recognition ever since the 1970s (Moellering, 1975). Andrienko and Andrienko (1999) call them necessary for the use of maps as visual thinking and decision making tools. According to Nielsen, "interaction possibilities are often being considered as the most important user question, because the interaction between computer and user is vital to the relevance of digital systems," (Nielsen, 2004, p416). In the words of Ribarsky “fast, intuitive, and effective interaction is at the core of an effective exploratory visualization system,” (Ribarsky, 2005, p462). Cartwright and Peterson (2007, p2) state that “interaction is the key to knowledge formation.” However, according to Hand, the techniques of efficient 3D interaction lag behind developments in visualization, and require further attention and research (Hand, 1997). This diagnosis, although made in the previous decade, seems not less valid nowadays, despite the passage of time – especially in the context of geovisualization and 3D cartography.

In the subsequent sections we will discuss different categories of cartographic interaction, both user- and map-driven, starting with a brief outline of the subject of human-computer interaction.

4.2.1 Human-computer interaction

Angel, in his book about interactive computer graphics, states that “one of the most important advances in computer technology was enabling users to interact with computer displays” (Angel, 2006, p99). This statement refers to computer systems in general, but is equally true in the case of digital maps.

Every digital map is viewed on some sort of a display device, which is necessary to communicate the image to the eyes of a user. The user, unless he is only passively watching the visualized map, must be able to interact with the displayed model. This can be done using various types of input device, such as a keyboard, mouse, joystick, trackball, Virtual Reality glove, steering wheel, or any other kind of a controller (Angel, 2006, pp101-103).

In reaction to the user's interaction with the controller, digital signals are generated, and sent to the mapping software running on the host computer. These are directed to and handled by the map's manipulation sub-system, and interpreted and translated into commands that control the map functions, modify the view, or change the model. The changes are instantly displayed on the screen, and the user can react to them to readjust his motions. This mode of interaction, based on a kind of real-time feedback loop, is called continuous interaction (Spence, 2007, p140). The process is illustrated in Figure 4.3.

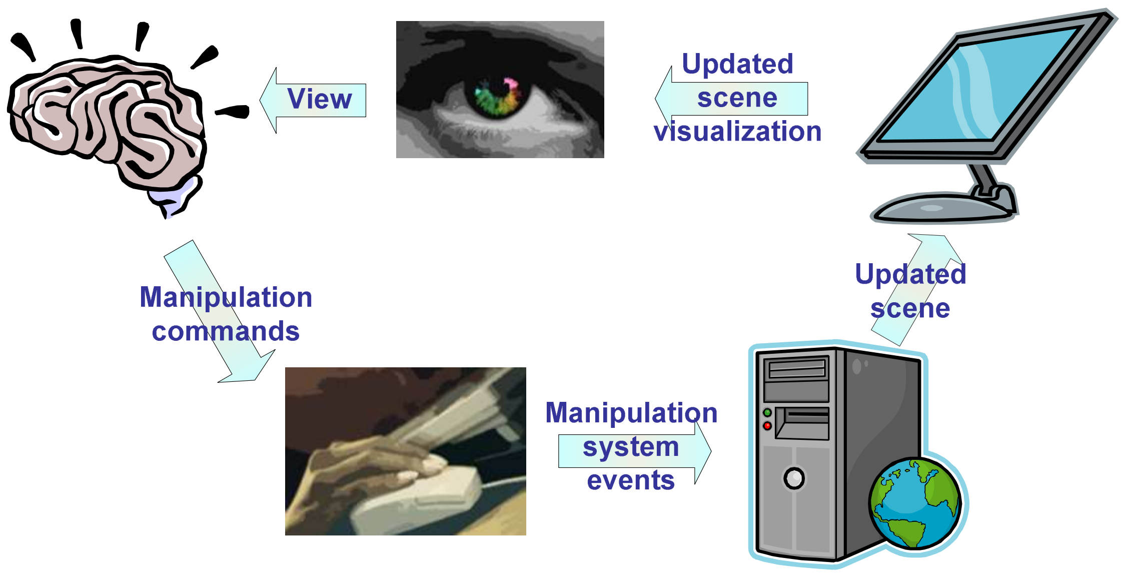

Figure 4.3. Human-computer interaction feedback loop in interactive visualization systems

In the context of mapping and geovisualization, Crampton (2002, p4) defines an interactive system as "as a system that changes its visual data display in response to user input." This definition, although clear and simple, however, is only true for user-driven interaction. When a map is fitted with intelligence another category of interaction, initiated by the map, has to be introduced. User-driven and map-driven interaction categories are discussed in the following section, and in Section 4.2.4, respectively.

4.2.2 User-driven map interaction

In a majority of cases interaction with a map is initiated by the user, and hence this is the broader of the two categories of map interaction. It includes several sub-categories, such as control of the view (zooming, panning, setting of the viewport and navigation within the scene), interaction with data (selecting, querying and modifying objects), data analysis (using various interactive tools, including taking simple measurements), editing of the map, and interaction with the map presentation settings and other functionalities. All the above sub-categories are explained in further detail in the dedicated sections below.

View control

Control of the view and navigation within the displayed model is the most fundamental interaction activity. In 2D maps this is realized with the provision of operations for panning and zooming, usually using dedicated GUI buttons, keyboard arrows, or a mouse dragging mode. In 3D the possibilities are wider, as there are more degrees-of-freedom (DOFs), or types of available operations. These include traditional control of the scene: setting the area visible on the screen, adjusting the zooming level, changing its orientation regarding the geographic directions using rotation; as well as control of different aspects of the view, such as the level of obliqueness – which may vary from the orthogonal (top) perspective, through different elevations in oblique elevated views, to ground-perspective (world view) – as well as the position of the observer. All this leads to a multitude of possible solutions, from simple to very complex navigation and manipulation mechanisms, that allow control of the viewpoint and of the scene. These may be based on use of GUI buttons, keyboard keys, and mouse, but may also employ advanced 3D controllers with multiple DOFs.

The complexity of 3D navigation may be simplified with the application of suitable metaphors to real-world operations. Slocum et al. (2001, p68) stated that the metaphor used is "a key element of interface design." Two most widely used metaphors are: "flying saucer" (Fuhrmann and MacEachren, 1999), or "flight simulator" – where the observer is flying freely within the scene, changing the viewpoint to any suitable position; and the scene-in-hand metaphor (Hand, 1997) – where the scene can be freely moved and rotated in space, and taken closer or further from the eyes. While the first metaphor involves immersion of the user within the displayed scene, called the *egocentric* frame of reference, the second metaphor is closer to the traditional use of a map or a globe kept in a hand, called the *exocentric* approach (Hand, 1997, p275). The second metaphor is typically used in CAD systems, for computer-aided 3D object design, although in the case of 3D maps it seems sensible to restrict available rotation axes to preserve the straight horizon. Both these metaphors modify the meaning of the traditional panning and zooming operations, replacing them with mechanisms for more comprehensive model and viewpoint control. The metaphors explained above are just two examples of available options, and there may be a multitude of other, more or less elaborate, metaphors and navigation mechanisms used, depending on the map's application and user needs.

Interaction with objects

Another important category of interactivity is interaction with geographical and other objects displayed within the map. This includes querying – the possibility to click on an object, in order to get additional information about its properties and attributes. The displayed information may include the object's type, or class, geographical location, altitude, physical dimensions, and all other attributes stored in the model's database. The provision of querying functionality greatly improves the capabilities of information transfer offered by a digital map.

Querying may be performed by a simple click, which displays a dedicated information window without modifying the state of the queried object, or may be based on the mechanism of object selection. Selection allows picking an object, or several objects within the map, usually by clicking on them in a dedicated mode, or selecting them from a special object table, for further operations. This usually involves modification of the graphical appearance of selected objects, for example by a change of colour. Selection may be used as a basis for various operations, including querying and editing of a selected object (changing its position, dimensions, representation, attributes, assigning notes, *et cetera*). Multiple-selection, i.e. selection of multiple single objects, or object groups at the same time allows simultaneous editing of multiple objects. Other, less typical, operations may include activation of the view associated with the selected object, or using selected objects as the basis (reference points) for measurements – as it is done in the 3DMV (Chapter 5).

Data analysis

Interaction with map objects, described above, may be classified as a part of the broader category that concerns interaction with data in general. Other parts of this broader category concern different forms of interactive data analysis, i.e. the use of special tools to facilitate spatial reasoning.

The simplest examples of this category, which are also the most relevant to typical 3D maps, are basic measurements, supporting typical uses of a map. These may include tools for measuring different variations of distances – straight line distance, difference in altitude, horizontal distance, and distance over-the-ground; and angles – in vertical and horizontal planes, as well as a true angle in 3D space. As seen in the example by Petrovic and Masera (2005), these should be supported by dedicated tools, to supplement 3D presentations. Provision of interactive tools seems necessary to overcome problems of distortion of dimensions and distances, associated with perspective views, which render manual measurements impossible.

In recent decades, with the advent of GIS and geovisualization, the role of maps has been redefined, and extended beyond the traditional understanding, to embrace their use as interfaces for GIS (Kraak and Ormeling, 2003; Ribarsky, 2005) and exploratory data analysis (Tukey, 1977; Andrienko and Andrienko, 1999).

Where the use of 3D maps as interfaces for GIS is concerned, more advanced interactive tools then these designed for simple measurements are required. Application of 3D maps in GIS requires extension of the operations known from two-dimensional systems, and of their underlying spatial relationship models, such as the 9-intersection model by Egenhofer and Franzosa (1991), into 3D. Key requirements include the support for adjacency, intersection, connectivity, containment and disconnectedness analysis (Ellul and Haklay, 2006). However, development of 3D spatial analysis tools seems to be slower than progress in visual representations, due to the large volumes of data combined with the complexity of the required algorithms and data structures. For that reasons authors such as Musliman et al. (2006) call 3D GIS systems not much more than just "pretty models." This is confirmed by the analysis of the leading commercial 3D GIS systems available on the market, performed by the team led by Zlatanova. As they conclude: "all the systems revealed little provision of 3D GIS functionality in terms of 3D structuring, 3D manipulation and 3D analysis" (Zlatanova et al., 2002b, p3).

When we speak about exploratory data analysis, interactive techniques are the enabling factor (Andrienko and Andrienko, 1999; Kraak, 2002b). Exploratory data analysis is based on a variety of tools that allow more advanced interaction with the data than a simple control of the view. These include tools based on techniques from statistical graphics such as dynamic classification, filtering, focusing and brushing (Andrienko et al., 2002; Crampton, 2002). These elaborate forms of interaction are not meant for popular 3D maps, but rather reserved for professional data analysis. Some of them are specifically designed and useful only for specific map types, such as choropleth maps (Dykes, 1997).

Map editing

Another user-map interaction category, which partially overlaps with interaction with objects, is map editing. Depending on the application, a 3D map may, but does not have to, provide different functionalities for editing of the presentation, and of its underlying cartographic model.

These may include, as already mentioned, modification of objects (positions, dimensions, representations, attributes, notes), object deletion, addition of custom objects, as well as editing of the terrain model. Terrain modification functionalities may include editing of its topographic features, modification of shading, application of textures, drawing (or hand-writing) on its surface, changing the vertical exaggeration, and assignment of custom notes to selected locations.

Depending on the particular map viewer implementation, modifications may be only temporary, facilitating spatial analysis and reasoning of the user within the current work session, or may be provided with an option to save them to the map database, thus permanently modifying the underlying cartographic model.

Control of map functionalities

The last category of user-map interaction is using the viewer's user interface to control its functionalities and settings. The most popular approach to this form of interaction is through a Graphical User Interface (GUI), although command-line tools and configuration files may also be used. The range of available operations and settings vary with the viewer implementation. A GUI usually allows the loading of map data, or the selection of the area of interest, the selection of layers to display, the control of interactive tools, the display of map information, and of additional communications and help messages. It is usually based on buttons and keyboard shortcuts, and complements the manipulation mechanism when the application of direct manipulation is not possible.

Settings, which may be done from the GUI level, or by editing of the configuration files, may include customization of the default view and presentation properties, as well as of the manipulation mechanism, and other application-specific options.

4.2.3 Ergonomics

3D maps' general requirement for high levels of interactivity, and the prerequisite to allow users free and unhindered manipulation, navigation, and viewpoint setting, puts a strong emphasis on the ergonomics of user interfaces. This involves the efficiency of manipulation (control of viewpoint, navigation, and interaction with objects), and display mechanisms. The ergonomics of manipulation includes design of efficient mechanisms – based on well-thought out metaphors, application of ergonomic human-computer interface devices, and the assurance of an appropriate level of responsiveness of interaction (the time of delay between user's actions and the corresponding reactions of the visualization), and the responsiveness of the data display (Bryson, 2005). The ergonomics of the display concerns the rendering speed and the assurance of acceptably high refresh rates (FPS). All the above factors are discussed below.

Manipulation

Control of the displayed scene and of the viewpoint, as well as interaction with objects, may be realized in different ways, using various manipulation metaphors discussed in Section 4.2.2. The choice of an appropriate metaphor and the design of an efficient, natural and intuitive manipulation system, are the fundamental factors for the ergonomics of a 3D map. As different metaphors work best for different people, a provision of several different metaphors that can be selected by a user may prove to be a sensible and a worthwhile effort.

The connection between the user interface and the manipulation mechanisms may also be realized in different ways. The user may use a dedicated device, directly coupled with the manipulation mechanism, or click on GUI buttons to send manipulation commands to the system. The requirement for high interactivity, as well as for real-time, unhindered and instant manipulation, suggest that the direct use of human-computer devices – be that typical mouse devices or special controllers – to control the view, is preferred over the use of GUI buttons.

Devices

In a majority of cases a map should use widely available devices for control of its user interface. This is necessary to allow its use by inexperienced users on typical PCs, or over the Internet.

However, special 3D controllers (Hand, 1997), popular in computer-aided design (CAD), offer better ergonomics, including continuous, smooth view transitions and control of multiple degrees-of-freedom with a single hand. This may be an important benefit for professional applications and expert users.

Responsiveness

An important aspect of the ergonomics of a system is its responsiveness, i.e. a measure of how quickly the system reacts to the interaction events initiated by the user. The shorter the delay the better the responsiveness and the ergonomics are.

Bryson, of NASA Ames Research Center, speaking about VR environments, distinguishes between two categories of responsiveness: responsiveness of interaction, and responsiveness of data display. The first determines "how quickly must objects in the environment respond to user actions in order to maintain a sense of presence and direct manipulation." The second concerns "how fast must interactive data-display devices, such as a data probe, update to give the user a sense of exploring the data" (Bryson, 2005, p418).

Regarding the above distinction, in the mapping context we can imagine that a map display system needs to update the presentation in accordance with the user's navigation events, for example to load the data in a higher LOD, or to read another sequence (tile) of the terrain model. It seems that responsiveness to navigation must be higher than the time required by the system to "catch up" with the display of data. In other words the data-display responsiveness may be lower than the interaction responsiveness (Bryson, 2005).

It is, however, difficult to assess the requirements in terms of precise numbers. Different sources quote different values. Crampton (2002, p4), referring to the interaction responsiveness, states that a "system response needs to be within a short interval (<1s) in order to maintain the sense of interactivity in real time." Bryson quotes 0.1s for interaction responsiveness, stating that "longer latencies typically cause the user to experience unacceptable difficulty in selecting and manipulating objects in 3D space" (Bryson, 2005, p419).

In regard to the data-display responsiveness Bryson states that it has to be less than about 1/3s, adding that "longer latencies in data display require such slow movements on the part of the user that usability is lost" (Bryson, 2005, p419).

Our guess is that the minimum levels of responsiveness depend on several factors such as the application, the offered level of immersion, and the zooming state. The higher the level of immersion, and the closer the observer is to the displayed objects, the lower (and hence more demanding) the required values are. Based on the fact that typical 3D maps are less immersive than Virtual Reality environments, we expect that acceptable values for 3D maps are noticeably higher (i.e. the changes may take longer time to appear on the screen) than these demanded from virtual environments.

Drawing refresh rates

Another factor with a strong impact on the overall ergonomics of a map display system is its drawing refresh rate or the number of frames it renders per second (FPS). Interactive 3D map presentations are not static – the view changes with user navigation or manipulation commands, or if the map displays kinetic animated objects. The usual approach is to redraw the whole scene continuously at a constant rate.

To assure that the presentation offers a high level of comfort of operation, including the feeling of continuity and smoothness of navigation, the frame-rate has to be as high as possible. Bryson quotes 10 frames-per-second as the minimum for graphics update in VR environments, adding that "10 frames/s is sufficient to maintain a sense of object presence even though the discrete frames of the display are easily perceptible. Slower update rates result in a failure of the sense of object presence, compromising the enhanced 3D perception advantages" (Bryson, 2005, p418).

Although lower frame-rates without a doubt negatively impact the ergonomics of map manipulation, we think that in the mapping context slightly lower FPS values could still be acceptable. As in the case of responsiveness, our experience suggests that the refresh rates required depend on the type of the view, and, for example, may be slightly lower for observation of moving objects from a distance. The need for smoothness of the animation will grow with the decrease in the distance to the animated object, and with the increase of the immersiveness. It is the highest for 3D view modes linked to, and presenting the world from the perspective of, moving objects. In general, we strongly encourage efforts to increase the rate to at least 20-30 FPS, and to assure that it does not go below 5 FPS, even on less powerful machines.

4.2.4 Map-driven interaction

A vast majority of interaction between the user and the map viewer is initiated by the user. In this interaction type the map responds, in an appropriate way, to the user's actions and commands. This is an important aspect, which is often discussed in cartographic and geovisualization literature. But there is anther possible type of user interaction with map – based on map intelligence – which is initiated by the map. This is a special and much less common type of interaction, and perhaps this is the reason why it seems to be absent from the cartographic literature. However, it offers great possibilities in enhancing the usability of maps, and should be a required functionality, at least for some applications. It has the highest appeal for application of maps in real-time decision support, where the underlying intelligent mechanisms of the map may automatically inform the user about potential dangers, or other important, automatically detected or predicted findings. Map-driven interaction includes visual, textual, audio or *haptic* (touch-based) communication with the user (Hand, 1997), as well as communication with external systems, initiated by a map.

To explain this let us consider the example of a marine navigator using a digital chart. A chart system equipped with intelligent collision prediction algorithms may raise an alert upon detection of a danger of collision with another vehicle, or grounding. Visual means, such as pop-up windows, scale changes, or marking of the dangerous ships with easily distinctive colour, as well as the use of blinking patterns and display of danger symbols, could be used, accompanied with warning sounds. In addition, the navigator could be equipped with a wireless vibration alert (haptic) device to draw his attention in the event of him not looking at the display, and being unable to hear the alerts due to noise or distance. The effects could be gradually increased depending on the likelihood and expected time of the predicted collision, including triggering of an external alerting system above a certain level of danger. Such a system could, for example, send automated rescue request messages, with location and other relevant details, to appropriate authorities, upon detection of an actual collision. Collision-detection alerts are already available in most of the market implementations of Electronic Chart Display Information Systems (ECDIS), which are official marine navigation aid systems, certified by the International Hydrographic Organization (IHO, 1996).

Map-driven interaction based on map intelligence seems a valuable extension of the traditional user-driven interaction modes. The appropriate level of map-initiated interaction that should be provided in a 3D map viewer, and the most suitable technical solutions to support it, depend on the specifics of an intended application, as well as the map purpose and requirements of its users. Different approaches to map intelligence, which is the enabling force behind map-driven interaction, and some example algorithms that can be used to facilitate it, are discussed in the next section.

4.2.5 Map intelligence

Map intelligence, which is the basis for map-driven interaction, is enabled by the dedicated background algorithms that facilitate it. These may be built around different technical approaches. For example, the logic described in the scenario presented in the previous section requires the analysis of spatial relationships between chart objects which represent moving ships, and navigational obstacles, including seafloor bathymetry. Such analysis could be based on *ad hoc* calculations, using methods from computer graphics such as ray-tracing (Akenine-Moller and Haines, 2002, pp633-634), or on designated data structures that would store, and perhaps kinetically maintain in real-time, spatial relationships between different objects of the underlying cartographic model.

An example of the possible approaches was proposed by the author of this thesis, who used the kinetic Voronoi diagram (VD) for real-time maintenance of spatial relationships between moving marine vessels and the sea-bathymetry (Goralski and Gold, 2007b). The same approach was used for collision prediction and avoidance in the maritime safety application of the 3D Map Viewer – our custom mapping platform developed as a practical part of this thesis, which is explained in Chapters 5 and 6. The relevant collision prediction and avoidance algorithms are discussed in Section 6.1.4, but the principles of the underlying VD methods deserve a separate introduction. This is provided in the following two sub-sections.

The kinetic Voronoi diagram and its dual Delaunay triangulation

The Voronoi diagram (VD), as shown in Figure 4.4, and its dual, the Delaunay triangulation (DT) are fundamental geometrical constructs that are now fairly well known. For a given set of generators, the Voronoi diagram partitions the space in such a way that each generator is assigned to the points closest to it with respect to a given distance function. For reasonable classes of generators (such as points, line segments and circular arcs) and reasonable distance metrics (such as the Euclidean one) the Voronoi diagram allows a compact representation of the topology. The VD can be represented by a topological data structure such as the Quad-Edge by Guibas and Stolfi (1985). It supports proximity and nearest neighbour queries – details of which can be found in (Okabe et al., 1992) – which have a potential to simplify the map intelligence algorithms, as it is the case for the collision avoidance mechanism implemented in the maritime safety application of the 3D Map Viewer. The Voronoi diagram for points and line segments with its dual, the Delaunay multigraph, provide the basic spatial adjacency properties between map objects. The DT is usually used as the basis for triangulating a set of data points, as it is guaranteed to be locally stable.

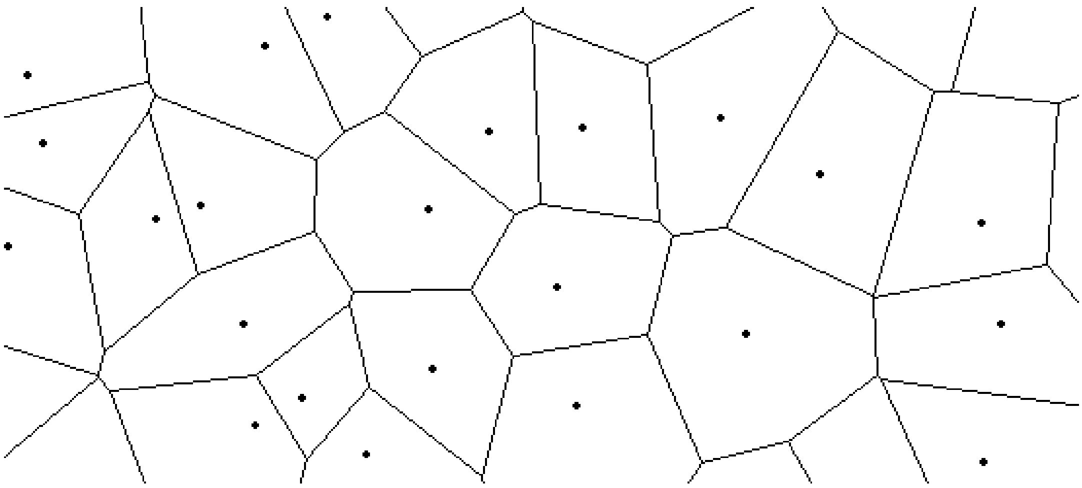

Figure 4.4. A simple Voronoi diagram

The VD can be constructed in many ways (Okabe et al., 1992; Aurenhammer, 1991), but the incremental algorithm has been found to be both stable and simple (Guibas and Stolfi, 1985). In simple terms, each new point is inserted into the existing DT by finding the enclosing triangle, using the counter clockwise (CCW) test of Guibas and Stolfi (1985), splitting it into three triangles using the new point, and then testing each edge recursively to see if it conforms to the Delaunay criterion: that neither of the adjacent triangles' circumcircles (CC) have an interior point. If they do, the common diagonal is switched and the new edges are added to the stack of edges to be tested (Guibas and Stolfi, 1985).

Point deletion (Mostafavi et al., 2003) can be performed by approximately following the inverse process: switch DT edges if the result gives an exterior triangle whose CC is empty except for the point being deleted. When only three triangles remain the central point is deleted.

The moving-point VD and DT

“Kinetic” data structures maintain their topological structure while the entities move; “dynamic” ones merely permit local insertion and deletion of these entities (points, segments, etc.). To maintain the spatial relationships of moving objects in real-time, as it is done in the collision avoidance mechanism of the 3D Map Viewer, the fully kinetic algorithms are necessary. The ‘moving points’ Voronoi diagram algorithm, as described below, is used for that purpose. The following brief description corresponds to that of Gold and Dakowicz (2006).

When a point MP moves as part of a DT/VD it may either travel a short distance without requiring a topology update, or else triangle edges must be switched to maintain the Delaunay criterion. These topological events (Guibas et al., 1991) occur when MP moves into or out of a CC. “Real” CCs are those formed from triangles immediately exterior to the “star” or set of triangles connected to MP. “Imaginary” CCs are formed by triangles that would be created if MP was moved out of its CC, and are formed by triples of adjacent points around MP’s star. When MP moves into a constellation of points in a DT it first enters the CC of a triangle, causing a triangle edge switch and adding the furthest point of the triangle to the star of MP. The original real CC is now preserved as an imaginary one. As MP continues to move, at some later time it moves out of this imaginary CC, the original triangle is recreated and the CC becomes real again.

As MP moves in any direction, it may enter or leave many CCs, and the triangle edges must be updated accordingly. Topological operators are used to extract the real CCs surrounding MP's star, and the imaginary CCs formed by consecutive triples around MP's star. These are maintained as a list.

Real CCs are dropped if they are re-formed from the imaginary ones. (Initially, before a point is first moved, all surrounding real CCs are found and tested against the proposed trajectory.) To maintain the DT during MP's movement it is therefore necessary only to find the intersection of its trajectory with the first CC (either real or imaginary), move MP to the intersection point, switch the affected edge, and then repeat the process (Figure 4.5). To avoid problems due to degenerate cases, e.g. when several CCs are superimposed due to a regular square grid of data points, the "first" intersection must be clearly defined. In practice it is critical not to "forget" an intersection because it is behind MP's current position, usually due to computer arithmetic limitations. This is achieved by always using the earliest intersection, even if it is behind MP, subject to a test that the intersection point is associated with an arc of the triangle edge to be switched.

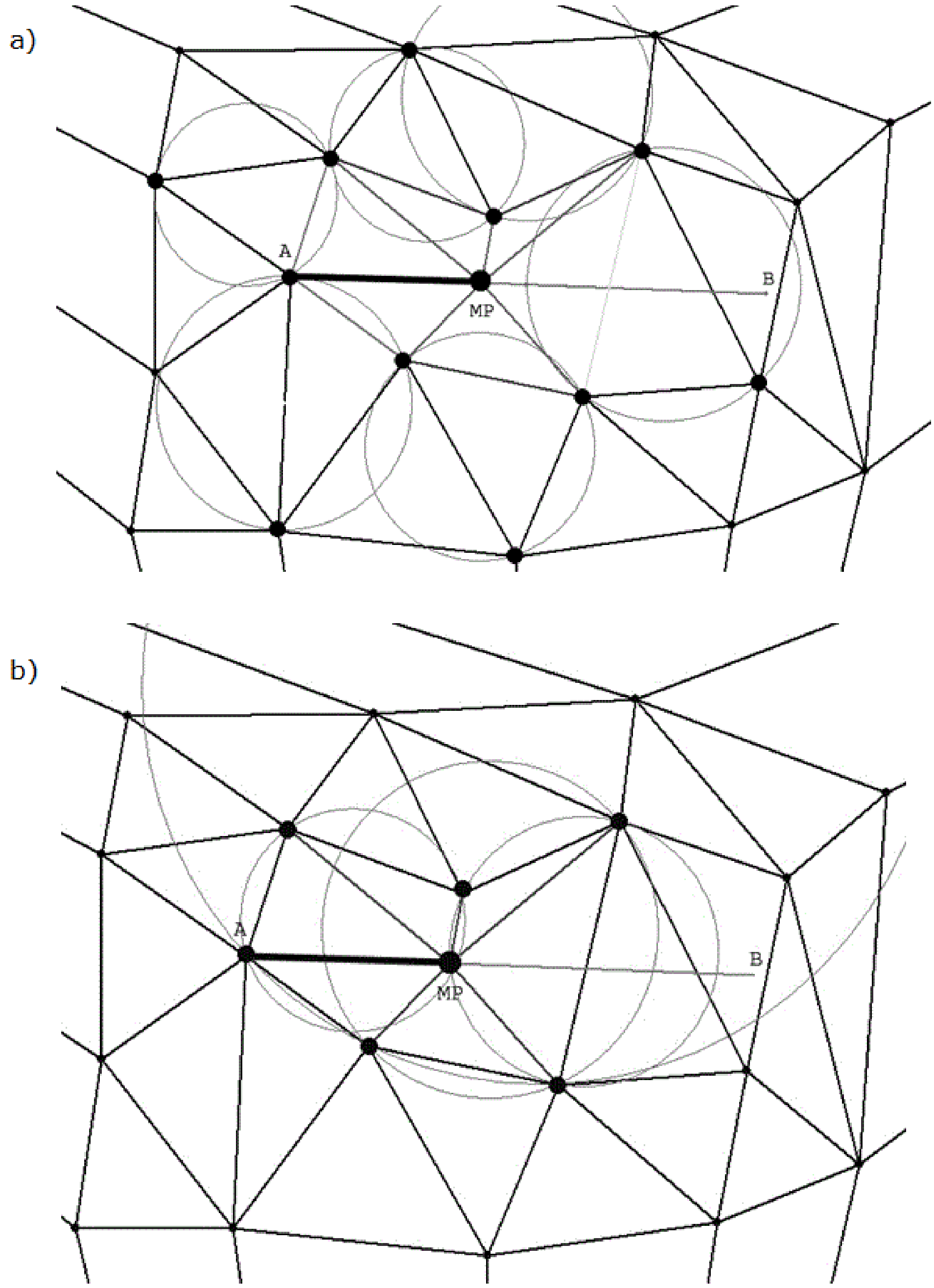

Figure 4.5. a) "Real" circumcircles to MP; b) "Imaginary" circumcircles to MP

This looping process: find the next intersection with a CC; move MP; switch the DT edge – is continued until MP's destination is reached. If there is already a node at the destination then the MP is merged with that node (removing that point and two triangles adjacent to the edge connecting those nodes). It is, however, possible that MP collides with an existing point, destroying the DT structure. Thus at each iteration of the loop the distance from MP to each new neighbouring point is tested, and if it is below some tolerance a collision is detected – the MP is rolled back to its origin, then moved again towards the collision point CP. Eventually the MP and CP are merged and the process is continued from the CP by splitting the MP again and moving it towards the original destination.

The VD-based approach is only one of many different algorithms and methods that can be used to facilitate the map intelligence. As stated previously, different solutions, based on topological data structures or on *ad-hoc* computations (or on a combination of different approaches), can be used, and the most suitable choice has to be made on the case-by-case basis. However, the kinetic Voronoi diagram-based methods seem to have many desired characteristics and advantages over the other approaches, the downside being a relative complexity of the implementation of the data structures and of the algorithms that operate on them.

4.3 Remaining cartographic and technical aspects

This section provides a discussion of the most important aspects of 3D maps, concerning both the 3D cartography and the technical perspective, which have not been discussed before. The topics are logically grouped and outlined in several dedicated sections below.

4.3.1 Dimensionality of data

Because three-dimensional maps present geo-referenced data in 3D, it would not be unreasonable to expect that they require real-3D (volumetric) data. However, for the majority of applications this is not the case. The main strengths of 3D maps are due to the high presentational efficiency and intuitiveness of 3D views, and not necessarily due to the use of volumetric data.

Creation of a real-3D, volumetric map, although it would be useful for some applications, involves application of very complex data structures, capable of efficiently storing and analysing very large quantities of 3D data. A map which would contain such data structures and relevant algorithms would in fact become a 3D GIS. Unfortunately, as we learned previously from the work of Musliman et al. (2006) and Zlatanova et al. (2002b), such data structures and algorithms are not ready, and progress in their development is slower than hoped for. In addition, the application of real-3D would increase the requirements for storage and processing power, and would limit the map's interactivity, by slowing down visualization and manipulation speed which are essential for 3D map usability and ergonomics. Instead, for most 3D map applications, the requirements can be satisfied with the use of non-volumetric, infinitely thin terrain surfaces (2.5D), with two- or three-dimensional objects placed upon these.

Moreover, a large proportion of 3D maps can be produced, at least partially, using a process of translation of two-dimensional data into three-dimensional presentations. As pointed out by Terribilini (1999), there is an abundance of 2D data for most regions of the world, and hence it would be beneficial if 3D maps could directly use these. This view is supported also by Nebiker (2003). 3D data are not as readily and widely available. For many regions, and for applications that specifically require them, these need to be collected. Hence the use of combined approaches, that use existing 2D data as much as possible, may decrease the cost of 3D map production, and is an option worthy of evaluation.

Depending on the application, 2.5D terrain surfaces may be good enough or fall short of the requirements. The limitation of 2.5D is its inability to present overhangs, caves, and volumetric data, required for example in geological analysis. An acceptable solution seems to be the use of a 2.5D terrain surface globally, in most of the model or for its lower LODs, and incorporation of 3D surfaces or real-3D volumetric representations locally, when necessary. However, such a combined approach seems necessary only for some specific applications.

4.3.2 Data sources

There are many possible data sources for 3D maps. Two main categories that need to be distinguished and discussed separately are the data for terrain models, and the cartographic data for map objects.

<u>Terrain</u>

The data from the first category describe the topographic shape of the terrain surface (its relief). This may be purposely collected or reconstructed from scanned topographic maps, or from digital sources of 2D vector data. Data that may be used include contour-lines and single-point elevation measurements. The reconstruction process is typically based on interpolation in the regions between known values, and slope reconstruction techniques (Dakowicz and Gold, 2003).

However, a preferred method, that offers more reliable reconstruction results, is to use purpose-collected Digital Terrain Model (DTM), or Digital Elevation Model (DEM) data. DTMs and DEMs are basically elevation grids with a pre-defined resolution (density). The difference is that DEMs include elevation of buildings and other man-made features, while DTMs ignore these and tend to present the ground-level. As such, DTMs seem a better choice for 3D maps, which in most cases will reproduce the man-made objects using additional symbols, when necessary. Because DTMs are not 2D, nor truly 3D, and they represent only a surface of terrain, these are called 2.5D.

Digital Terrain Models derived from satellite measurements have been available for most of the world for several years. The sources include the Global Land One-km Base Elevation (GLOBE) and Digital Terrain Elevation Database (DTED) (El-Sheimy et al., 2005, p16). The resolution and accuracy of such global data are limited – the sources mentioned above offer a resolution of 1km. A recent, and very valuable, addition to the global data sources – that offers a much better resolution and accuracy – is the ASTER Global Digital Elevation Model (ASTER GDEM) database, released to the public in June 2009. The database has been created by Japan's Ministry of Economy, Trade and Industry (METI) and the United States National Aeronautics and Space Administration (NASA). It is named after the Japanese Advanced Spaceborne Thermal Emission and Reflection Radiometer instrument which has been used for the data collection, while being mounted aboard the NASA’s Terra spacecraft. The database covers 99 percent of the globe (from 83 degrees north to 83 degrees south) with a 30m resolution, and an estimated 20m vertical accuracy. Data sets, divided into 22600 1°-by-1° tiles, may be acquired online, from the websites of the NASA's Warehouse Inventory Search Tool (WIST)[3] and the Japanese Earth Remote Sensing Data Analysis Center (ERSDAC)[4].

If the resolution or accuracy is not acceptable, different surveying methods need to be used to collect terrain data with a higher resolution and precision. Starting from the less precise, and offering lower resolutions, but cheaper and capable of efficient coverage of larger regions, to the most precise and dense, but costly and laborious, data collection methods include: airborne interferometric synthetic aperture radar (IFSAR), aerial photogrammetry, airborne light detection and ranging, or airborne laser terrain mapping (LIDAR or ALTM), as well as terrestrial laser scanning (TLS) and other ground survey techniques (El-Sheimy et al., 2005, p64).

Underwater

Underwater data are more difficult to acquire. The coverage of global data sources is usually limited to land, for example the ASTER GDEM database contains only tiles that contain at least 0.01% land area. The surveying techniques described above, except for the airborne LIDAR, are not suitable for the collection of data for maps which are required to present the sub-sea bathymetry.

Offshore surveying is based on a different set of techniques. These include, apart from the airborne LIDAR, various types of echo-sounding devices, such as a multibeam echosounder. These may be

[3] https://wist.echo.nasa.gov/~wist/api/imswelcome/
[4] http://www.gdem.aster.ersdac.or.jp/

mounted beneath or over the side of a boat. For more precise results remotely-controlled, autonomous or towed underwater vehicles and probes, with side-scan sonar systems, may be used (Tyce, 1986).

Map data and objects

Although terrain alone could be considered the simplest form of a 3D map – that presents exclusively the topography of terrain – its usability without the inclusion of geographic and other classes of objects would be very limited. When the terrain-basis of a 3D map is completed, the map is ready to display other categories of objects and data. These may come from different sources, and may be displayed in many different ways (see 4.3.4).

The simplest way for the inclusion of map data, which has serious limitations but often used (Haeberling, 1999; Petrovic and Masera, 2005), is through overlaying a scanned map as a terrain texture. This approach has almost all the drawbacks of traditional paper maps. It does not allow any operations on map objects, as these are not interactive – cannot be selected, queried or modified – and their representations are not visually efficient – symbols are not three-dimensional and cannot be changed. Another limitation is that the classes of objects selected for display cannot be changed, and cartographic algorithms that enhance the display efficiency cannot be applied.

A more advanced approach is to digitize the scanned map – to translate its information from the scanned image into the cartographic database – and then use a map viewer, with all its advanced capabilities, to display the data. A mixed approach, where a scanned map or an orthophoto is used as a terrain texture to provide a background for objects contained within the cartographic model, is also possible.

A far better source of data – in terms of ease of adaptation and quality – are existing digital maps, and GIS databases, that contain data layers in a vector format. These may be converted into the underlying database of a 3D map, using external conversion software or manual processes. However, a more efficient approach is to include support for external data formats directly in the 3D map viewer. The most popular formats, in which most of data sets are stored, include the Geospatial Markup Language (GML) standard (Lake and Farley, 2007), and commercial formats which became *de facto* standards due to their popularity: Google's KML (Boulos, 2005; Kibria et al., 2008) and ESRI shape files (Anselin et al., 2006).

If the required map data cannot be obtained using the methods described above, they need to be collected using photogrammetry or other surveying methods.

For some applications enabling the display of external data may be a requirement. External data may come from the data sets available on the Internet, may be sent on-the-fly by external applications (for example these performing simulations), or read in real-time from physical input devices.

4.3.3 Terrain modelling

A terrain model is a fundamental building block of a topographic 3D map. It is used to provide a reference for the geographic objects placed upon it. A good quality representation of the terrain surface, and efficient handling of large volumes of terrain data (challenging especially for high resolution presentations of large regions) is therefore crucial to the overall quality of a 3D map.

Data model

To assure a good quality terrain representation, an appropriate data model for DTMs has to be implemented. According to El-Sheimy et al. (2005, p9) "during the process of acquiring terrain data, a relatively unordered set of data elements is captured. In order to construct a comprehensive and usable DTM, it is necessary to establish the topological relations between the data elements as well as interpolation model to approximate the surface behaviour."

El-Sheimy and his team point out that the surface model should fulfil the following five criteria:

1. Represent the surface accurately
2. Be suitable for efficient collection of data
3. Minimize the requirements for storage
4. Maximize the efficiency of data handling
5. Allow analysis of the surface

There are several approaches to the problem. Commonly used terrain models include contour lines, grids, and triangulated irregular networks (TINs).

Contour lines – isolines of constant elevation – were mentioned in the previous section, as one of the possible formats of data for terrain modelling. These do not seem a good choice for direct use as 3D map terrain model, as they are too discrete and require algorithms to reconstruct the slopes they represent, as well as additional data samples, such as maximum and minimum elevation points, to do it well. The shape of the terrain model based entirely on contour lines will depend on the chosen interpolation and slope reconstruction methods, and will almost always differ from the real shape of the represented area.

Grids – matrices of equally spaced elevation data samples – are popularly used, due to their simplicity. These are simple to store and manipulate, and easy to integrate with raster databases. However, these have inherent problems, such as inefficiency of sampling, and the fact that the highest and lowest points on the landscape will most likely be omitted – as they are unlikely to fall exactly on the sample grid. Another drawback is their inability to adapt to the variable complexity of relief (El-Sheimy et al., 2005, p12). The key problem with grids is their unsuitability for regions with highly variable complexity. A dense grid, chosen for accurate representation of complex areas, is extremely inefficient in terms of storage in low complexity areas, while a low-resolution grid is not capable of accurately representing complex features.

Triangulated irregular networks (Figure 4.6) are much better suited for the representation of variable complexity relief, and offer multiple other benefits, such as the efficiency in data storage, the possibility to include the highest and lowest points, and the ability to describe the surface at different levels of resolution (Li et al., 2005). Their disadvantage is that they require more complex algorithms and higher computational power for their construction, handling and manipulation, and these requirements get even more difficult for TINs that support multi-resolution. However, the algorithms are well known and robust, and the computational power of even the slowest modern computers is sufficient for efficient application of modestly sized TINs.

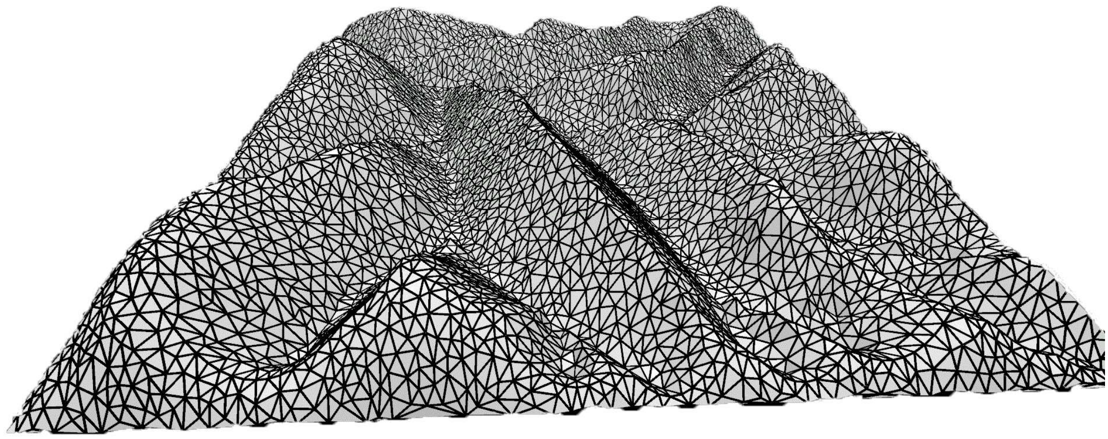

Figure 4.6. An example TIN-based representation of a fragment of modelled terrain

TINs are comprised of nodes, edges and triangles, and maintain information about topology, i.e. the spatial relationships between its different elements. Nodes originate from original input data points, and are the fundamental buildings blocks of a TIN. Edges connect neighbouring nodes to form triangles in a specific way. Each edge has two nodes, while each node may have two or more edges. Triangles describe the behaviour of a portion of the terrain model that falls within them. Connected triangles aggregate to create the whole surface. Topology is defined by maintaining information about each triangle’s nodes, numbers and types of edges, and adjacency to other triangles (El-Sheimy et al., 2005, p13).

There are different approaches to TIN generation, handling and modification which have varying resulting visual properties. One important aspect for terrain visualization is avoidance of long and thin triangles, which existence deteriorates the visual quality of a model. The Delaunay triangulation (DT) – which is a dual of the Voronoi diagram and was explained in Section 4.2.5 – is often used, for its desirable property of generation of triangles that are as equiangular as possible (Terribilini, 1999; Li et al., 2005). Another advantage of the DT is that it offers a unique solution, independent of the order in which the data points are processed (except of co-circular points), which is important for the repeatability of the model construction process. Moreover, a DT can be constructed dynamically – by addition and deletion of points – using locally-updateable data structures, such as Quad-Edge by Guibas and Stolfi (1985). An interesting property of the Quad-Edge is that it simultaneously stores the DTs dual, Voronoi diagram, which offers rapid solutions to multiple spatial analysis problems (Chen et al., 2001; Gold, 2004).

For a comprehensive summary of TINs as well as other approaches to, and aspects of, terrain modelling, refer to El-Sheimy et al. (2005) and Li et al. (2005).

Handling and drawing optimisation

Terrain models vary in coverage and in the resolution of data. These two factors determine the size of memory required for storing the terrain model. Large areas, depicted with high density, may require storage and processing of extremely large volumes of data. Their efficient handling and drawing may be impossible without the application of special optimisation mechanisms.

Efficient handling and drawing of large terrain models is a complex issue. Authors such as Dollner and Hinrichs (2000) emphasize the need for multi-resolution terrain representations that allow the minimization of the number of polygons drawn on the terrain, depending on the distance from the viewer. Such Level-of-Detail (LOD) algorithms are based on the fact that details of the distant parts of terrain may be drawn at a lower resolution, without the loss of quality being noticed by the user. This is due to the limited resolution of display devices and the limitations of human perception. The simplest approaches alter the whole terrain model depending on the zooming state. Advanced approaches include division of the terrain model into segments, or tiles. Tiles which are closer to the viewer are drawn in higher detail than the distant ones. This allows the maintenance of acceptable drawing times, without the loss of representational quality in the areas which are currently at the centre of the user's interest.

But multi-resolution alone may not be good enough. Some models represent vast areas, which are never displayed in whole, unless at a very low resolution. If only a part of such a terrain is displayed, there is no need to load the whole model into the memory. Division of the model into tiles, and reading only segments that are required at the moment is another memory-usage and drawing optimisation technique. It may be combined with predictive caching algorithms, to avoid long delays, when the user navigates through the map, and the viewer needs to catch up loading the missing data of the newly requested segments. In the simplest example, data of the tiles neighbouring to the currently displayed one(s) may be preloaded and kept in the memory. When the user moves out of the current tile it is first moved into the cache, and released once he navigates sufficiently far away.

The optimisation solutions required of a map viewer depend on the purpose. They are essential for high-resolution representations of large areas, but may be redundant in maps which present smaller areas in limited detail.

When a viewer can easily keep and manage the whole model in the memory, and draw it with a satisfactory refresh rate – due to the small area or low resolution of the available data – terrain drawing optimisation is not necessary. In this case it may be best to avoid it, as even the smartest and most perfectly implemented optimisation mechanisms introduce additional complexity into the system and may negatively affect the user's experience.

Visual efficiency

The visual efficiency of terrain drawing involves supporting human cues for perception of depth and shape. The best cues are provided simply by enabling interactivity – the ability to change the viewpoint (as to move ones head) and see how it affects the perspective, is the natural way of supporting depth and shape recognition used by humans.

But there are other ways in which even a static view can be enhanced. These involve effects such as simulation of fog and shadows (Dollner and Buchholz, 2005). Fog and shadows enhance the recognition of depth (Nielsen, 2004). Appropriate use of lighting and shadows also enhances the visual effectiveness of the terrain shape presentation (Haeberling, 2002). Perception of terrain elevation can be enhanced by application of appropriate shading – for example the terrain model may be shaded in different tones or colours to indicate elevations.

Vertical exaggeration is another important aspect, with regard to supporting the recognition of the terrain's shape and elevation. 3D models of large areas appear flat on screen, as the difference in altitudes is usually small, comparing to the other dimensions of the portrayed area. The appropriate level of exaggeration depends on the application and on the specifics of the displayed model, and may vary between one (no exaggeration) to double-digit values.

4.3.4 Data representations

Once the terrain model is ready and functions efficiently, map data can be displayed, using it as a reference. Most of the data will be placed upon the terrain surface, but that does not always have to be the case. For example, in marine maps vessels will be placed on a virtual surface of water, above the seafloor bathymetry, while for maps used in aeronautics flying objects will be positioned at some altitudes above the terrain.

Representation forms

Geographic data and objects may have different representations, which partially depend on their types; and partly on the technical capabilities offered by the map viewer, the application, and the user needs. Different innovative approaches, other than those mentioned here, may also be used.

Single, tangible objects may be presented using 3D models, drawn with different levels of realism. In some cases map objects will need to represent their real counterparts with a high level of similarity; in others general, easily recognizable class symbols will be sufficient. Non-tangible, numeric or textual values may be displayed as numbers and text, in the form of 3D labels, or drawn in 2D on the terrain surface.

Lines and polygons may be drawn on the terrain's surface. Polygons may alternatively (or in addition) be represented by an associated 3D symbol (for example a model of a tree, for a polygon representing an area of a forest) that is repeated across the area, or displayed just once at its centre. Volumetric objects or real-3D data that occupy a given 3D space may be represented with translucent volumetric shapes, or isosurfaces.

In addition a map may contain different types of embedded multimedia, such as images, movie clips, charts, spreadsheets, etc; and hyperlinks to different locations within it, or to documents which open in external applications, stored on the local hard-drive, LAN, or on the Internet.

Visual optimisation

A cartographic approach and focus on the presentation efficiency demand the use of visual optimisation techniques. Generalization techniques known from 2D cartography are of limited use in 3D. Three-dimensional equivalents, or new approaches specific to 3D, may need to be used.

The approaches typically used in geovisualization are based on the concepts of LOD and of multi-representations of objects. In these approaches different models, with different levels of detail or representation quality, are used depending on their distance from the viewer's eye (camera). Such approaches are focused on improving the efficiency of drawing, not on maintaining the visual efficiency.

3D maps may use some alternative techniques, partially based on the cartographic methods, and in part on the concepts used in geovisualization, to assure that the displayed map is easy to comprehend, is not cluttered, and that important objects are displayed and remain clearly recognizable, independent of the selected view and the distance to the camera. For example objects may be drawn with dynamic sizes that change with changes of the distance to the observer. In this approach objects would be drawn in smaller sizes when in close-up, and gradually grow when the camera moves away. To assure clarity, objects that are no longer important at a given distance could be switched off, or displayed by another object which aggregates several surrounding occurrences of data points from the same category. This "intelligent zooming" concept (Haeberling, 2002) may also maintain a similar density of the image regardless of the zooming status (Sieber and Baer, 1997).

Another aspect is the readability of numeric and textual information, both drawn on the terrain surface and presented in the form of 3D labels, which concerns also 2D symbols. Current technology allows for dynamic rotation and orientation of such information, to support their readability. 3D labels may be automatically oriented in space to face the user, while 2D text, numbers and symbols drawn on the surface of the terrain may at least be rotated, to always appear with the right side up. Alternatively even flat 2D elements may be drawn to face the user using "billboarding" techniques (Dollner and Kersting, 2000).

These are just few examples of possible techniques. The current section does not exhaust the topic, and does not describe all solutions which may be used. This is due to the simple fact that not all of them are known to us at present. We believe that some innovative and highly efficient methods may still be proposed. Our aim, instead, was to signal that blindly copying techniques from geovisualization or 2D digital maps may not guarantee good enough results in 3D mapping. Alternative techniques may, and need, to still be searched for, and we look forward to seeing the results of future research in this regard.

4.3.5 View and navigation efficiency

The efficiency of a 3D map viewer depends on several factors, including the ergonomics of its manipulation and navigation mechanisms, and its visual efficiency. The latter involves the terrain, the data presentation and the visual optimisation mechanisms discussed above, as well as its capabilities regarding the efficiency of view: the possibility to define and switch between different viewpoints; the ability to simultaneously display several complementing views; the functionality of linking views and the automatic orientation of maps. In this section we will discuss the listed above factors related to view efficiency, which have a huge overall impact on the perceived map quality.

Multi-views

Due to the limitations of perspective views, such as hidden regions and distortion of the distances and sizes, several views may be necessary to fully understand a 3D situation. Researchers in geovisualization and 3D cartography typically list multiple views among the most important requirements for 3D map viewers (Terribilini, 1999; Germs et al., 1999).

Different approaches are also possible. In the least interactive option a viewer may allow the definition of several different viewpoints, which can then be switched between. There may be also several generic view categories to choose from: top views, perspective (elevated oblique) views, and world (ground-level perspective) views (Kraak, 2002b).

More interactive approaches allow fluid and unhindered interactive setting of a view, and a smooth transition between separate view categories. In our experience such a lack of a hard distinction between top, perspective and world views offers a more integrated user experience. Systems that allow free navigation may still offer the possibility to predefine views as an addition.

Some systems allow the assignment of viewpoints to map objects, which simplifies the view setting operations and improves the functionality. The possibility to quickly see the scene from the perspective of any object within the map supports navigation and spatial reasoning. In maps that allow animation views may be linked to moving objects, to change the perspective automatically with the motion (Goralski and Gold, 2007a).

Linking views

An advanced functionality offered by some viewers is to allow the simultaneous display of several selected views. This may enhance the understanding of the scene by the user, and different views may be tailored to answer specific questions (Arsenault et al., 2003). The views to be displayed may include presentations of the scene from different viewpoints. In addition 2D maps or simplified outlines of the displayed area may be used, to complement 3D perspectives and provide a general orientation facility.

Simultaneous display of significantly different views may in some cases lead to confusion, and decrease the efficiency of situation understanding, instead of increasing it. To prevent this, views may be linked and different viewpoints indicated on each other, or on an overall outline. Not only the position of a viewpoint, but also the view frustrum, may be indicated on a 2D map.

Arsenault et al. (2003) describe other view linking tools and options, such as: *view proxy* – a representation of one view within another, with optional *tethers* for indicating the central point of attention in each view; *3D mouse cursor* – which, used in one of the views, indicates what is placed under the cursor in every other view; and *view coupling* – defining views which will be changed together by animation or user interaction, to, for example, present the same area, or view from the same position, at different perspectives or angles.

Automatic map orientation

In maps used for navigation it may be appropriate to automatically rotate the map, to match the geographic orientation of the user or the device on which it is displayed. The alternative is to use a static North-up orientation. The most suitable approach depends on the purpose, as well as on the user preferences. Porathe (2006) demonstrated the superiority of automatically oriented maps for the purpose of navigation. The automatic orientation of a map is also necessary in user-centred (egocentric) view modes, where the forward-up principle is used (Darken and Sibert, 1996). The principle states that the upward direction on a map (assuming it is mounted perpendicular to the floor) must always show what is in front of the viewer. North-up maps allow quicker recognition of known shapes of areas which users are used to seeing and recognizing orientated in this way, such as the outlines of coastlines, countries or continents.

The orientation of a map which is used in motion is possible with all types of satellite receivers: it is enough to compare the subsequent location updates to determine the motion direction. Depending on the receiver's type it may be more difficult when the user is stopped. An additional device, such as the digital compass, may be required to efficiently rotate the map to reflect the user's orientation on the display.

4.3.6 User orientation

Research indicates that in user-centric immersive views it may be difficult for users to understand their position within the 3D map, and they may feel lost as a result (Koller et al., 1995). Slocum et al. (2001) list the development of methods to assist users in navigation and maintaining their orientation among the significant research concerns. Several techniques may be used, including the presentation of the user's location within the map, the display of landmarks, and clear marking of geographic directions.

User location

Automatic presentation of the user's location on a digital map used for navigation has been indicated as the biggest advantage of digital maps over their traditional paper counterparts by participants of the field test by Nivala and Sarjakoski (2003).

Depending on the technical capabilities of the map displaying device, and the intended purpose, digital maps may, or may not, be required to present this information. For maps installed on mobile devices the availability of a satellite navigation receiver (usually GPS) is a prerequisite. For interactive maps installed on fixed devices, the user location can be preconfigured to indicate the geographical position in which these are placed.

The presentation of the user's orientation during free exploration of a 3D map – as opposed to real-time navigational use – is listed among the map design principles by Darken and Sibert (1996). It may be done using a 2D outline of the area presented in 3D.

Landmarks

According to Darken and Sibert (1996) "landmarks are point-references that are external to the observer. They are not entered into but rather are viewed from a distance. A landmark must be distinct from its surroundings and should have directional information associated with it. Directional information is essential to the navigator's ability to remain oriented with the environment."

Inclusion of recognizable landmarks in a 3D map is another way of minimising the confusion of its user. The availability of geographic objects which can be identified helps to maintain the understanding of the user’s position within the model (Musliman et al., 2006).

Landmarks are especially useful in navigation when satellite positioning is not available. They are essential for the ability to determine the user’s position in the real world. This is done by matching the topographic features and geographic objects displayed in the map with the physical surroundings.

Landmarks are also useful with satellite navigation. They support the matching of the displayed map with the surrounding world (heads-up display). A special case is a map used in bad visibility conditions, when topographic features and objects of the real world are not visible, and their counterparts displayed in the 3D map are the only navigational features available to the user.

Geographic directions

When a user navigates in a 3D map his sense of geographic (compass) directions may be lost. To avoid this, the directions should be displayed in some form within the map’s interface. The indication of directions should frequently be updated to reflect changes.

Darken and Sibert (1996), discussing the principles of 3D map design, summarize this requirement in the following way: “Provide frequent directional cues. This information can be supplied in the form of directional landmarks or independently, as in a compass.”

This is illustrated in the case of a prototype 3D GIS designed by Koller et al. (1995), in which the addition of navigational features, including a directional compass to aid orientation, was a primary request from the users testing their system.

4.3.7 Understanding of a map

There are several concepts traditionally used in 2D maps to support or enhance the completeness of their comprehension. These include the use of a grid to display the geographic coordinates, the use of labels and legends, and the indication of a scale. Let us discuss how the introduction of the third-dimension affects these: whether they are still necessary; how these can be modified; and what alternatives can be used.

Geographic coordinates

Geographic coordinate grids are traditionally used on maps, to provide a reference regarding the geographic positions of map data. According to Haeberling (2002) these are "absolutely necessary to express the accurate geo-positioning (…) of map objects." But the truth is that in 3D maps this may have some specific flavour, or be done using alternative methods.

Geographical coordinate grids, if used, may have variable density, to allow gradually more accurate reading of positioning information as the user zooms in on the map. They may be drawn on the terrain surface, and should be offered as an option, to keep the view clear when they are not needed.

Alternatively the position may be displayed using a querying mechanism. A special tool for querying the position at any location may be provided. The position should also be a part of the results for querying map objects. In another approach the information regarding the mouse cursor's position may be continuously displayed in the user interface. Other approaches are also possible.

Labels

Provision of textual information regarding the properties of objects and regions has always been one of the most fundamental map requirements. This is equally true for 3D maps. Haeberling (2002) lists labels among the fundamental orientation features. These, however, may also be used as convenient on-demand querying tools. Labels in interactive maps should be provided as an optional, switchable functionality, preferably with a possibility to select the categories of objects for which these need to be displayed.

The recent study of user preferences for different types of mountain maps by Petrovic and Masera (2005) is a practical illustration of the fundamental role of labels for map usability. In the study, a 3D symbolic view was assessed by respondents as the most helpful for the ease of recognition of geographical objects. Unfortunately, as it lacked labels, it achieved a lower overall result comparing to a less-efficient DTM with an overlaid scan of a map, simply because the second offered the possibility to read names of places.

Different display forms of labels in 3D maps, and approaches to their visual efficiency were discussed in Section 4.3.4.

Legends and symbols

Legends are traditionally used to provide descriptions of the symbols used on a map, so a user will be able to understand its content. As such they are linked to the problem of symbolization.

In some 3D maps the need for legends may be diminished, as they offer a possibility of using natural-looking, self-descriptive symbols, which may be understood easily based on the life-experience of a user. For example almost everybody would recognize a house, or a tree, even if presented in a simplified symbolic way. However, there are several factors which should be considered. Firstly, there are classes of objects that cannot be represented in such an obvious way. Secondly, the understanding of objects may depend on the cultural background of a user. Thirdly, appropriate symbols will depend on the target group of users. For example experts in the field for which a map is designed will have background knowledge that will allow them an understanding of symbols that a layperson would not comprehend, but they will also have some habits regarding the expected representations.

Neglecting legends and symbolization is listed among the problems that affected most of the examples of topographic 3D maps analyzed by Haeberling (1999): "We notice that the symbolization and legends of topographic 3D-maps are often neglected. Many map symbols are not fully designed according to the objective. Some producers rely on their own subjective preferences for map symbols without examining whether they are appropriate for their purposes."

If a legend is not provided, an appropriate effort should be made to assure that symbols are clearly recognized by the target group of users. The lack of a legend may also be compensated for with the provision of some interactive mechanisms, such as permitting object queries, and allowing on-demand display of labels.

Scale information

Provision of information regarding the scale of a map presentation is another essential feature, traditionally included in maps. Two-dimensional maps provide it using different techniques: using a rectangular grid where every side of a rectangle denotes a defined distance; using a small ruler, which describes distances in the map; or by displaying numeric information about the scale, for example 1:100000, which means that every 1cm denotes a 1km in the represented area.

The display of scale information in 3D maps was recognized as essential by Haeberling (2002), but in three dimensions this is more problematic than in 2D. In a perspective view there is no constant scale across the display (the screen plane), which rules out the use of a standard 2D ruler. The grid may still be overlaid on the terrain surface, and it should be optional, switchable on a user's request. Numeric information would not have much value, but a distance between the camera and the centre of the displayed model, or the eye's altitude, may be displayed instead.

Different interactive tools may also be provided. A special ruler that slides on the surface of terrain, and may be rotated to indicate distances in every direction may be an idea. This, however, may be done in an easier and more comprehensive way, by providing the functionality of measuring different types of distance (vertical, horizontal, straight-line, and over-the-ground) with dedicated tools.

4.3.8 Map projections

Two-dimensional maps, traditional and digital alike, have to use cartographic projections to represent fragments of the geoidal Earth surface on a flat plane – be that a sheet of paper, or a computer screen. The application of a projection, although necessary, involves the introduction of different types of distortions, which affect the correctness of the represented distances, angles and areas. The choice of an appropriate projection is related to the application and is always a trade-off between the drawbacks of different projection types. It requires the acceptance of some types of distortion, over others (as explained in Section 2.3.3).

The choice of the most suitable projection is a significant issue, which also concerns 3D maps. Unfortunately, the use of map projections in 3D mapping is one of the research themes that do not seem to have attracted much prior academic interest. We were unable to find any background research on this interesting and important aspect. Our experience suggests that there is no single best answer, and that the most suitable option has to be chosen on a case-by-case basis. It depends on the need, purpose, and application of the map, as well as on the characteristics of the available data sets, and the technical capabilities of the map-hosting devices. However, it is worth noting below one fundamental difference between two- and three-dimensional maps, which makes the selection of the most appropriate projection even more difficult.

With respect to projections, 3D maps are less restricted than their 2D counterparts. Designers of digital 3D maps have an option to elect not to use any projection. Instead, they may represent an area as a fragment of the surface of the Earth, or rather of a reference geoid, in 3D space. This makes the use of any map projection not necessary. Even though the 3D scene is eventually projected on a flat screen, the cartographic model is three-dimensional. This alternative functionality of the use of 'no projection', if implemented in a 3D map viewer, would allow it to share one of the biggest advantages of digital globes. The presentation of an area without the use of any projection allows the true representation of the Earth's curvature, and the correct representation of all three properties that form a triple constraint restricting all map projections: distances, angles and areas.

However, although 'no projection' in 3D maps is possible in principle, it may not always be practical. Depending on the purpose of the presentation, it may be more suitable to use the traditional approach, involving the use of a projection for translation of the cartographic model into the flat plane, before the application of elevation data. An example of such a situation may be when a 3D view is provided merely to supplement a 2D map, in which case it may be more appropriate to use the same projection as for the 2D map, to preserve the coherence between both views. The suitability of direct 3D rendering also depends on the source of the data. For example, for data acquired from scanned 2D maps an operation the reverse of the original projection used in their production may be needed, before the application of the global datum. This may be deemed too difficult, or lead to an unacceptable increase of representational error. Another example is when a scanned map is to be used as an overlay texture of a 3D model. In this case the 3D model should be created using the same projection as the overlaid map, in order to preserve the representation accuracy. If a different approach was used, features represented on the overlay might not match the topography of the terrain model.

Another concern is that direct representation of the cartographic model complicates the calculation of distances. If the terrain is represented as a fragment of the reference geoid these have to be measured on the curved surface of the geoid, rather than on a plane. It also affects the measurement of heights, and adds complexity to the calculation of topological relationships. The use of 'no projection' is also technically more difficult to implement. An assumption that the Earth is locally flat makes development of digital 3D products technically easier: it simplifies operations performed within the model, requires a lower precision, and speeds-up related computations.

The issue of the selection of the most appropriate approach to map projections is less important for the representation of small areas, and grows in importance with the growth of their sizes. The Earth's curvature may be an issue of primary importance in some applications, where visibility testing is involved (Elsner, 1979), and then the use of 'no projection' offers the most accurate results. Also, in the cases of maps that are designed for use with satellite navigation systems, the use of the same reference geoid which is used by the positioning system for the representation of terrain and map objects, may be the best choice.

In general we suggest that the flexibility offered by digital technology should be fully used. With a little extra effort the choice may be left to the user. Map viewer producers may build different projections, including an option to use none, into their systems. If that is not possible, the appropriate solution has to be selected on a case-by-case basis, depending on the factors discussed above.

4.3.9 Animation

The usefulness of animation in maps for the representation of complex processes, the temporal and non-temporal changes in spatial data, and the stimulation of exploratory analysis, was pointed out in a number of publications, including Fairbairn et al. (2001), Slocum et al. (2001) and Kraak (2002b; 2003). Nebiker states that animation plays a more important role in 3D environments than in 2D (Nebiker, 2003).

Fairbairn et al. (2001) argue that dynamism is an increasingly common characteristic of contemporary data. They are convinced that animated representations can adequately address the problem of integrating time-referenced data in geovisualization systems. They, however, note that the inclusion of animation is not a trivial problem. In their words "the problem is not how to represent 'temporal data' but how to represent 'processes occurring over time.'" The authors conclude that time-dependent, dynamic and animated data require special consideration and the examination of optimal methods for their incorporation.

Slocum et al. (2001) point out that "animation is a natural way of depicting temporal data because changes in real world time can be reflected by changes in display time." They note that although some forms of animation are executed without direct control from the user, "the greatest understanding may be achieved when the animation is under complete user control." They also argue that "temporal animations are often difficult to understand because it is hard (with a rapidly changing display) to keep track of the match between the display time and the real world time," adding that "for temporal animations, a critical concern is associating a proper time with various points in the animation."

Kraak (2003) shares the views of the teams led by Fairbairn and Slocum, stressing "the importance of the link between display time and world time," and pointing out that "interaction with an animation is also seen as a requirement in order to allow the user to query specific moments or periods in time."

Maintaining the reference to real-world time, and allowing users to control the animation, appear as the most often repeated and important requirements. The first issue requires control of the speed of animation, as well as linking of its every moment to the real-world time. Animations which are not linked to any particular period in time require only the control of speed of time propagation, within their durations. To satisfy that, animation changes should be linked to the flow of real-world time. The speed may be multiplied, to run the animation faster or slower, but it should remain in reference (as a multiplication) to the flow of real-time. This requirement is also true for temporal animations that present a situation at particular moments (periods) in the real-world time. In addition to the above they must maintain the connection of the inside-animation time with the real-world time throughout all the execution, and allow clear recognition of the time of every presented moment by the user. To address the second requirement – user control of the execution – users should have a full control of the animation time. They should be able to start and stop it at their discretion, as well as to rewind and forward it to select the exact moments that interest them. Control of the time-direction in animation may be also provided, allowing displaying it backwards as well as forwards.

In the light of the above requirements, from the technical perspective, a crucial issue is the assurance of constant speed of animation, regardless of the speed of a particular machine used to display it, or of the temporal fluctuations in its drawing speed. The frame-rate is seldom constant, as it may vary depending on the complexity of the currently displayed view, and on the variable workload of the machine. This requires an effort from the map viewer's designers, to implement mechanisms for decoupling the speed of animation from the speed of rendering of single frames.

4.3.10 Graphical environments

Every 3D map has to include several components, as discussed in Section 4.1.1, and presented in Figure 4.2. This includes a visualization system, responsible for the translation of the cartographic model into the visual presentation. The implementation of a visual system involves the use of a graphical environment that supports the process of 3D rendering.

There are several possible approaches to map rendering, and different types of graphical environments that can be used. The most common ones are discussed below.

VRML / X3G

Many researchers select Virtual Reality Modelling Language (VRML), or its later XML-based edition (X3G) to present their 3D maps. VRML is a language that allows the description of a 3D scene in a text file, which later may be displayed in any VRML-compatible viewer.

VRML is a very convenient tool – its syntax is simple, it does not demand advanced programming skills, and it allows defining the whole scene using only a text-editing tool. The availability of viewers which work as Internet browser plug-ins allows easy dissemination of the defined scenes over the web. Many people have tried to interface it with GIS systems, using purpose-written software to translate the underlying databases into VRML (Coors and Jung, 1998; Huang et al., 2001).

However, VRML does also have some serious drawbacks that stem from its universality and independence of the underlying cartographic model. It is not dynamic – defined scenes are static and do not allow real-time updates, and it lacks mechanisms for handling large datasets. Some workarounds were tested (Zhu et al., 2003), but the fact is that at present it cannot provide, for instance, direct and instant modification of the scene in response to the user's manipulation and map editing actions. The extent to which it can be coupled and optimised with the cartographic model is limited. Its interactivity is also limited in this sense.

Another limitation is that a designer of a map has no control over the interaction and navigation interface. The interface is designed and implemented by the producer of a VRML viewer. Usually the interfaces are based on GUI buttons. Direct manipulation and the use of special devices is not an option, unless a custom viewer is implemented.

Despite the above drawbacks VRML may still be the optimal choice, depending on the purpose. If an application does not require a high level of dynamism and interactivity but web-access is essential, it may be the best option.

Game engines

3D game engines are specialized, comprehensive graphical packages, designed for the creation of three-dimensional computer games. They are optimized for drawing speed and efficiency, and include extensive sets of libraries and an API for the handling of different game-related tasks and functionalities. For example, these may include support for different input devices, sounds, animation of game objects, artificial intelligence of creatures and enemies, and many others. The use of a ready, well-tested and robust API may lead to a much decreased product development time, comparing to the implementation from scratch.

The visual efficiency and optimisation for rendering speed and quality are the greatest advantages of game engines. These were successfully used for 3D mapping, for example in landscape visualization and planning (Herwig and Paar, 2002), and in geovisualization (Fritsch and Kada, 2004).

However, the bulkiness of game engines, where the majority of functionalities are irrelevant to mapping, as well as potential licensing constraints, are serious drawbacks. Moreover, game engines lack support for map-specific requirements, such as cartographic view optimisation (for example symbolization and generalization) and support for topology. They may be difficult to integrate with cartographic models, and may not allow for the implementation of map-specific interaction metaphors and querying mechanisms.

Custom code

The most laborious approach, which gives the most flexibility and control over the resulting product, is to develop a custom graphical environment. Custom code may be seen as a map-specific game engine, with all their advantages, and no drawbacks. It may be smaller, stripped of all the irrelevant elements, and optimised for use with 3D maps, while still efficient for speed and rendering. It has the serious drawback of increased complexity and development time, but is free from potential licensing constraints, and allows optimization and specialization for the particular application.

If requirements for the product demand specific functionalities not provided by gaming engines, while high interactivity and direct manipulation – which are an Achilles heel of VRML – are important, custom development may be the best choice. It does demand significantly more effort (time and cost), but when properly designed and implemented, it offers the best, uncompromised results.

The custom code approach involves the implementation of a *scene graph* – a hierarchical representation of graphical objects in a scene – which is also a part of every game engine. Scene graphs are optimised for efficient rendering, and may be thought of as internal representations of cartographic models within map visualization systems.

Different libraries may be used to support the implementation of a custom graphical environment. There are open-source implementations of scene graphs – such as the Open Scene Graph[5] – available on the Internet. An absolute minimum seems to be the use of low-level graphical libraries that handle the rendering of graphic primitives, such as OpenGL[6] or Java 3D[7].

There are multiple handbooks available on the market, usually targeted at aspiring gaming professionals, which can be used for the design of custom scene graphs and necessary parts of game engines. Two examples are the works by Eberly (2001) and a more recent one by Sherrod (2007). Interested readers may also refer to Appendix A for a simple mapping-oriented introduction to 3D computer graphics.

4.4 Chapter summary

In this chapter the subject of interest of 3D cartography – the 3D maps itself – has been discussed from the theoretical and practical angle. We started with a definition of 3D maps – firstly by providing their technical description, and secondly by proposing a set of four defining, differentiating factors, which are: the use of 3D visualization, the application of cartographic rules, high interactivity and map intelligence. That was followed with the discussion of these factors.

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[5] http://www.openscenegraph.org
[6] http://www.opengl.org/
[7] http://java.sun.com/javase/technologies/desktop/java3d/

We stated that interaction is the key to efficient 3D mapping, and we moved on to a description of different types of interaction (user- and map-driven), as well as other related aspects such as map ergonomics and underlying map intelligence algorithms.

In the last part several other cartographic and technical aspects of 3D maps have been discussed, including the problem of dimensionality of data, available data sources, terrain modelling, types of data representation, efficiency of navigation and orientation within the map, map understanding, map projections, the use of animation and possible graphical environments for the implementation of a mapping platform.

As the whole, this chapter is meant as, and we hope that it provides, a useful source of information and guidance to 3D map enthusiasts, researchers and developers.

Chapter 5

3D Map Viewer

To achieve the goals of our research project, the implementation of a fully functional 3D mapping platform was necessary. The platform would be used for three different purposes: 1) to provide an environment for experimenting with and testing of different ideas – to enhance our understanding of the problem; 2) it would be used as a means for practical verification of our hypothesis – that efficient 3D maps may be built based entirely on the technology and data available today; and 3) it would provide a basis for practical demonstration of example applications – in order to prove that 3D maps may be used for a wide area of problems, where they improve the efficiency of data understanding, enable better (both quicker and more reliable) decision-making, and more educated planning decisions. Example applications would demonstrate also that 3D maps are very versatile – that they may be used for different categories of tasks, which require either real-time or simulated display – and that they have a potential to save human lives, time and cost. The mapping platform – called the 3D Map Viewer (3DMV) – has been developed by us in the course of research, and is described in this chapter. It is the core for all the example applications described in Chapter 6.

In this chapter we will discuss the 3D Map Viewer (3DMV) platform, including its functional description and the details of its technical design. The functional description follows the structure of, and refers to, diverse aspects (functional, cartographic and technical) discussed in Chapter 4. It is followed by the technical description of our development approach, the 3DMV's system architecture, and a discussion of its important technical aspects.

5.1 Functional description

The 3D Map Viewer (3DMV) is a general three-dimensional mapping platform, which can be easily adapted to different applications. It has been designed to meet the industry software quality standards, with sufficient functionality to prove our case. It is, however, not a commercial product, and as such some of the functionalities required from a production-ready system, may be missing.

Generally speaking, the system allows opening sets of data in defined formats, which are then displayed as 3D models. The possibilities include creation of three-dimensional models from 2D data. The model is optimised for visual efficiency, and it may be freely and intuitively navigated. Data categories may be selected for display, and the displayed data objects may be queried and manipulated. Simple data analysis tools are also provided.

The system allows a wide range of customization options, regarding the terrain model and presentation forms for each category of data.

Well thought-out object-oriented design and open architecture allow extension of the 3DMV, to enable its use for a wide range of potential applications. The platform's potential is enhanced by its moderate hardware requirements, which allows its deployment on cheap PC computers, including notebooks with dedicated graphic cards.

Different aspects of the system are described in detail in the sections below, illustrated with images captured from the 3DMV system, when appropriate.

5.1.1 User interface

The user interface allows the user to communicate with a mapping application (user-map interaction). Its design is crucial for the efficiency of the work with, and the overall user's experience of, the system. The desirable qualities include clearness, ergonomics and intuitiveness. The notion of the user interface includes all of the ways and elements that facilitate the communication and interaction of the user with a system. In the 3D Map Viewer the user interface is comprised of three distinct elements.

Graphical User Interface (GUI)

The GUI comprises of the main application window, in which maps are displayed, and a number of logically organized toolboxes, or utility panels, filled with different controls. Toolsets group different types of information and tools that may be required for specific tasks, and are displayed and switched between with a special set of large, ergonomically laid out buttons. Controls used in toolsets include textual and numeric labels, checkboxes, dropdown selection lists, edit text fields, sliders and buttons, which can be operated using a pointing device and keyboard.

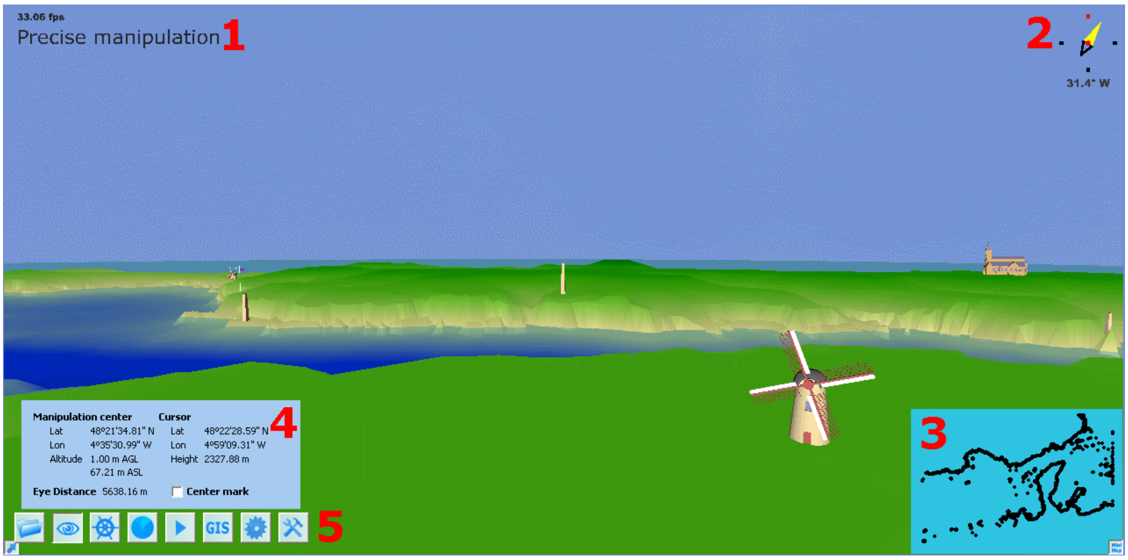

Figure 5.1. A view of the system with different elements of its Graphical User Interface: 1 – On-Screen Display (OSD), 2 – Compass, 3 – Mini Map, 4 – View Info toolset, 5 – toolset selection (main menu) buttons

These are complemented with special components such as compass and mini map (described in detail in relevant sections), as well as with the on-screen communication (OSD) system and information panels. The general layout is shown in Figure 5.1.

Direct manipulation interface

GUIs are intuitive and ergonomic ways of facilitating general control of an application. They are, however, not the most efficient and ergonomic way to provide control over the view in a highly interactive 3D map.

Instead, the displayed 3D scene may be more suitably controlled with a direct manipulation interface, which uses a control device (a controller) working in a (near) real-time feedback loop with the user, through a display device. In this interaction form the user controls the view by operating the controller, and observing the resulting changes.

The 3DMV supports two types of control devices: a standard mouse, and a special 3D controller. The use of the first is natural to almost every computer user, and these are available with almost every PC. The second option offers more ergonomics and precision (Figure 5.2), but requires training and is not available as a standard.

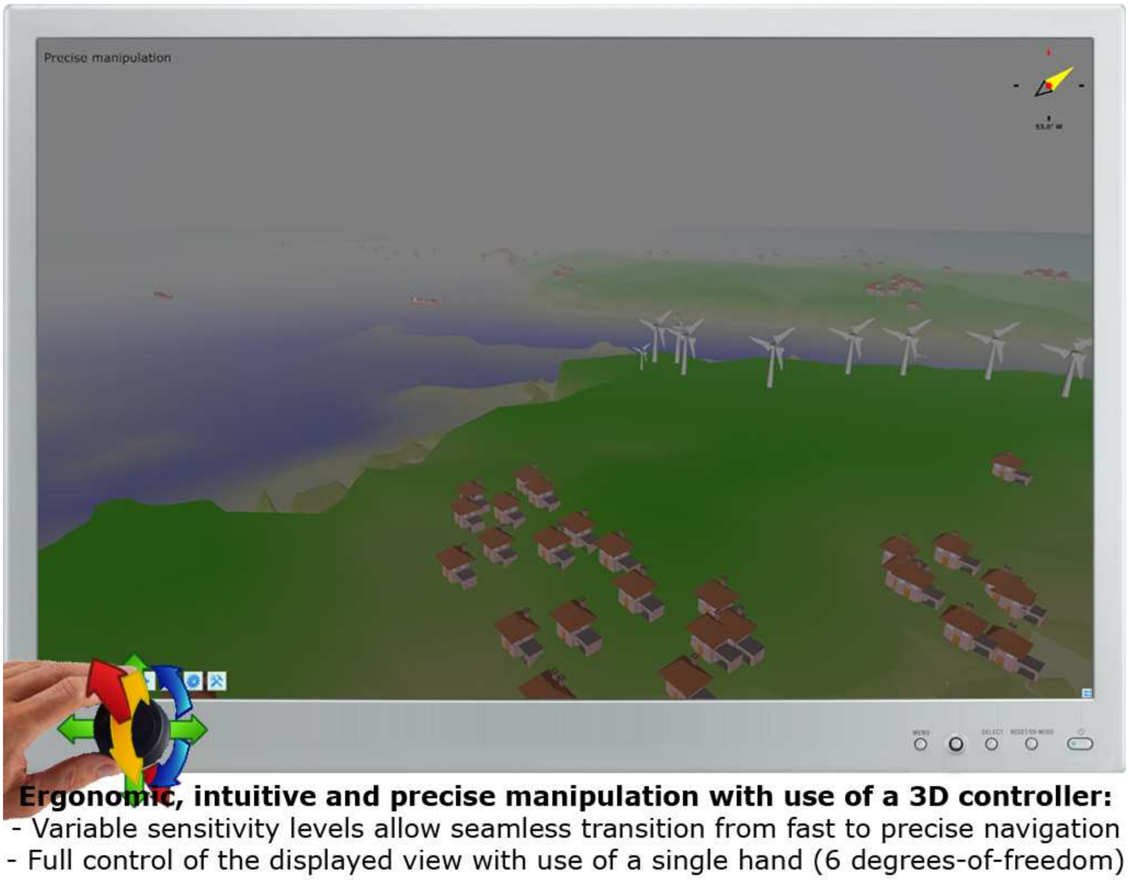

Figure 5.2. Ergonomic manipulation with a 3D controller

The map control interface is discussed in more detail in Section 5.1.2.

Configuration files

The last way to interact with 3DMV's options is through manual editing of its configuration files. This allows control over a number of settings which affect the system's behaviour and map presentation.

The three most important categories of user-map interaction are: the navigation within the scene and manipulation of its objects, analysis of the presented data, and map editing. These are described in dedicated sections below.

5.1.2 Navigation and manipulation

The system provides a direct manipulation interface for navigation within the presented scenes. Navigation may be performed with one hand, using a 3D controller, while the second hand remains free to interact with the map objects. This follows the sculptor metaphor principle described by Hand (1997). The sculptor metaphor, combined with high responsiveness of the direct manipulation interface, guarantees a highly ergonomic and intuitive user experience.

If no 3D controller is present, the same operations may be performed using a standard mouse, working in two separate modes – the navigation and operation mode – which have to be switched when the user wants to change from navigating to interacting with objects, and vice versa. The switching operation is very simple and quick, to assure that a lack of a 3D controller does not deteriorate the system's ergonomics.

The navigation mode provides two separate metaphors, which can be freely selected depending on the user’s preference. One treats the whole scene as an object kept in a user’s hand, similarly to the “scene-in-hand” metaphor described by Hand (1997). The other one is close to the “flying saucer” metaphor, by Fuhrmann and MacEachren (1999), and allows free flying within the scene.

Figure 5.3. Object selection and query

Each of these metaphors employs additional optimisation mechanisms, such as adaptive sensitivity, and unifies the three traditionally separate view modes – the top, perspective and world view (Kraak, 2002b) – into a continuous and coherent whole. In addition, object-centred views, based on the objects’ selection mechanism, are provided.

Object selection (Figure 5.3) is the basis for interaction with objects (manipulation). Different operations may be performed on a selected object (or a set of objects), including querying, editing, or selection of the object-centred view.

5.1.3 Data analysis

The 3DMV platform offers a set of basic tools to support analysis of data. These include two forms of object queries, and GIS-type measurement tools.

Queries

Queries allow display of object information upon a request. Two different query types are provided in the 3D Map Viewer:

- Single-object query – the usual query, based on selection – where all available information about an object is displayed upon a request, in a dedicated panel (Figure 5.3)
- Multiple-object query – based on labels – where values of a selected attribute are displayed simultaneously for all objects from a selected category

Measurement tools

The 3DMV offers three-dimensional versions of typical measurement tools known from GIS systems and more advanced digital maps. These allow measuring distances (direct, horizontal, vertical) and angles (projected onto horizontal or vertical planes, as well as true-3D). Measurements can be made in two ways:

- Manually – by freely setting control points in the 3D map space
- Automatically – based on a reference to existing map data objects

5.1.4 Map editing

The viewer offers several ways of editing a displayed map. This allows user-introduced updates of models, for example to recreate a region with higher-than-default precision and realism, or to emphasize selected categories of information for visual analysis. The available options include:

- Editing of map objects
  - Adjustment of positions
  - Modification of dimensions
  - Adjustment of orientation
  - Change of representations
- Addition of custom objects
  - Adding single objects
  - Loading custom object lists from a predefined file
- Editing of terrain models
  - Application of custom DTMs
  - Manual editing of terrain topography
  - Overlay of custom textures
  - Application of custom shading programs

Editing also provides mechanisms for the creation of brand new visualizations.

5.1.5 Map-user interaction

The 3D Map Visualization platform includes several mechanisms to facilitate communication of a map with its user. This may be done using the GUI elements such as on-screen display (OSD) messages, and information panels, as well as via outgoing communication with external systems. While the GUI elements are restricted to visual means of information transfer, communications sent to external systems may be disseminated by these in any appropriate way, including the use of sound, touch and light, as well as automatic text, email or radio messages.

To support map intelligence, the platform allows integration with custom data structures and algorithms, as well as incorporation of information received from external systems. Both these options may be used to provide additional map operation, analysis or decision support to the user. Practical examples of their use – for collision detection and visualization of maritime traffic respectively – are provided in Chapter 6.

5.1.6 Data representation

The 3D Map Viewer provides several forms of visual representation, for different types of data objects.

Point-type objects may be represented with 3D numbers, 3D text labels or 3D models (symbols) – or a combination of the above (Figure 5.4). Visual representations are placed on the terrain surface or suspended freely in 3D space. Optimisation mechanisms explained in Section 5.1.7 are employed, to maximize the visual efficiency of presented information.

Figure 5.4. Representation of point-type data objects with a combination of 3D models and 3D text labels

Line segments may be drawn using the above representations located in their control points, or repeated with a defined density along their paths.

Polygons may be represented with the same representational forms as points and line segments, repeated throughout the area with a defined density and an optional randomisation parameter. Alternatively, a single object may be displayed at the polygon's centre.

It is our intention to extend the representational forms for points, lines, and polygons with two-dimensional representations:

- Two-dimensional labels and symbols drawn on the terrain surface, or in any location within the 3D scene (with auto-orientation mechanisms)

- Lines drawn on the terrain surface
- Polygons drawn on the terrain surface, with or without boundary lines, transparent or filled with a defined colour, pattern, or a repeated symbol

Volumetric representational forms – such as solid objects or transparent isosurfaces – also need to be introduced.

5.1.7 Visual efficiency

The viewer employs a set of mechanisms designed to enhance the visual efficiency of presented data. A cartographic approach is used, with the aim of maximizing readability and efficiency of information transfer, not to provide a high level of photo-realism.

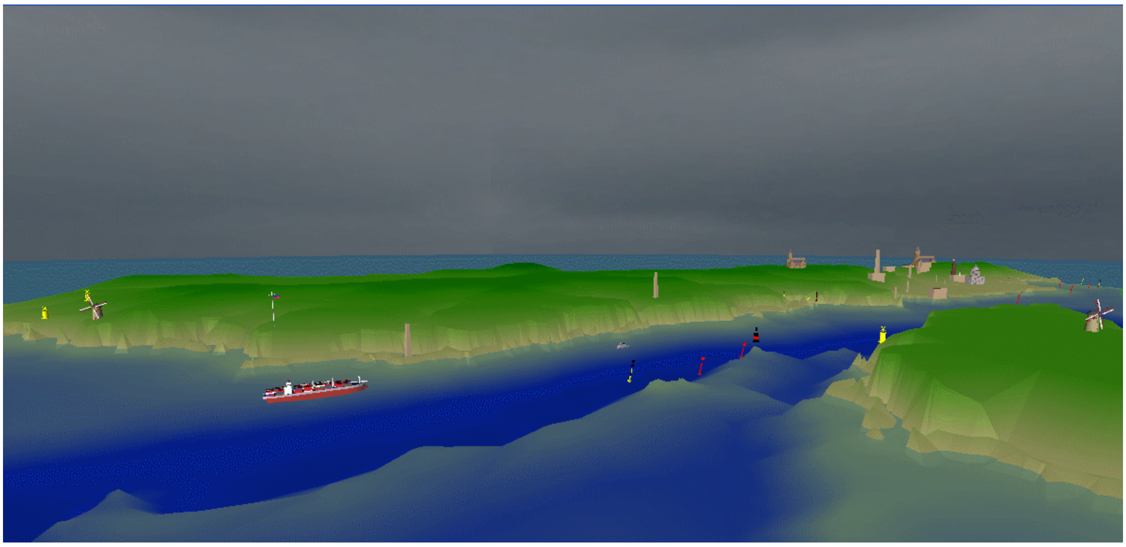

Figure 5.5. Weather conditions simulation: heavy clouds with a reduced light level

The most important mechanisms are listed below:

- Dynamic control of object representation – or visual optimisation, depending on the distance from the observer's eye (camera). The dynamically optimised aspects of representations include:

- Size
- Aggregation
- Visibility

- Size balancing – to assure the optimal visibility of objects of different sizes
- Automatic orientation – of selected representation forms, such as 3D labels – to assure that they can be easily read
- Vertical exaggeration of terrain models
- Weather conditions – simulated in a basic range of aspects, including:
    - Cloud types
    - Light levels (with day and night modes)
    - Fog

All the above mechanisms are configurable, to allow adjustment to the requirements of a specific application, or to the user's preference.

5.1.8 User and map orientation

The viewer is equipped with different tools to improve the user's understanding of the displayed area, and of his orientation within it, and therefore increase the efficiency of map navigation. The tools include the elements presented in Figure 5.1 – the compass, the mini map and the OSD communication – as well as the mechanism for automatic orientation (rotation) of the map.

Compass

The compass is displayed in the right-top corner of the screen, to indicate the geographic North within the model, and the azimuth, that is the angle between the North and: a) current map orientation (general view mode); or b) direction of view (object-related view mode).

Mini Map

The mini map, which presents a two-dimensional outline of the displayed area, is (optionally) displayed in the bottom-right corner. Depending on the application the mini map may be used to display the location of the user, the shape of the current viewport, or the positions of the map elements (both static landmarks and moving objects).

Automatic orientation

When the map viewer is used in an object-related view mode, for example during an animation, or in real-time navigation, the map may be automatically oriented (rotated) to match the direction of the object's movement, or of the geographic orientation of the device providing the positioning information (for example a GPS receiver).

On-Screen Display (OSD)

OSD messages, provided as a means to facilitate map-driven user interaction and communication, may be used to provide textual navigation guidance, when appropriate.

5.1.9 Animation

The 3DMV allows time-referenced animation of map data, i.e. the presentation of data objects that are moving within the map area, in reference to real-world time. It may be used to present objects moving in real-time – with data updates coming from an external device or system, or for display of a pre-recorded or simulated situation.

During replay, or in a simulation, the user has control over several animation settings, such as the time speed and direction, including full control of the animation timeline, using the dedicated toolset (Figure 5.6).

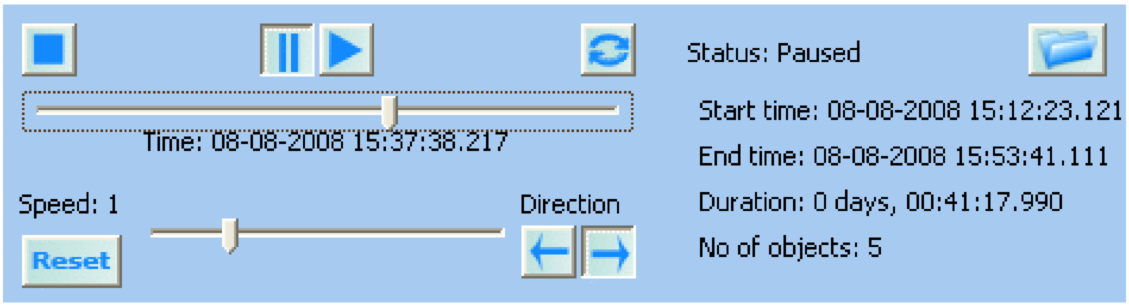

Figure 5.6. The animation toolset

Animation is time-referenced, which means that for a real-time animation, as well as during a replay, a precise time in which the situation is taking/has taken place is adequately indicated. In all of the possible modes, including the ones discussed above, as well as the simulation, the speed of animation is constant, and kept in reference to the real-time speed (although it may be set to a multiplication of the real-speed in the simulation and replay modes).

The animation mechanism includes the predictive display of discretely-updated temporal objects. These additional algorithms were implemented to allow a smooth animation, with a sufficiently high drawing frequency – even if the frequency of data updates does not match the animation frame-rate.

5.1.10 Remaining cartographic aspects

Several other, remaining, cartographic aspects of the 3D Map Viewer are discussed below.

Geographic coordinates

Geographic coordinates are displayed in a dedicated panel for the position of the user within the map, and for the mouse cursor position. Coordinate grids are not available at present.

Scale information

Map scale information is not displayed in a traditional form. Instead, the information about the distance of the camera (observer's viewpoint) to the rotation centre within the map is displayed in a dedicated panel.

Map projections

The 3D Map Viewer is built to support different map projections, which may be added to the system when necessary, in the form of source-code extensions.

In its basic form, at present, the 3DMV supports the Gnomonic and Mercator map projections.

5.2 Technical description

This section describes the most important technical aspects of the 3D Map Viewer's development, design and use.

5.2.1 Development

<u>History</u>

The development of the system was based on the experience gathered during the development of the Marine GIS prototype, created by the author of this thesis and the other members of the research team during their work at the Hong Kong Polytechnic University between the years 2000 and 2004 (Gold et al., 2004). The Marine GIS, developed then, was a practical implementation of the original idea by Gold and Condal (1995), extended by Gold (1999). It was our early attempt to answer the question 'what a marine – as opposed to a terrestrial – GIS is?'

The current version, based on redefined research goals and requirements, has been developed from the ground-up by the author at the University of Glamorgan in South Wales, between the year 2005 and 2009. Experiences gathered during the development and testing of the original Marine GIS (including feedback from the users) were extensively used in the process of designing and developing the 3D Map Viewer, and its example applications.

<u>Approach</u>

The system has been created using a modular, object-oriented approach, based on the UML design and best industry practices, to assure a high quality, flexibility and extendibility, and low maintenance costs.

It has been developed entirely in-house, including the graphical engine. The consequences of the decision regarding the custom implementation path included a longer development time and a higher cost. These were offset by the resulting achievement of a far greater flexibility, and control over the application in terms of its functionality, as well as by the freedom of an unrestricted future use of its source code.

The development was performed in stages: the Graphical Engine (GE) has been developed and tested first, prior to the implementation of the remaining elements. This was followed by the development of the core mapping platform that used the GE for visualization and management of 3D scenes. The platform was then used as the basis for the creation of our example applications, described in Chapter 6. The stages were iteratively repeated, when necessary, to assure that the input from the testing, and the development experience gained in the subsequent phases, are incorporated in the GE and the 3DMV.

Environment

The 3D Map Viewer, and all its example applications, have been developed using the CodeGear's Turbo Delphi Explorer for Win32, and the OpenGL low-level graphics library. The Turbo Explorer is a free version of the popular Delphi Integrated Development Environment (IDE)[8], which is based on the Object Pascal programming language.

[8] Unfortunately, the free version of Delphi IDE – the CodeGear's Turbo Delphi Explorer – has been quietly discontinued around August 2009, and is no longer available

The choice of the programming language and of the IDE was dictated by several factors:

- Compatibility with software developed in different research projects within the team
- The ease to use the software in teaching of students with no background in programming
- The development efficiency and productivity
- Full support for object-oriented design
- Free licence with no restrictions for use

Regardless of our generally good experiences with the development environment chosen, it is our conviction that successful mapping products can be produced using any suitable language and technology, including, but not restricted to, C++, C# (.Net) and Java. Any low-level 3D graphics library may be used to support drawing, including OpenGL and Direct3D (DirectX).

A combination of OpenGL and Java (or C++, if an ease of porting between different platforms is not paramount) seems a particularly good choice for operating systems other than Microsoft Windows.

5.2.2 System architecture

The system architecture has been designed to assure good quality – including robustness, extendibility and flexibility, as well as the ease of testing, modification and maintenance. The architecture is presented in Figure 5.7.

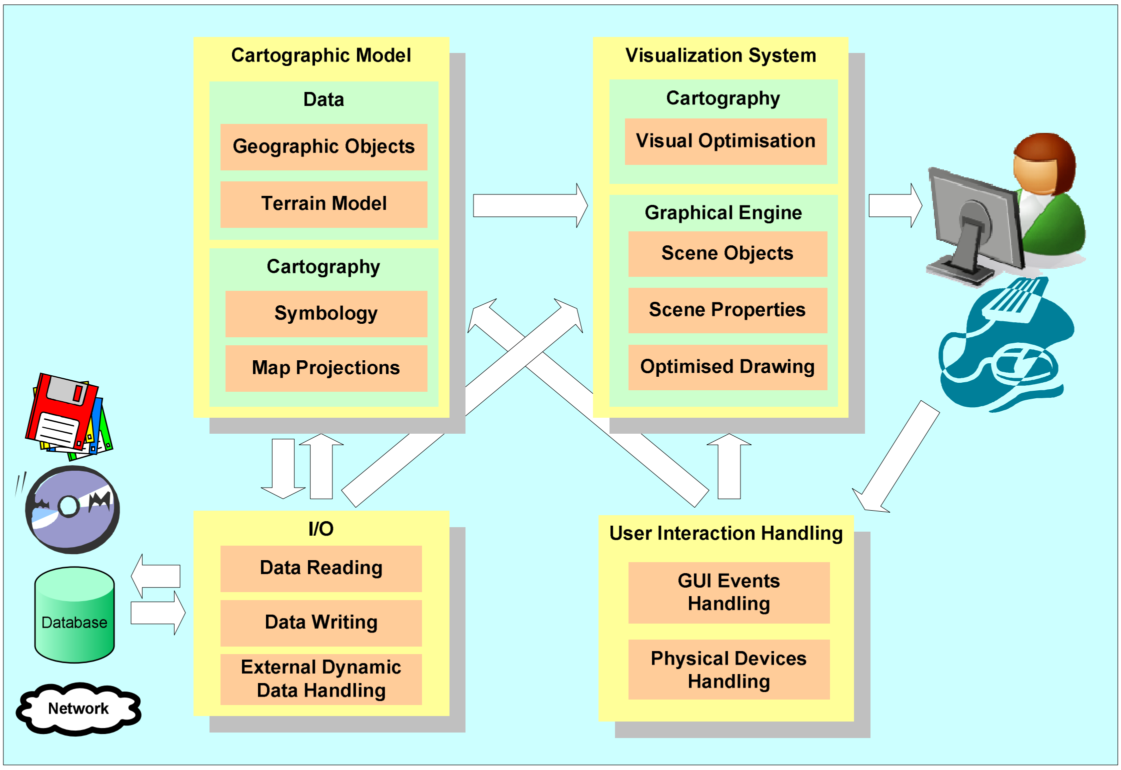

Figure 5.7. The software architecture of the 3D Map Viewer

The main modules are described below:

- Input/output – the module contains source code elements (classes) responsible for the reading and writing of different formats of data, from various sources. A limited number of formats are supported (see Section 5.2.5), but the module includes well-specified interfaces, that allow easy addition of new formats through object-oriented inheritance mechanisms.

  The module also contains mechanisms for exchange of data with, and the real-time visualization of the data from, external systems. These are described in more detain in Section 5.2.6.

  The data read by the I/O module are transferred to the Carto-graphic Model (CM). The data received from the external systems may be transferred to the CM, or sent directly to the Visualization System for drawing, depending on the need

- The CM is responsible for the internal handling of the map data model. It also includes dynamic symbology mechanisms, and the support for multiple map projections. As in the case of the data formats, the number of supported map projections is limited (see Section 5.1.10), but the module includes object-oriented interfaces to allow introduction of new projections
- The Visualization System is the module responsible for 3D maps' drawing. The data from the Cartographic Model are handled there in an internal cache format, optimised for the efficiency and speed of drawing. It is based on the Graphical Engine – a 3D visualization library, discussed in detail in Section 5.2.3 – extended with the cartographic mechanisms responsible for the maximisation of the visual efficiency of the presented maps (Section 5.1.7)
- "User Interaction Handling" is the module that handles events generated by different forms of user activity. These include interaction with the Graphical User Interface (GUI) through its various controls, as well as manipulation with physical devices, such as a mouse or specialized 3D controllers (see Section 5.1.1). Support for new types of devices may be added, using object-oriented interfaces and the inheritance mechanism.

  Interaction and manipulation events are translated into actions within the system, and, depending on their type, sent to the Cartographic Model (data editing), or to the Visualization System (navigation, changes of view or of the properties of the scene).

5.2.3 Graphical Engine

The Graphical Engine (GE) is the visual heart of the 3D Map Viewer. It is a high-level graphic library, with an extensive object-oriented programming interface (API), modelled on the example of game engines. It is, however, specialized, and optimised for use in geovisualization. The core of the GE is the scene-graph – a hierarchical data structure that describes the scene, and handles all of its properties and graphical objects. The Graphical Engine uses the Open Graphics Library (OpenGL) for low-level operations.

The main responsibilities of the GE are discussed below:

- Handling and rendering of 3D scenes – i.e. of the hierarchies of graphical and auxiliary objects that create them, with their various properties – using a tree called the scene-graph
- Drawing objects in various forms of representation, including three-dimensional objects, as well as two-dimensional symbols, text and numbers within the 3D scene, and on screen
- Handling of lights, materials and cameras
- Selection and querying mechanisms
- Basic manipulation handling
- Reading of different input formats of graphical objects
- Support for textures and procedural shading
- Special effects such as fog and variable light levels
- Refresh-rate measurement and levelling
- Reporting of the performance control information
- Drawing optimisation

- Animation

The first edition of the Graphical Engine had been created as a separate package, prior to the development of the 3D Map Viewer. It is a complete and successful product on its own, and has been used in several applications within our research team, including:

- The visualization platform, for research on the Voronoi diagram-based data structure that stores the primal and dual subdivisions of a three-dimensional manifold (Ledoux and Gold, 2007)
- A 3D CAD-like modelling platform, for construction of 2.5D surfaces with bridges and holes, based on Euler operators (Tse and Gold, 2002)
- Display of 3D terrain models (Dakowicz and Gold, 2003), and visualization of runoff flow modelling (Gold and Dakowicz, 2005)
- The experimental visualization platform, for development of atomic operators that simultaneously construct the primal and the dual structures (Voronoi diagram and Delaunay tetrahedralization) in modelling of 3D objects (Boguslawski and Gold, 2008)

The early Graphical Engine has been tested and enhanced in an iterative process during the development of the above applications. It, however, turned to be limited and hence required extensive redesign and extension for the 3D Map Viewer. This resulted in largely-modified and enhanced version 2.0 being developed in parallel with the 3DMV.

5.2.4 Terrain modelling

Terrain models in the 3DMV are represented as shaded, or textured, Triangle Irregular Networks (TINs). The Quad-Edge data structure (Guibas and Stolfi, 1985) is used, to simultaneously construct and store a model as both the Delaunay triangulation, and its dual Voronoi diagram.

Models may be built from sets of points, or reconstructed from 2D contours. The area-stealing interpolation by Sibson (1980) and several methods from work by Dakowicz and Gold (2003) – such as Voronoi crust and skeleton-based slope reconstruction and smoothing – are used in the process. These original methods were extended with algorithms such as dynamic sampling, to allow fully automatic creation of 3D terrain models from 2D map data. The terrain models are not limited to representations of rectangular areas, and may have polygonal boundaries.

The terrain models are shaded with procedural textures, using the OpenGL Shading Language (GLSL). Image textures, such as scanned maps or orthophotographs, may alternatively be used.

5.2.5 Data sources and formats

The 3D Map Viewer supports several data formats from different sources. The number of formats available at present is limited, but the system has been designed to allow easy introduction of additional formats in future.

The types of supported data include:

- Digital maps – complete models, described in standard formats. At present, the International Hydrographic Office's S-57 format of Electronic Navigational Charts (IHO, 2000), based on the ISO/IEC 8211 encapsulation standard, is the only format supported

- Customized models – custom or edited maps, stored in the dedicated format of the 3D Map Viewer
- Custom terrain models – stored as sets of points with altitudes
- Custom terrain textures – scanned maps, orthophotographs or other images in popular image formats
- Custom objects – single geographical objects, including polygons, text, numbers, as well as 3D objects in the 3D Studio Max and OBJ formats
- Custom object lists – sets of pre-defined custom objects, stored in a 3DMV-specific format
- Temporal data – real-time, simulated or pre-recorded data of moving objects, used for animation – defined in a 3DMV format
- External data – discussed in the next section

It is our intention to extend this list in the near future, to support more digital map formats, as well as to enable loading of single or multiple layers of data in popular formats, such as the ESRI shape files.

5.2.6 Flexibility

The system's flexibility allows modifying and adjusting the 3D Map Viewer for different areas of applications, and for various classes of problems, through configuration and extension mechanisms. These include:

- Map editing functionalities (described in Section 5.1.4)
- Configuration of application behaviour and presentation
- Capability to work with both real-time and simulated data

- Design of the source code to allow extensions
- Support for integration with external data structures
- Mechanisms for connectivity with external systems (see Listener-Connector Architecture below)

Listener-Connector Architecture

The Listener-Connector Architecture (LCA) was implemented to allow integration and display of external data in the viewer. In this approach, connectors, which are extensions of the mapping platform, communicate with external systems, and transfer information between them and the platform (Figure 5.8). Their other task is to translate different formats of data used by external systems into the format understandable to the 3DMV listener.

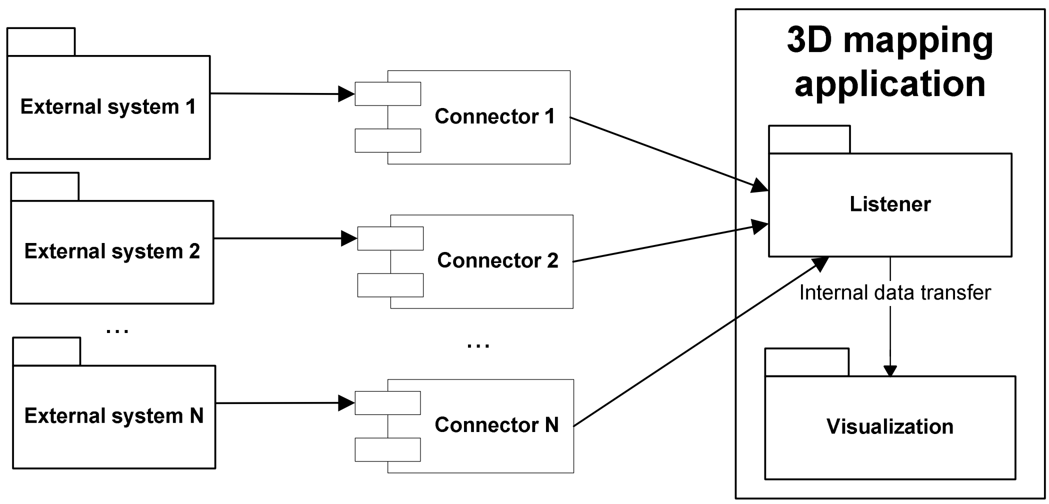

Figure 5.8. Listener-Connector Architecture for integration with external data sources

Example use of this architecture is discussed in Chapter 6 (Section 6.1.6).

5.2.7 System requirements

In order to run the 3D Map Viewer, its minimal requirements regarding the software and hardware platforms, need to be satisfied.

Software

The 3D Map Viewer requires an MS Windows operating system. It has been successfully tested on the following versions of the Microsoft OS: Windows 2000, Windows XP, and Windows Vista.

It is also required that appropriate drivers will be installed for the computer's hardware, particularly for the graphics card.

Hardware

The 3DMV has moderate hardware requirements, which may however differ, depending on the details of a particular application. It generally may be run even on relatively slow computers, providing these are equipped with dedicated graphic cards. The performance (drawing quality, refresh-rate (FPS) and responsiveness) will be better for faster machines, and may get unacceptably slow if a computer does not meet the following minimum specifications:

- Processor: Intel Pentium 4 1.6Ghz, or a comparable CPU from AMD; all later single- and multi-core CPUs may be used
- Graphics card: graphics accelerator with a dedicated memory of at least 64MB; full support for OpenGL 1.4 (including GLSL), preferably OpenGL 2.0 or higher; this excludes integrated graphics controllers such as the Graphics Media Accelerator (GMA) family from Intel

- Human-computer interaction device: a keyboard, and a standard mouse with two buttons and a wheel
- HDD: At least 200MB of free hard-drive space
- Display: colour display with 800x600 minimum resolution (1024x768 or higher recommended; standard of widescreen)

5.3 Chapter summary

In this chapter our custom mapping platform – the 3D Map Viewer (3DMV) – has been introduced and described in detail. The functional description – covering diverse aspects of the system functionality, such as the user interface, navigation and manipulation, data analysis capabilities, map editing, map-driven interaction, available data representations, visual efficiency optimisation mechanisms, orientation, animation, and other cartographic aspects – was given first. It was followed by the technical description, which focused on the development process and system architecture, as well as on other aspects of system implementation, including the graphical environment, terrain modelling mechanisms, supported data sources and formats, solutions extending the system's flexibility and the system requirements.

Most of the topics discussed in this chapter correspond to the list of the technical and cartographic aspects of 3D maps discussed in Chapter 4.

Chapter 6

Applications

Three-dimensional maps have a wide range of potential applications, both on land and at, or under, sea. In some of these areas interactive 3D visualizations have been used before. Other applications, when three-dimensional maps are concerned, are still largely uncharted territories. As application areas, problems, and related requirements vary, so do the 3D maps suitable to address them. For some problem categories simple, fully-symbolic maps will be a sufficiently good answer. Other applications may require more advanced visualizations, which range somewhere between cartographic 3D maps and geovisualization systems.

This chapter outlines some of the possible applications of three-dimensional maps, demonstrating, in a practical way, that even a relatively simple system, such as the 3D Map Viewer, may complement, or offer advances over, existing methods. Discussed are both the applications for which the 3D Map Viewer is ready, and has already been used, as well as the potential ones, that may require additional development and tailoring work. In each of the discussed examples the status of the 3DMV's readiness is provided, together with a discussion of the potentially required extensions. The list is not, nor is meant to be, complete – the readers are welcome to, and it is hoped that they will, consider their own application ideas.

The applications presented in this chapter have been divided into three main categories, discussed in the dedicated sections below. This classification was based primarily on the distinction between marine and land applications. In addition, maritime safety is discussed as a separate category, due to its high importance, the number of applications that fall within it, and the fact that it is the area in which the most of the 3D Map Viewer research, extension and testing has been undertaken in the course of our project. These are also the reasons why it is discussed first, followed by the discussion of the other marine and land application examples.

6.1 Maritime safety

This section discusses maritime safety and its areas where innovative products, such as the 3D Map Viewer, can offer improvements – as well as technical extensions of the 3D Map Viewer, required for its application to the outlined problems.

Problem significance and the state-of-the-art of maritime safety are discussed first, followed by the discussion of marine accident causes and areas where 3D maps can offer a positive difference. Technical requirements for application of the 3D Map Viewer in maritime safety are discussed next, followed by the detailed discussions of several specific applications.

6.1.1 Problem significance

The importance of sea transportation, and of its important aspect, which is maritime safety, is not fully appreciated by most members of society. This is mostly true, except for people who are directly involved or personally interested in the subject. Despite this, the marine industry has a huge impact on the world economy and on our everyday lives.

Let us give a few examples of why maritime safety is so important. The vast majority of world cargo is carried by sea in huge container-carriers. This includes food, cloths, electronics, cars, parts, production materials and components, as well as natural resources, such as minerals, oil and gas. Moreover, the EU strategy for transport development includes plans to significantly increase sea-shipping, by establishing Motorways of the Sea (European Commission, 2006). Cargo ships carrying hazardous loads pose serious threats to the environment, as well as to the lives and health of the people and animals inhabiting coastal zones. The disaster and damage caused in the event of a major sea collision can be difficult and costly to deal with (Ward et al., 1999; Talley, 2003). This also has a huge impact on the world economy, where the cost of shipping, clearly related to the level of safety, is a big factor. Furthermore, the increasing number of pleasure boats and the growing density of sea traffic increase the risk of collisions between pleasure boats and cargo ships, where consequences are often fatal.

6.1.2 State of the art

Given the problem importance, it is far from surprising that many companies and organizations strive to provide solutions to improve maritime safety. The range of innovation is wide and includes engineering efforts such as ships hull design improvements and the use of new materials, chart production, data distribution, real-time traffic monitoring – Vessel Traffic Services (VTS), search and rescue (SAR), communication protocols and on-board monitoring equipment (Automatic Identification System, radars). Other maritime safety improvement efforts concern production of specialized software for training and navigation. The integrated maritime safety system, its different elements and main components, are described by Kopacz et al. (2001).

Because shipping is probably the most international and dangerous of all industries, it was necessary to establish an international marine authority. The International Maritime Organization (IMO) was established in Geneva in 1948. The International Maritime Organization's main task has been to develop and maintain a comprehensive regulatory framework for shipping and its remit today includes safety, environmental concerns, legal matters, technical co-operation, maritime security and the efficiency of shipping. Other organizations interested in the safety of navigation are the International Hydrographic Organization (IHO) and many state (national, EU) regulators.

Two developments introduced by the IMO and IHO have had the greatest impact in the last decade. Electronic Chart Display and Information System (ECDIS) and Automatic Identification System

(AIS) are the leading technologies designed to minimize human error in maritime safety.

<u>ECDIS</u>

Electronic Chart Display and Information System is an on-board navigation aid standard, meant for supporting navigation and decision-making by navigators. ECDIS systems comprise of the official nautical chart data, stored in the International Hydrographic Organization’s Electronic Navigational Chart (ENC) format (IHO, 2000), real-time 2D display associated with the current position of a vessel obtained from GPS, and a simple user interface to perform basic navigational tasks.

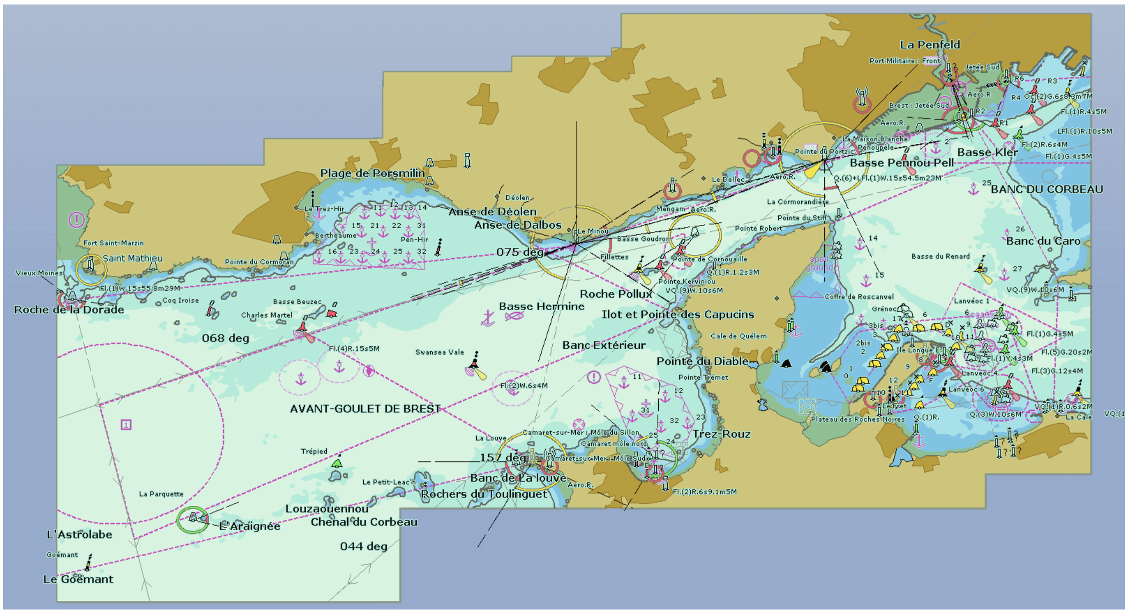

Figure 6.1. ENC chart FR501130 (Brest area, France) displayed in an ECDIS

A system has to meet special requirements concerning function and reliability, published by the IMO, to be approved as an ECDIS. This allows the use of an ECDIS as an equivalent of the official paper nautical charts, as required by Regulation V, Chapter 20 of the 1974

International Convention for the Safety of Life at Sea – SOLAS (IMO, 2004).

ECDIS drastically improved navigation safety, and minimized the number of accidents among vessels that must be equipped with it by law (Ward et al., 1999). Figure 6.1 presents an ENC chart displayed in a standard ECDIS.

AIS

The Automatic Identification System (AIS) was designed to monitor and identify vessels at sea. It is used by ships and Vessel Traffic Services (VTS). It is particularly useful to identify vessels out of sight (in radar blind arcs or shadows, at distance) or in bad visibility. AIS uses a VHF transponder (Figure 6.2) to exchange a vessel's ID, position, course, speed and other data with other ships and VTS stations in range. The system is integrated with a GPS receiver and other on-board navigational equipment like a gyro compass, speed meter or rate of turn (ROT) indicator.

Sea regulations require AIS to be fitted aboard all ships of 300 gross tonnage and upwards engaged on international voyages, cargo ships of 500 gross tonnage and upwards not engaged on international voyages, and all passenger ships irrespective of size.

Figure 6.2. SAAB R4 AIS Transponder System

Due to the limitations of radio characteristics, and because not all vessels are equipped with AIS, the system is meant to be used primarily to look out for, and to determine the risk of, collisions, in accordance with International Regulations for Preventing Collisions at Sea – COLREGS (IMO, 2003), rather than as an automated collision avoidance system.

6.1.3 How 3D maps can make a difference

Studies on marine accident classification show that human error is the most common cause of problems. According to Talley et al. (2006) it accounts for over 90% of all cases. In the light of the above, it seems reasonable to focus on the human element in pursuits to minimise the number and severity of accidents.

Navigators, who guide and directly control sea vessels, are clearly among the people whose mistakes can have the most negative consequences. To address that, over a decade ago, researchers proposed information management and decision support systems for use by navigators (Goulielmos and Tzannatos, 1997). Since that time, the sea authorities have introduced numerous standards and technologies that support navigation and communication, including ECDIS and AIS discussed above.

Despite the remarkable success of ECDIS and AIS systems, there still is room for improvement. Claramunt et al. (2007) argue that officers on the watch and monitoring authorities would benefit from development of advanced, cartography-based, decision-aid solutions. All of the state-of-the-art systems are based on 2D maps, and, as pointed out by Porathe, efficiency of their information transfer is limited (Porathe, 2006). ECDIS and other 2D map-based systems place a significant cognitive load on navigators, who are often working long shifts, and whose cognitive capabilities are compromised by high levels of tiredness. Porathe (2006) has proven that three-dimensional maps fare much better in this regard, leading to a better navigation precision, speed, and a dramatic decrease of the number of mistakes made.

Providing 3D navigational aid software on board marine vessels is, therefore, one of the potential measures that may be taken to tackle the maritime safety problems. Other points where improvements can be introduced include the use of 3D maps in vessel traffic monitoring to effectively communicate the situation, the integration with intelligent decision support systems that predict and communicate dangerous situations using 3D visualization, as well as improving the level of training for mariners and pleasure boats owners. All of the above examples of 3D map use are discussed further in this section, after the discussion of technical extensions to the 3D Map Viewer, which were necessary to allow its application to maritime safety.

On the other side of the process, 3D maps may be used to enhance the speed and improve the quality of bathymetric data collection and processing, leading to an increase in the efficiency of nautical chart production. However, hydrographic surveying is a broad application which does not relate mainly, or exclusively, to maritime safety, and therefore it is discussed among the other marine applications in Section 6.2.6.

6.1.4 Mapping platform extensions

In order to use the 3D Map Viewer in the marine safety applications listed above and described later in the section, the basic mapping platform had to be extended in several ways. This was done with help from selected members of staff of IRENav, the Research Institute of Ecole navale (French Naval Academy), who advised on the necessary changes and became early adopters of the system. This provided an opportunity for efficient real-world testing. The extensions introduced to the 3DMV are discussed below.

<u>Marine navigation symbols and representations</u>

One of the necessary extensions to the basic platform was the creation of an extensive library of symbols relevant to the marine environment, such as navigational signs and ship models. 3D models corresponding to S-57 navigational objects described by the International Hydrographic Organization's Transfer Standard for Digital Hydrographic Data – Special Publication No. 57 (IHO, 2000) – have been created and added to the standard symbol library.

Additionally, models of several ship and marine vessel categories have been also developed.

The process of symbol design and development was carried by two cadets of the French Naval Academy, working for their Final Scientific Project at the University of Glamorgan, under our supervision. Figure 6.3 presents some of the developed models, while the design and development process is described in detail in the cadets' report (Busset and Fournier, 2008).

Figure 6.3. Navigational symbol (S-57) library

On the other end of the system, this was complemented with extensions to the ENC data reading mechanism, to enable efficient reading and handling of all S-57 objects. Although most navigational object types are represented in the standard way – using 3D models – some special categories, such as soundings or shipping lanes, needed to be drawn in a specific form on the water surface. For these special object forms new representations had to be implemented as extensions to the 3DMV's source code, using its object-oriented API.

Ship equipment connectivity and data integration

Another of the steps necessary for the use our platform in maritime safety was enabling the 3D Map Viewer to communicate with on-board ship equipment. The GPS receiver and the AIS transponder, providing real-time positioning information of the host ship and other surrounding vessels, respectively, was of particular importance.

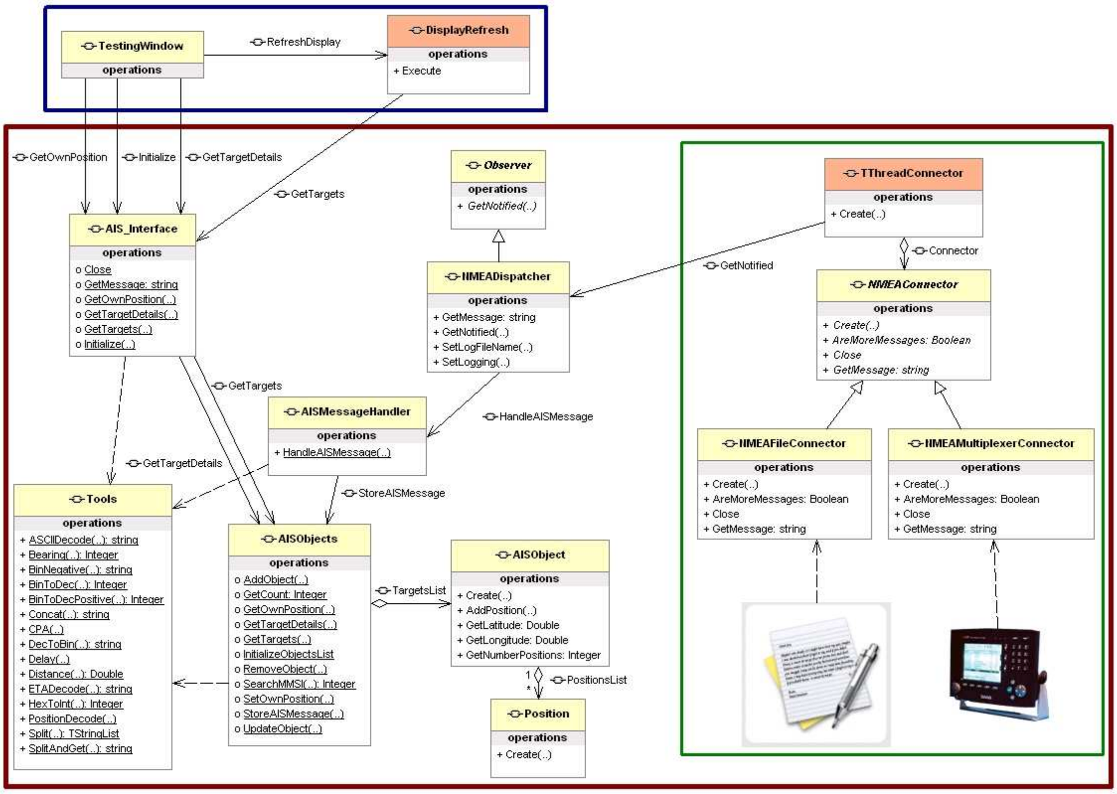

Figure 6.4. UML class diagram of the NMEA/AIS library (Stroh and Schuldt, 2006)

The integration was based on the National Marine Electronics Association's NMEA 0183 V3.01 standard communication protocol (NMEA, 2002), which is widely adopted and used in marine devices. A dedicated NMEA connectivity library was developed to our design by a second group of the French Naval Academy cadets, completing their Final Scientific Project under our supervision (Stroh and Schuldt, 2006). A Unified Modelling Language (UML) class diagram of the NMEA/AIS library is presented in Figure 6.4.

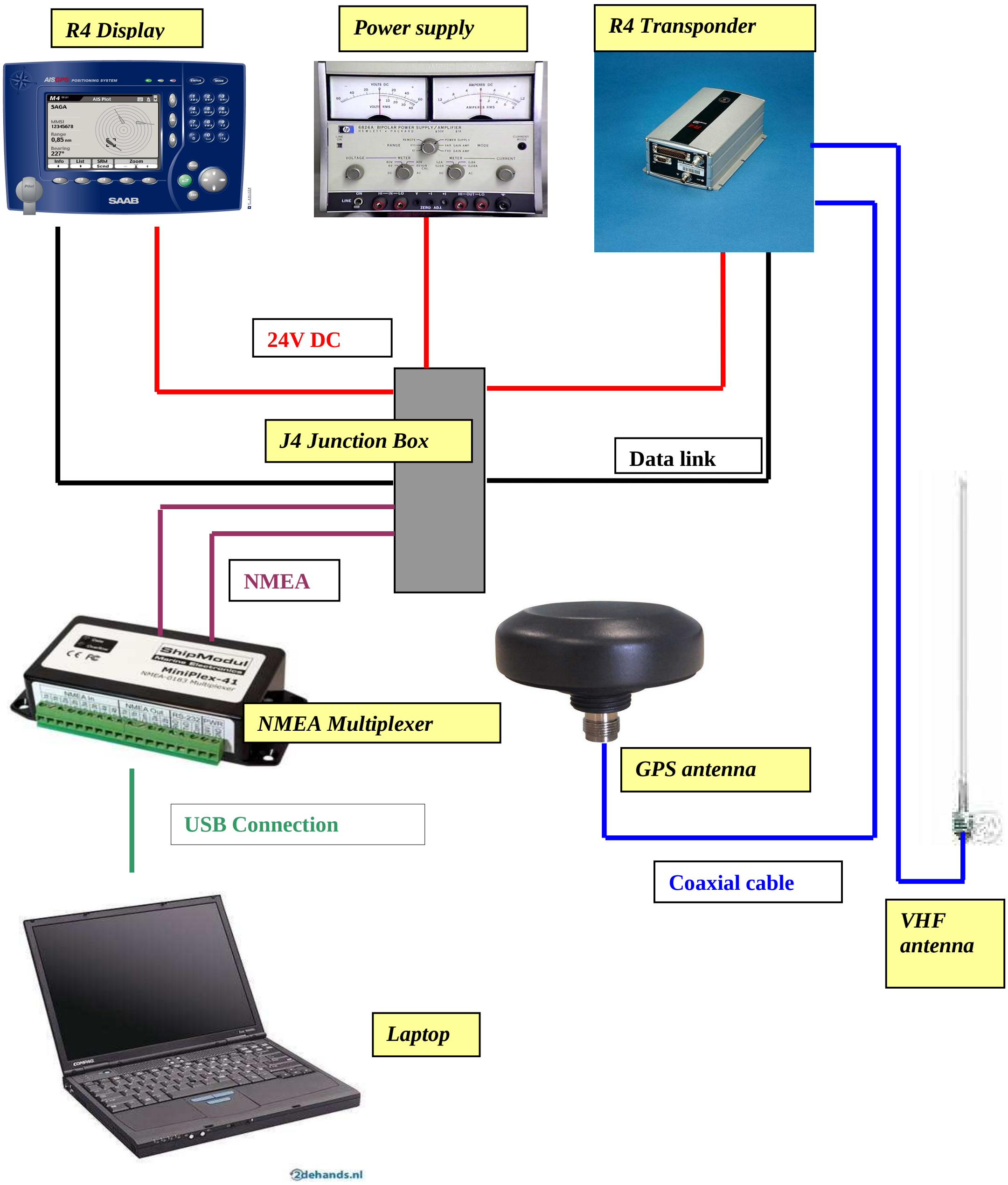

Figure 6.5. AIS transponder – physical connection scheme (Stroh and Schuldt, 2006)

An NMEA multiplexer was used for physical connection to the SAAB R4 AIS Transponder System, with built–in GPS (Figure 6.5). Handling of the communication with both the GPS and AIS receivers was fully implemented and tested. No other devices were integrated at present, although the open design of the NMEA library allows extending it for other devices – including radar, echo-sounder, gyro compass, turn indicator, speedometer and wind meter – at a later stage, if required.

Once the connectivity library was completed, the real-time data received from the AIS transponder had to be incorporated in the 3D Map Viewer's display. This had two separate aspects: 1) presentation of the ships tracked with AIS in the 3D scene, as well as 2) indication of the surrounding objects in the 2D Mini Map (including speed vectors, and colour-coding).

The NMEA/AIS integration task also included the use of additional ship information transmitted over AIS – including the rate of turn (ROT), course over ground (COG), acceleration, and others – as described by Redoutey et al. (2008) – for improvement of the built-in 3DMV location prediction algorithm, used in animation of discretely-updated objects.

<u>Collision prediction and alerting</u>

Another important aspect was the implementation of collision prediction and avoidance mechanisms. A unique approach has been used to enhance the efficiency of predictions, and extend the mechanisms to include detection of groundings, based on ship attributes such as draught and dynamically changing tidal conditions.

The algorithms are based on a dedicated kinetic Voronoi diagram (VD) data structure (Quad-Edge), and the 'moving points' algorithm (Guibas et al., 1991) described in Section 4.2.5. The Voronoi diagram includes: points generated along the coastlines, navigational objects classified as dangers, moving ships, and the 'grounding safety outline'. The outline is composed of the points created at the intersection of the horizontal plane with the terrain model, at a depth specified by the selected ship's draught and the current tide level. The VD points are grouped into different categories which may be included in, or optionally excluded from, the computation, as needed. The coastline and the grounding points are dynamically recalculated upon changes of the tide level, or of the ship's properties.

The application of the Voronoi diagram allows simple and efficient filtering of potential dangers, and focusing on the most likely collision points, based on the Quad-Edge's topology, where all points at the closest distance to any other point are stored as neighbours, and directly linked to each other. Other algorithms, such as ray-tracing, are then used more efficiently to monitor potential dangers. The approach is described in detail in (Goralski and Gold, 2007b).

Predicted collisions are rated depending on their likelihood, the expected severity (collision with a ship, obstacle, or grounding), and the time remaining to their occurrence. Potential collisions above a certain threshold level are communicated to the navigator, using pop-up messages and emphasis of the situation in the display – including the use of colour coding, modification of sizes, as well as automatic changes of the viewed area (viewpoint shift) – applied to a gradually growing extent, until acknowledged by the navigator.

The VD-based approach is complemented with a more traditional computation of the closest point of approach (CPA), and the time to the closest point of approach (TCPA). The first of the two parameters, which are typically available in navigational software, describes the anticipated point at which the distance between two objects, of which at least one is in motion, will be minimal. In navigation the CPA is provided as the minimal distance value, which, combined with the time to CPA, is used to evaluate the risk of collision.

Other navigational functionalities

Other navigational features of the extended 3DMV-based system include:

- New navigation view modes – automatic views (perspectives) useful for navigation and monitoring – that complement the generic view-setting capabilities of the 3D Map Viewer. The new views include :
  - A freely set view linked to a moving ship – a user can select the target object, and set the distance and the perspective (horizontal and vertical angle) of the camera in relation to it
  - A view from on board a ship
- Navigation information display – with marine units and naming, including heading, course and bearing
- Integration of navigation-related measurement results in object query results – with automatic updates on the move
- Waypoint settings, and on-cruise guidance
- Safety contour display

- Automatic recording and replay of cruise information

User interface extensions

All functionalities related to marine navigation had to be integrated within the 3DMV's Graphical User Interface. New toolsets containing dedicated controls and information panels have been added to enable control of navigational functions, configuration of the on-board device connectivity, and display of the related information.

6.1.5 Maritime navigation

The idea of 3D navigational charts was presented by Ford (2002), with the conclusion that 3D visualization of chart data had the potential to be an information decision support tool for reducing vessel navigational risks. This was later proven in a practical experiment by Porathe (2006), who demonstrated that using three-dimensional charts leads to more efficient navigation in terms of speed, precision, and the number of mistakes made by a navigator.

Despite the evidence of the potential of three-dimensional charts, there are few leisure market products that offer 3D views, and no professional ones, as of today. The absence of professional 3D navigational aids may be explained by the conservatism of the official regulations that do not allow such presentations to be used in ECDIS. Such restrictions do not apply to the leisure market, but despite this 3D in leisure products leaves much room for improvement in almost all aspects, including the efficiency of visualization, manipulation and control. This relative weakness of the 3D charting modes is caused by the fact that they are offered as an addition to the primary navigational mode, which is still 2D. Not only is the 3D often buried in complicated menu structures, and restricted to a limited selection of regions where additional bathymetric data are available – but its functionality, interactivity and ergonomics are seriously impaired by chart plotting equipment designed for traditional, two-dimensional charts. Among other things such traditional chart plotters lack human interaction controls necessary for the efficient use of 3D. No map with 3D as the primary presentation mode, designed from ground-up to maximize the potential of 3D cartography, has been commercially released as of yet.

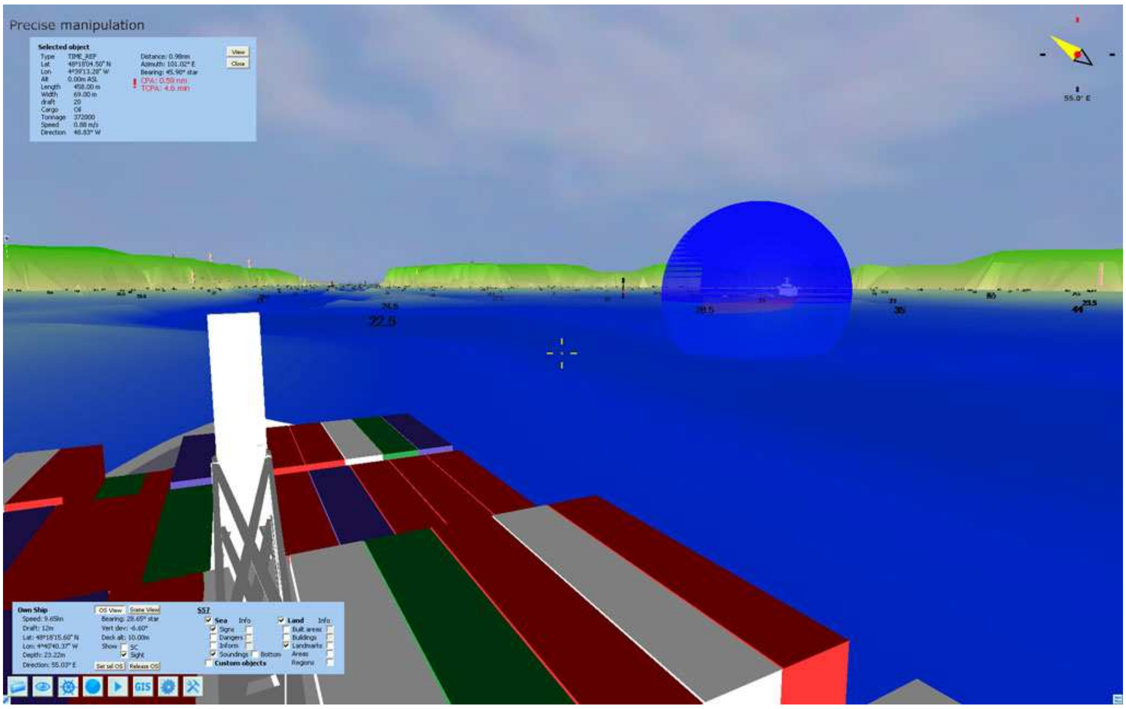

Figure 6.6. The 3D Map Viewer-based aid to navigation

The 3D Map Viewer has some potential to fill in this gap, by both providing an example of a fully 3D-oriented functional and technical map design, as well as by demonstrating the potential of 3D visualization for the professional navigation market.

In order to accomplish the second objective, a 3D prototype Electronic Chart Display Information System (ECDIS) has been created, based on the 3D Map Viewer, and on the extensions discussed in the previous sections (Figure 6.6). This task was attempted, and the prototype was presented at SeaTechWeek, a marine conference series and a trade show, in September 2008 in Brest, France – a photo from the official inauguration of the 3D ECDIS is shown in Figure 6.7.

Figure 6.7. Inauguration of the 3D ECDIS at SeaTechWeek 2008

Both the efficiency of 3D visualization, and a slightly provocative name of the product (as mentioned before, the ECDIS regulations prohibit the use of 3D) contributed to the ignition of a vivid discussion between the authors, navigators and representatives of international regulatory bodies present at our presentation, including a member of the IHO ECDIS standards committee. The discussion led to a conclusion that – at least in some aspects and situations – properly designed 3D charts may offer advantages over their 2D counterparts, and that 3D should be carefully considered by the ECDIS committee for the upcoming revision of the navigational chart presentation standards.

6.1.6 Traffic monitoring

Marine traffic monitoring is another means used to improve the safety of marine navigation, especially in congested waters, such as popular fairways and ports – and is another application in which three-dimensional charts may offer benefits over their currently used 2D counterparts.

Maritime traffic is monitored by the dedicated coastal stations called Vessel Traffic Services (VTS), which are run by harbour or port authorities. A VTS monitors the real-time movement of ships in a given area using radar and AIS, and may be thought of as a marine equivalent to solutions used in air traffic control (Claramunt et al., 2007). Vessels are displayed to VTS officers using digital maps, which are similar to navigational charts used on board ships.

As in the case of marine navigation, the efficiency of information transfer is important for the overall effectiveness of traffic monitoring. And as in the case of on-board navigational aids, this can be improved by the use of 3D. Three-dimensional charts could not only improve the speed and ease of understanding of presented situations, but would enable the monitoring staff to assess and analyse situations in ways that 2D maps do not allow – for example to monitor the views from the perspectives of ships which are heading into a difficult situation. Three-dimensional visualization is also an excellent tool for analysis of pre-recorded situations, to allow deeper understanding of what has happened, and what could be done to avoid dangerous scenarios in the future.

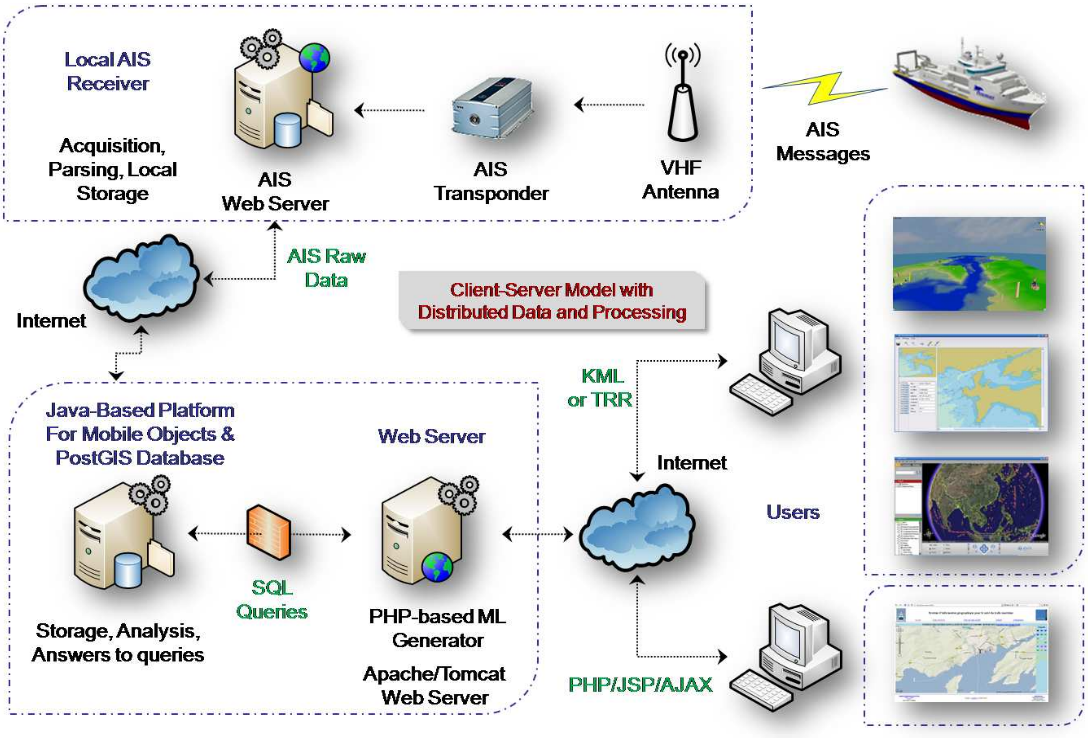

Figure 6.8. The IRENav's monitoring platform architecture (Ray and Goralski, 2009)

The advantages of 3D maps for maritime traffic monitoring have been recognized by Dr Cyril Ray of the French Navy Research Institute (IRENav), who decided to integrate 3D visualization in a prototype traffic monitoring system (Ray and Goralski, 2009), using the Listener-Connector Architecture discussed in Chapter 5 (Section 5.2.6). The 3D Map Viewer has been used to complement other forms of information presentation available in the system, which include a web application and Google Earth, as shown in Figure 6.8.

6.1.7 Decision support

Another way of improving the safety of marine navigation is through the development and use of intelligent systems that support mariners in their cognition and decision-making processes. Such decision support systems – designed to autonomously analyse the situation surrounding a navigating vessel, or an area monitored by a VTS station – may not only increase the efficiency of prediction of potentially dangerous situations, but also support a human in taking the right actions which maximise the chance of successful collision avoidance.

An example of such a system is the CogTRANS, developed by Le Pors et al. (2009) from the French Navy Research Institute (IRENav) to simulate naturalistic decision making of marine navigators in the context of collision avoidance. The system may be used to predict potentially dangerous situations, and to help in their avoidance, by advising the VTS staff and ship navigators about the probability of different actions of ships that are involved in a situation. A VTS team may be alerted as a potentially dangerous scenario develops, and take an appropriate action, for example by contacting the involved parties, in order to prevent it. A navigator may be advised about the probability that a ship approaching on a collision course may ignore the right of way regulations, or behave in an unexpected way.

CogTRANS integrates a cognitive model, presented in Figure 6.9, with a multi-agent system "with the purpose of producing realistic simulated decision via the notion of role. This model uses fuzzy representations for the identification of different elements of a situation, and pattern matching between the current situation and a set of typical known situations" (Le Pors et al., 2009, p1).

The system discussed above is a good example of a mechanism with the potential to support map intelligence, as discussed in Chapter 4. Likewise, 3D maps seem a suitable interface for presenting the information from decision support systems to users. Ideally, systems like the above should be integrated within charts used in navigation and monitoring.

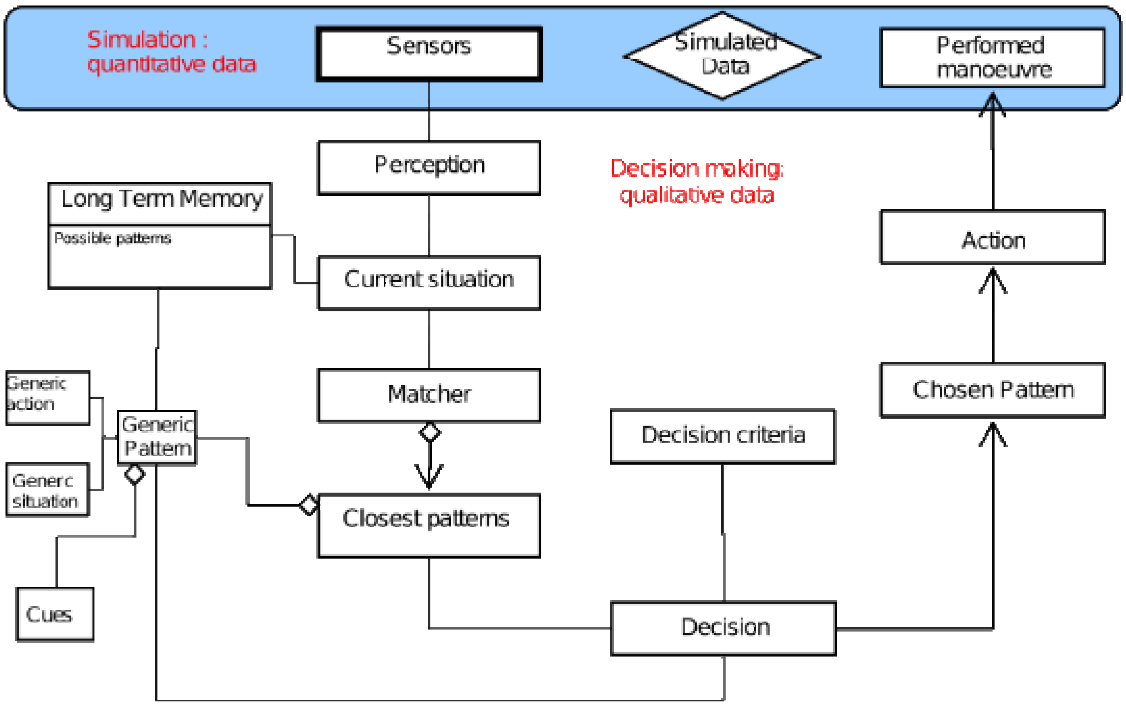

Figure 6.9. CogTRANS – cognitive role in collision avoidance (Le Pors, 2009)

This mutually beneficial relationship, which has a potential to enhance and strengthen both the 3D maps and the decision support systems, has been acknowledged by marine researchers. This knowledge was the basis for the future work plans of the discussed system's authors, who intend to use the 3D Map Viewer to present the information from CogTRANS in a visually efficient manner.

6.1.8 Sailing directions

Maritime charts do not necessarily offer every type of information that is required by a navigator. That is why sailing directions, or pilot books, are usually offered for coastal navigation. Such publications contain written information about landmarks, tides, currents, dangers and other local aspects of a given harbour, which complement standard charts and increase the safety of navigation. The textual form of information transfer used in sailing directions predates the introduction of marine charts, and has been criticised for its low efficiency. That is why pilot books have been often enriched with drawings and, more recently, photographs.

Lately, new forms of sailing directions have been discussed. Grabowski and Wallace (1993) proposed an expert system for maritime pilots. Gold et al. (2004) proposed 3D marine charts as a modern replacement for pilot books, arguing that their superior visual efficiency – which is not compromised even in bad weather and poor visibility conditions – constitutes a significant improvement over the *status quo*. Millan extended that list with GIS and digital video in his technical report on digital sailing directions (Millan, 2007). One of disadvantages of 3D charts, quoted in his report, was that they do not provide orderly sequenced explanations about the currently displayed features – in other words do not guide the navigator in the way traditional sailing directions do.

To overcome this, without loosing the great visual efficiency of 3D charts, a basic mapping platform should be extended to include:

- A knowledge database, with information entries (text and multimedia) linked to chart objects and areas
- Efficient forms of knowledge presentation in charts
- Conditional mechanisms for triggering the information display
- A steering module, responsible for ongoing monitoring of the current map position and interpretation of the knowledge data-base content

Sailing directions are used in maritime pilotage by all types of navigators who visit the described waters. The notion of pilotage is also linked with professional pilots, who guide ships through dangerous or congested waters. Pilots are probably most often seen guiding ships into and out of marine ports.

6.1.9 Professional pilotage

Maritime pilots are well trained navigation specialists, with expert local knowledge, who board a ship and offer their advice in safely navigating it through difficult areas and congested fairways, with use of their knowledge of tides, currents, depths, swells and shoals and other aspects that are not typically available on the navigational charts.

To increase the safety, most of major marine ports require that large ships are guided inwards and outwards by pilots, licensed by a local port authority. The training process of a port pilot is demanding, costly and time consuming, which, combined with the growth of maritime traffic, often leads to the shortage of skills – and long delays for ships waiting outside the ports. The introduction of mandatory pilotage regulations, although beneficial to maritime safety, may also be too costly for smaller harbours.

3D charts could help in two ways. For smaller or less congested harbours automatic guidance software, certified by the local port authority, could be offered to vessels that visit the port on a regular basis. Such software, as a minimum, would not need any extensions beyond those discussed in Section 6.1.8, except for the precise reconstruction of a port area, and any specific requirements that a port authority may have.

Another approach would be a remote pilotage platform, where a professional pilot would guide ships remotely, using a 3D map to examine (in real-time) the view from a given ship's viewpoint, advising through a radio communication channel. In a more complex scenario a client version of the software may be installed on board participating ships, and live pilot's guidance may be displayed within their 3D maps, as in the automatic pilotage example. The difference would be that the knowledge database would be replaced, or complemented, with the live guidance of a professional pilot.

Remote pilotage would save time required to transport pilots on board ships and back, and, if required, would even allow monitoring and guiding several ships by one pilot simultaneously. The second, more advanced, version of the remote pilotage software would require an additional module for secure communication between the distant software instances. The availability of a data transfer link between the onshore pilotage station and remotely piloted ships would be a prerequisite.

6.1.10 Navigation training

Real-time guidance and navigation decision support are not the only, and not necessarily the most efficient, ways of reducing the number of mistakes made by navigators. Another, and at least equally important approach, is to provide an appropriate level of suitable training to ship navigators.

The trouble with this approach is that real-life training on board ships is expensive, and there is limited access to the training fleet. Moreover, real training is restricted with regard to the sea conditions and areas where it may be conducted due to a number of constraints, including safety, distance, time, cost and politics. To overcome these problems, and to increase the number of navigational training hours and its overall diversity, special training simulators have been extensively used (Magee, 1997; van Maanen and du Marchie Sarvaas, 2009). Such simulators offer a panoramic, highly-realistic and immersive three-dimensional view, accompanied by a reconstructed navigational bridge. Although they are not meant to, and will never fully substitute for the real training, these can complement it, and improve its efficiency. They allow near-realistic training in a number of simulated real-world locations, in any sea and weather conditions.

Modern simulation systems allow installation of multiple navigation stations which may work in a network to facilitate complex training scenarios for multiple participants. Each station may vary in complexity, from a simple bridge of a small-boat, powered by several

PC computers, with screens that display the view, controls and simulated navigational equipment, to large rooms surrounded by screens, and fitted with a fully-fledged ship bridge in the middle. The cost varies as well, from just around a hundred thousand up to several million US dollars (as of 2009). However useful and realistic they may be, the cost and complexity of such simulation systems restricts their use to large maritime navigation schools and professional training centres. Smaller schools are unlikely to be able to afford these, and they are without a doubt out of range of a typical leisure boat user.

Recently a cheaper alternative appeared with the introduction of highly realistic, gaming technology-based PC training simulators, capable of executing predefined single- or multiple-participant training scenarios, which can be overseen and modified in real-time by an instructor (van Maanen and du Marchie Sarvaas, 2009). The scenarios include training of navigation in different types of water, practice of port approaches, manoeuvres, racing, and so on. The software is significantly cheaper than typical simulation stations. This makes it a more accessible alternative to fully-fledged marine simulators, for all sizes of training institutions.

However, such simulation software does not necessarily require an excessively high level of realism. A simplified version could be produced based on a symbolic 3D mapping platform, such as the 3D Map Viewer. This could further reduce the price and hardware requirements, extending the range of potential benefactors to include different categories of navigators, such as professional ship captains and pilots, as well as leisure boat owners.

In order to make such an application possible, the basic mapping platform would need to be extended to include networking functionalities, as well as a control software module, designed for defining, running, monitoring, and coordinating the execution of the training scenarios.

6.2 Other marine applications

Three dimensional maps may be used in a variety of marine purposes, including numerous applications which are not related directly to maritime safety.

6.2.1 Regatta visualization

Visualization of sailboat racing is an example of the use of maritime safety-related concepts and technologies for a different, less serious, purpose. The idea is an extension of the traffic monitoring systems, to enable efficient visualization of a regatta for audiences watching the competitions from the shore. The purpose is to make racing more engaging to observers, as the lack of visibility from the ground – due to the distance to the coast – is a general drawback which limits the appeal of sailing races (Claramunt et al., 2007).

To tackle that problem in the case of the international regatta organized by Ecole navale, the French Navy Research Institute (IRENav) developed a prototype system, composed of a wireless network and an experimental adaptive GIS. Ship locations during the race are acquired through a VHF-based real-time infrastructure, and displayed on different devices, using different types of presentation (Claramunt et al., 2007).

The current prototype is mostly 2D based, but the use of the maritime safety-extended version of the 3D Map Viewer for presentation in 3D is being evaluated by IRENav. The ability to interact with the displayed scene and watch the visualized race from any perspective should improve the race's appeal to the public.

In the simplest version no further extensions would be needed, although more elaborate systems, that would incorporate the specifics of a sailboat regatta into the basic traffic monitoring, are also planned. Such extended versions, designed to improve the visualization realism, would present boats' spatial orientation – including the vertical waving, as well as longitudinal and crosswise heel – together with realistic reproduction of the boats' sails. This would require extension of the boats' equipment with, and transmission of data from, a gyroscope and a set of sensors mounted in the rig, along with mechanisms for the incorporation of such information in the real-time visualization.

6.2.2 Offshore planning and simulation

Planning and simulation software is often used in the offshore industry. Such software enables engineers to evaluate the efficiency and cost of multiple possible scenarios in construction projects, and allows the selection of the optimal approach, prior to the actual development. With the use of simulation this is done in a cheap and timely manner, without committing scarce resources to the implementation of any of the sub-optimal project variants. Potential savings of cost, time and materials may be significant.

The projects which may benefit from the use of simulation at the planning stage include underwater construction, such as laying pipelines and cables. Furthermore, simulation may be used to maximise efficiency of tidal power renewable energy sources, such as underwater electricity generators, by determining the optimal location and orientation of the turbines.

While precise low-level planning typically involves application of elaborate physics simulation engines, as well as requiring significant processing power and complex programming of the potential scenarios, a lot of initial higher-level planning may be done using simpler and more interactive real-time visualization systems.

Such systems may be based on interactive three-dimensional mapping platforms, which should be fully suitable as interfaces for easy construction and quick evaluation of potential scenarios, based on visual assessment and supporting algorithms. Application-specific user interface extensions would be necessary, together with the implementation of supporting logic, and integration with the external data models – such as the models of tides and currents in the tidal power planning example.

6.2.3 Fishery

Seabed mapping, combined with 3D visualization, has been used in fishery for several years. A number of commercial products exist on the market, including packages that integrate seabed scanning devices (side-scan sonars) with visualization software and chart plotters, as well as some built around centralized databases, where registered users can share their custom-collected bathymetric data.

The idea behind such systems is simple – the knowledge of seabed bathymetry combined with that of fish behaviour and preferences may be used to determine the most efficient fishing locations. In addition, side-scan sonars may be able to detect fish shoals, and these may be integrated in real-time within the 3D display.

Simple mapping platforms, such as the 3D Map Viewer, are sufficient for this application. To maximize the efficiency of fish location prediction, and to support fishermen in chart analysis, additional automated logic algorithms may be implemented.

6.2.4 Underwater navigation

Application of 3D maps to underwater navigation may be seen as a special case of the navigation aid software discussed in Section 6.1.5 – with the exception that it is specifically concerned with the guidance of submersed vehicles. The topic, however, is only partially related to maritime safety, as apart from manned vehicles, such as military submarines, it also includes unmanned remotely operated vehicles (ROVs) used in the offshore industry (Figure 6.10).

Regarding the first category, navigational charts are as important as in surface navigation, although standard charting systems need to be adjusted to the specifics of subsurface pilotage. The unique requirements of underwater navigation are considered in the work of Clarke (1999), who discusses ECDIS for submarines. However, perhaps even more surprisingly than for standard navigation – given the three-dimensional nature of underwater motion – 3D charts are not typically used. While in surface navigation this may be explained by the fact that vessels are navigating on an approximately flat plane, defined by the surface of the water, the use of 2D underwater involves much more serious drawbacks than the lack of efficiency and cognitive load associated with the use of standard 2D charts in surface navigation. Underwater, the two-dimensional charts are completely incapable of presenting, and therefore fully omit, an important aspect of navigation, which is the vertical motion.

Figure 6.10. Seaeye's Falcon ROV

For ROVs, three-dimensional visualization may offer a reliable interface for precise navigation of vehicles, and for manipulation of their instruments, as an alternative to exclusive reliance on cameras, which are not efficient in low-visibility conditions typical to deep or silted waters.

The use of 3D mapping platforms in underwater navigation requires serious consideration of the application specifics and requirements, and the subsequent implementation of the relevant functionalities. Examples of these may be collision prediction and avoidance, as well as route planning in 3D, for submarine navigation, and suitably-precise representation of vehicles and their instruments, for remote control of ROVs.

In certain conditions 2.5D representations of the terrain surface – typically seen in 3D maps – may be insufficient, as these do not allow for modelling of caves and overhangs. If these are of interest in a particular application, the terrain data structures and display algorithms have to be modified accordingly.

6.2.5 Marine GIS

In the last two decades many researchers from GIS interested in marine applications have been trying to describe and provide a prototype of a suitable GIS for marine purposes – a Marine GIS (Li and Saxena, 1993; Wright and Goodchild, 1997). The need for marine-specific GIS stems from the fundamental differences between the terrestrial and marine realms – the multiple dimensions and dynamism, as well as the uneven distribution of data that characterizes the second – that traditional two-dimensional and static land-based systems are unable to handle.

Depending on the interests and needs, different possible solutions have been described, varying from the traditional terrestrial 2D GIS extended for marine use (Su, 1999), to electronic charting and navigational aid applications, such as ECDIS – proposed by maritime safety experts, to new real-3D specialized temporal systems for oceanography. Marine GIS systems are a combination of underlying data structures and algorithms, with data visualization and user interfaces. To address the marine specifics, the data structures need to be kinetic and multidimensional – as for example is the volumetric data structure proposed by Ledoux and Gold (2004) for oceanographic analysis – and their content needs to be presented in 3D.

Three-dimensional maps are well suited as user-interfaces for Marine GIS (as well as for other types of 3D GIS). Sophisticated geovisualization systems are used for this purpose nowadays, but simpler cartographic 3D mapping platforms should not only be sufficient, but could offer better visual efficiency, combined with higher interactivity – which are both crucial for efficient data analysis.

In order to allow their use as a Marine GIS, or as general 3D GIS interfaces, the mapping platforms have to be integrated with the underlying GIS infrastructure (tools and data). That means extensions on both ends – the addition of dedicated toolsets on the user side (front-end), and the integration with GIS databases on the back-end.

6.2.6 Hydrographic survey

Another group of example applications of three-dimensional visualization in the marine sector is concerned with hydrographic surveying, where 3D may be employed for the collection, processing and management of bathymetric data. The potential and existing applications are based on 3D data presentation and analysis capabilities, and as such may be seen as relevant to the broader realm of geovisualization rather than to cartographic maps. However, as algorithms for the display of terrain – which includes also underwater bathymetry – are among the most important and advanced components of 3D mapping platforms, these should be sufficient for this new application area.

The range of applications is broad, and includes real-time display of data in the monitoring of underwater structures, in underwater search and exploration, as well as in multiple stages of the chart production process. In chart production 3D may be used for on-the-fly assessment of the quality and completeness of collected data, as well as for the analysis of the bathymetry, for the selection of important features that need to be included in charts. It is also a potentially powerful tool for quality control at later stages.

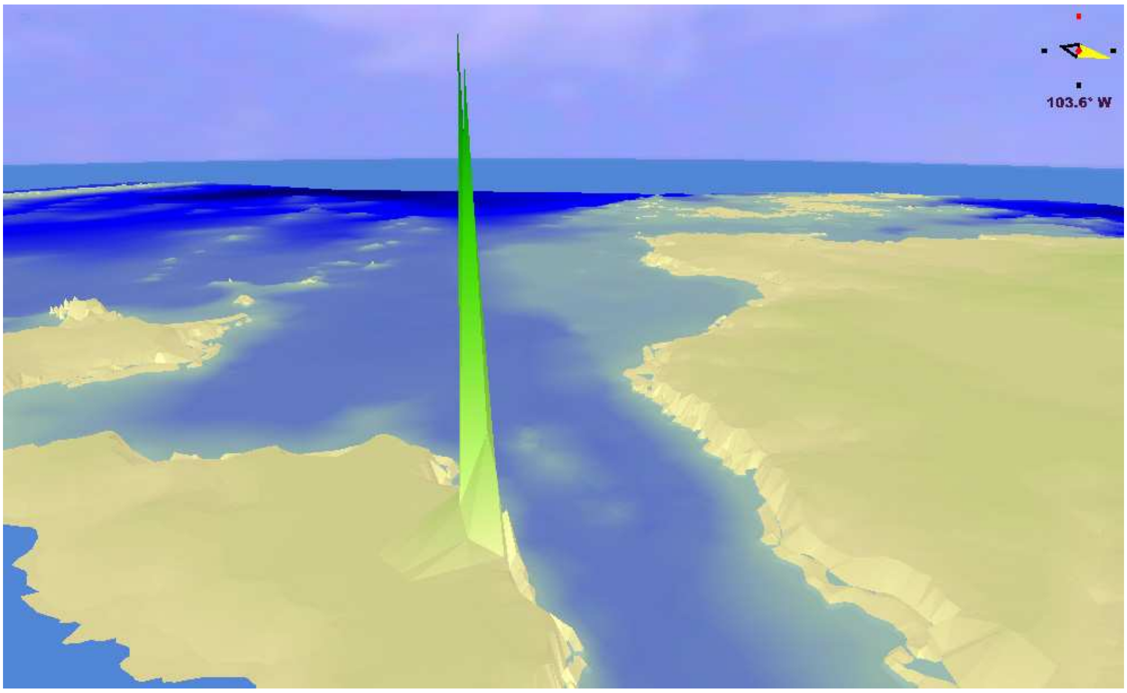

Figure 6.11. Quality problem in the official ENC chart number FR401580

Routine tests of our 3D marine navigation platform proved, accidentally, its usefulness in chart quality control. Figure 6.11 presents an official ENC chart number FR401580 produced by SHOM, the French marine charting agency, displayed in our viewer. Detailed evaluation of the underlying chart data showed that the tall steep spikes, seen at the front of the model, are caused by three accidental 1000m values mistakenly placed on a 60m contour line. Should a 3D visualization be used at the QA stage of this chart's production process, such an error – otherwise very difficult to spot – would easily get detected.

The accidental existence of erratic data values in the example discussed above is also a lesson for 3D mapping platform designers that – apart from the intended use in data quality control – they should include some algorithms for the filtering of such obvious quirks.

6.3 Land applications

Three-dimensional maps have no fewer applications on land than they have in the marine realm. A limited number of examples are discussed in this section. These were grouped in a few broad categories which are outlined below.

6.3.1 City modelling

City modelling, with its precise reconstruction of buildings – including shapes, roof tops, façade details, photographic textures and advanced LOD algorithms – as well as city infrastructure – streets, sidewalks, car parks, greenery, and so on is usually linked to geovisualization.

The reconstructed models may be used for preparation of presentations, in simulations, urban planning, or as virtual tours of the city (Ishida, 2002).

But there are a number of city modelling applications where no such details are necessary, and where photorealism of the models described above would be excessive and counter-productive. Sometimes the inclusion of purely indicative shapes of buildings – with only roughly correct shapes, sizes and proportions – on a topographic model of the terrain is sufficient. This is true, for example, when a city model is used as a 3D map, meant to efficiently present some kind of statistical information – which is not only geo-referenced – in which case a traditional 2D presentation would suffice – but also specific to the spatial organization of the city, or even to particular buildings.

An example may be noise maps, which are required by the European Union's Environmental Noise Directive (European Parliament and the Council of the EU, 2002) to be created, maintained and made available to the public for all cities populated by above 100,000 people, as well as for all major roads, railways and airports. Another example may be maps of electromagnetic signal distribution, used in the planning of mobile telecommunication infrastructure.

6.3.2 Environmental and urban planning

Different forms of 3D visualization have been used in environmental and urban planning for several years. The benefits are obvious – the simulation-based visualization enables examination of different possible planning scenarios, and provides an effective means for understanding and for visual assessment of the consequences of alternative decisions.

Moreover, such visually attractive 3D models are an effective way of communicating the planning decisions to the public, and were proven to increase the level of public participation in the planning processes – leading to a decrease of the number of protests and to the improvement of the social consensus in urban and environmental projects (Pereira et al., 2003).

Traditionally, planners use elaborate highly-photorealistic geovisualization software, where they can model the planning scenarios which then take hours, or even days, to generate. But apart from the late stages of the planning process, such high levels of photorealism are not necessary, and can be traded in for better responsiveness, real-time answers and higher interactivity offered by the 3D mapping platforms.

3D maps – which are not only visually efficient, but may also be designed to be simple to operate – could be used for higher level planning, also for those stakeholders that are not usually involved in the modelling activities, such as officers of local governments or even private citizens. To simplify the process the options could be limited to presentation and evaluation of selected pre-defined scenarios. The goal is a possible further increase of the engagement of different stakeholders.

Figure 6.12. Visual impact assessment of a wind turbine development project

In order to enable the use of simple mapping platforms for planning and visual impact assessment, user interface extensions enabling planning activities have to be provided. At a minimum, these should enable the addition of custom objects from a possibly-wide built-in object library, and adjustment of their different properties, such as sizes, locations, colours and orientation. Because maps are typically symbolic and do not necessarily display objects in their true sizes, platforms may need to be modified to enable the display of custom objects in their correct real-world sizes, and without the application of the cartographic optimisation mechanisms. Simulation of different weather conditions, as well as night and day-time, would also be of benefit.

Figure 6.12 presents a 3D Map Viewer-based simulation of a wind farm development project near Brest, France, displayed for visual impact assessment, from the perspective of the nearby village of Le Dellec.

6.3.3 Navigation

Three-dimensional maps may be used in land navigation – for tasks ranging from route planning, and simulation, to maintaining orientation during actual travel. As in the case of marine navigation, they offer some benefits over their traditional counterparts.

Examples include route planning for pedestrians or cyclists, especially in a hilly environment or in mountains. The use of 3D offers a much better understanding of the terrain topography, and hence allows more educated planning, based on a more comprehensive understanding of the route. Changes in the terrain altitude play a significant role in distance, travel time and expected fuel consumption calculations, especially in areas where altitudes are highly variable.

During the actual navigation, the presentation of the route in a 3D perspective, even in a symbolised simplified way – but preferably with the outlines of buildings and major landscape objects – enables quicker understanding of the user's location, as in heads-up display (Brenner and Elias, 2003). Such novel three-dimensional forms of presentation are, as of late, becoming more common in modern car navigation systems.

The use of standard 3D mapping platforms in car and pedestrian navigation requires their integration with the road network data and satellite positioning devices, as well as the implementation of the route planning algorithms and real-time guidance-related interface extensions.

6.3.4 Command and control

Another group of three-dimensional maps' applications is in electronic command and control systems. Such systems, known as C2, are designed for efficient monitoring of a situation and effective transfer of commands through the command chain. They are mainly used in military, but apply also to civilian situations such as emergency response and disaster management.

Three-dimensional maps may be used to present, and allow the analysis of, the life scene information in an efficient way. For example the scene of a natural disaster may be displayed as a 3D map in the control centre, presenting the real-life locations of all resources involved with the rescue action. Alternatively, the field of a military operation may be visualized, allowing the commanders real-time monitoring of all soldiers and equipment deployed. Such maps may not only present the positional information, but also contain data from sensors, such as seismographs, radars and personal equipment that monitors the life-functions of soldiers.

Another way in which 3D maps may be used is in the navigation of remotely controlled vehicles and robots (Nguyen et al., 2001) involved in search and rescue, disaster management, or military operations.

6.3.5 Aeronautics

Aeronautics is the discipline that popularized the use of 3D flight simulators, which are extensively used in the training of both military and civilian pilots. In their simplest form, such simulators are basically specialized 3D maps, extended to meet particular training requirements. But 3D maps have even more potential applications in the domain of aeronautics.

Figure 6.13. Mariner UAV by General Atomics Aeronautical Systems

For example, 3D airport models may be created and integrated with external sensors, to monitor greenery and airport infrastructure. The results may be displayed in real-time, or analysed against the historic airplane landing and take-off information, to assure the safety of the approach. Such models, even simplified non-photorealistic 3D maps, may be used as valuable additions to the air traffic monitoring and control systems, increasing the situational awareness of their operators.

Another application which is growing in importance concerns Unmanned Aerial Vehicles (UAVs). UAVs of different sizes and categories are now used almost exclusively by the military in restricted war and combat zones. At present they are not commonly used in civilian sector, mainly due to the lack of regulations governing their use in civilian air space and the lack of appropriate telecommunication systems. This is, however, expected to change, to allow the use of the UAVs exceptional potential in applications ranging from law enforcement and counter-terrorism, road monitoring and telecommunications, to forest fire-fighting, border surveillance, search and rescue, and agriculture (European Commission, 2008). Figure 6.13 presents a General Atomics Aeronautical Systems' Mariner UAV, used by the U.S. Coast Guard for marine and coastal surveillance.

3D maps may be used for efficient navigation of remotely controlled UAV systems, and hence may contribute to their efficient use in a wide spectrum of applications.

6.3.6 Visibility testing

Finally, 3D maps may be used in a whole range of applications which involve visibility testing. It may be argued that interactive 3D is an alternative for complex visibility-calculation algorithms, and that a 3D map may be used instead to allow real-time evaluation of the visibility of an area, an object, or a feature, from different positions.

Moreover, 3D maps may be used for planning of placement of objects that need to be located in a line-of-sight, such as certain elements of the telecommunication infrastructure. Examples include microwave towers, laser transmitters, or some types of beam antennas. The process may be based on an iterative selection of the next element's location, based on the perspective view from the previously placed object. An example of such an approach is presented in Figure 6.14, where a microwave tower is planted in the visibility range of a previously placed tower, using the perspective view related to its location.

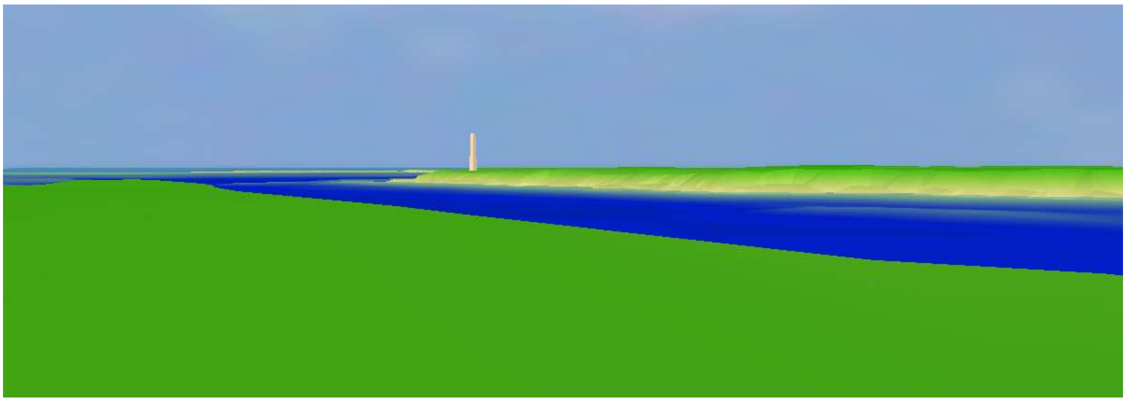

Figure 6.14. Selecting a location for a microwave tower

In order to enable such an application, a basic mapping platform has to enable the addition of custom objects, with correct representation of their sizes and proportions, and allow the interactive selection of the viewpoints related to their perspectives. For the best results, the Earth's curvature should be taken into account and represented within the visualized models.

6.4 Chapter summary

This chapter discussed a range of applications and domains in which the benefits of 3D maps have the potential to advance the state-of-the-art, by improving some aspects of the current situation, such as for example the safety of people or the operational efficiency.

A special focus is dedicated to maritime safety, which was initially chosen as the main area of interest for this research project. The significance of the problem is outlined, followed by a summary of the state-of-the-art. The advantages of 3D charts over their currently used 2D counterparts, and their potential of minimising the number and severity of sea accidents, are illustrated. This leads to the introduction of the marine-safety orientated edition of the original 3D Map Viewer, and a description of the mapping platform extensions introduced to enable the use of the 3DMV for the maritime safety purposes.

Subsequently a number of applications in which 3D maps offer advantages over the currently used systems were presented. These include the use of 3D charts in marine navigation and traffic monitoring, decision-making support for navigators and monitoring stations operators, the use of 3D mapping as the modern alternative to sailing directions, the application of 3D mapping-based platforms to professional pilotage as well as their use in navigation training.

Then we outlined several other marine-related applications including regatta visualization, offshore planning and simulation, fishery, underwater navigation, marine GIS and hydrographic survey, where 3D maps can be beneficially used, followed with a number of non-marine uses, such as city modelling, environmental planning, land and air navigation, command and control and visibility testing.

The applications presented in this chapter can be divided into a number of categories, based on different sets of criteria. Let us make two such distinctions: 1) based on the "readiness" of the 3D mapping technologies for the application; and 2) based on the "importance" of the improvements that they would bring about. Using the first distinction let us divide the applications into three categories: A) "application ready"; B) application that require mapping platform extensions and new mechanisms to be implemented prior to use; and C) applications that require significant developments in areas not directly related to 3D mapping. The importance of each application may be determined by answering the set of three questions: 1) does it save lives; 2) does it improve operational efficiency; and 3) does it engage users. The results of such categorization exercise are presented in the table below.

Application	*Saves lives*	*Improves efficiency*	*Engages users*	*Level of "readiness"*	*Comments**
Marine navigation	✓	✓		A	Leisure boating products with 3D capability available
Marine traffic monitoring	✓	✓		A	May require integration with existing systems
Marine decision support	✓	✓		B	Requires integration with external logic mechanisms
Sailing directions	✓	✓		B	Requires additional mechanisms
Professional pilotage	✓	✓		B	Requires additional mechanisms
Navigation training	✓	✓		B	Requires additional mechanisms
Regatta visualization		✓ (for planning and refereeing)	✓	A/B	May require additional mechanisms
Offshore simulation and planning		✓		A/B/C	Requires additional mechanisms – scope depends on the application

Fishery		✓		A	Some products exist on the market
Underwater navigation	✓ (for manned craft)	✓		B	Requires additional mechanisms
Marine/3D GIS		✓		C	Requires developments in 3D data structures and algorithms, 3D maps act as the interface
Hydrographic survey		✓		A	Requires minor developments
City modelling		✓	✓	A	Some products available on the market
Environmental planning		✓	✓	A	Some products available on the market
Land navigation		✓	✓	A	Some products available on the market
Command & Control	depending on the application	✓		B/C	Requires additional mechanisms, scope depends on the application
Aeronautics		✓		B/C	Requires additional mechanisms, scope depends on the application
Visibility testing		✓		A	Requires minor developments, some products exist on the market

*For the details of the required additional developments for each of the applications please refer to the corresponding sections of this chapter.

Of course the list of applications presented here is not final, nor is it complete. Other applications that have not been discussed here – due to a lack of space or the limits of our awareness – may already exist, and new ones are sure to be discovered with the growing popularization of 3D mapping, and technological progress, in the future.

The importance of dedicated 3D cartographic research is a recurrent theme in this thesis. Let us state again that, regardless of their belonging into a specific category of readiness and importance, all of the applications discussed in this chapter would benefit from the research in, and developments of, the rules of 3D cartography.

Chapter 7

Conclusions

This chapter concludes this thesis with a short summary of what has been done, in the context of the research goals stated in the introduction, as well as with an outline of the original contribution to the body of knowledge, and a discussion of future work.

7.1 Summary

This work provides a broad summary of knowledge relating to the subject of three-dimensional interactive maps, including their different theoretical, functional, technological and practical aspects. In the process of its completion all of the research objectives stated in the introductory chapter were successfully fulfilled:

1. Definition of 3D cartography: the state-of-the-art of the 3D mapping and geovisualization has been analysed. The importance of 3D cartography, as well as its boundaries and interrelations with geovisualization, have been defined. Further research requirements have been identified and clearly stated

2. Definition of 3D maps: three-dimensional maps have been defined through a technological description, and through a unique proposed set of defining factors, which include: the use of 3D visualization, the employment of cartographic rules, high interactivity and intelligence
3. Core development and practical validation: a 3D mapping platform – the 3D Map Viewer – has been developed, enabling the validation of the discussed 3D cartographic principles, and of the proposed defining factors
4. 3D map functional description: practical knowledge and feedback from test users has been gathered, and combined with the practical know-how of mapping platform development, in order to discuss functional aspects and recommendations that maximize usability of 3D mapping products
5. Application development: a specialized 3D marine navigation application, based on the developed platform, has been developed and validated
6. Practical demonstration: the developed platform has been used to demonstrate the possibility of successful development of 3D maps, without the need to wait for further technological or scientific progress
7. Identification of applications: the usability of 3D maps in different application areas has been further demonstrated by the identification and discussion of a wide range of potential applications
8. Guide book: this thesis constitutes a comprehensive guidebook that covers various issues related to the theory, the develop-

ment process, the functionality and practical use of three-dimensional interactive maps

7.2 Contribution

This thesis is a summary of an original research work, which is unique in several regards. Firstly, it is a unique and original synthesis of the subjects related to 3D cartography and practical 3D mapping, which is based on an analysis of a broad range of theoretical and practical resources from traditional and modern cartography, as well as from the related disciplines such as geovisualization. Secondly, the discipline of 3D cartography is defined and discussed, with a focus on its distinguishing aspects, as well as on its interrelations and interdependencies with the broader field of geovisualization. Thirdly, three-dimensional maps are defined through both a technological description, and by the proposed unique set of defining factors – differentiators, which are: the use of 3D visualization; the use of cartographic rules for the presentation efficiency maximisation; high interactivity; and map intelligence – which are also thoroughly discussed. Fourthly, numerous theoretical and functional, as well as practical and technological aspects of 3D maps are described in depth. Fifthly, the theoretical assumptions and rules are tested in practice, and validated through the practical process of development of a 3D mapping platform. Sixthly, the developed mapping platform is used in real-life applications, to demonstrate that efficient and effective 3D maps may be developed today, without the need to wait for any further advances in computer technologies, or in data availability. Finally, a number of diverse applications of three-dimensional maps are presented, with a discussion of how and where they can be of benefit, as well as of the extensions of the basic mapping platform required for their implementation.

The research work outlined in this thesis contributes to the body of scientific knowledge in a number of aspects, on two levels: theoretical and practical. A summary of the respective contributions is presented below:

Theoretical work:

- Definition of the boundaries of traditional, digital and 3D cartography
- Definition of the boundaries and relationship of 3D cartography and geovisualization
- Definition of 3D maps through a set of 4 differentiating factors:
  - Use of 3D visualization
  - Use of cartographic rules for presentation efficiency
  - High interactivity
  - Intelligence
- Definition of map-driven interaction
- Description of interaction as an alternative to expensive computation-based data analysis algorithms
- New mechanisms for monitoring of spatial relationships between objects and for collision avoidance
  - Combination of VD and traditional techniques
- Application of Voronoi diagram for map generalization
- Description of the 'no-projection' approach to 3D maps

Practical work:

- Development of the 3D Map Viewer mapping platform
    - Enhancements and extensions of the Graphical Engine
    - Cartographic model and object handling mechanisms
    - Drawing optimisation
    - Time-referenced animation handling
    - Selection mechanisms
    - Handling of multiple views
    - Procedural shading of terrain
    - Numerous custom user interface solutions
    - Development of map-driven interaction mechanisms
    - Reading of ENC and other formats of data
    - Numerous cartographic efficiency mechanisms derived from the theoretical work
- Development and demonstration of the experimental 3D marine navigation aid (3D ECDIS)
    - Integration with AIS and GPS
    - Development of navigational objects library
    - Weather conditions simulation
    - Map intelligence for navigation decision support
    - User Interface enhancements
- Creation of a highly intuitive direct manipulation interface
    - Based on a new combined metaphor

    - Merging the usual 3 separate view modes into a single continuous navigational space
    - Allowing for both quick and precise navigation
    - Application of a 3D controller for simultaneous control in 6 Degrees of Freedom
- Development of new visual efficiency optimisation mechanisms
    - Dynamic object size control
    - Object size balancing
    - Level of Detail mechanisms
    - Camera distance control
- Automatic generation of 3D terrain models from 2D vector data
- Introduction of GIS measurement capabilities based on object selection
- Development of the Listener-Connectors Architecture for real-time communication with external systems

All this constitutes what we believe is a unique and significant contribution – both theoretical and practical – to the disciplines of 3D cartography, and to related fields such as geovisualization, as well as to the process of 3D mapping popularization.

7.3 Future work

Proposed future work encompasses four distinguished themes: 1) improvements of the 3DMV mapping platform; 2) improvements of the existing applications of the 3DMV; 3) the development of new applications; and 4) the continued popularization of 3D mapping.

The first theme concerns functional and technical improvements of the 3D Map Viewer. These include: the introduction of new data formats, the broadening of the range of the representational forms available, the strengthening of the terrain handling mechanisms, the further development of the drawing optimisation mechanisms, as well as other improvements which will be identified as desirable in the future.

The second theme focuses on the improvements of the 3DMV applications implemented to date. This concerns the maritime safety extension of the 3D Map Viewer, and includes such aspects as the integration with tidal models and weather forecasts, as well as the conducting of practical sea trials.

The third theme is concerned with development and – where possible – practical deployment, of a broader range of applications of three-dimensional maps. This includes the practical development of the already-identified applications, as well as the identification, analysis and the potential subsequent implementation of the completely new application ideas.

The last theme relates to the intended continuation of our efforts in the popularization of 3D mapping, which may be done both through practical demonstration of the newly developed applications, as well as through publication of our research results in the future.

Appendix A

Introduction to 3D computer graphics

This appendix is provided as a simple introduction to selected aspects of 3D computer graphics, which have a relevance to the design of 3D maps. It is not meant to be a comprehensive study of this broad and complex subject. Readers interested in computer graphics may refer to textbooks such as by Watt (2000), Lengyel (2002) and Nielsen (2005).

A.1 Scene, object, model

3D visualization systems display situations composed of one or more 3D objects that are spatially organized in 3D space. Objects are lit by one or more *lights*, and the situation can be viewed from different perspectives or points of view. A *viewpoint* is determined by the position, the direction of view and other properties of the eye, called – by analogy to movie making – a *camera*. Such sets of objects, with defined lights and viewpoints are called *scenes*.

Scenes are created for the rendering process from internal data models. A *model* is a container for data, composed of objects with different properties defined within it. It is stored in computer memory, and maintained with the use of a dedicated, application-specific data structure. An example may be a cartographic model (CM) that describes all the geographical and other (tangible and non-tangible) objects and properties of a digital map.

During the rendering process of a digital map, or any other 3D visualization, the underlying model is translated into a 3D scene. The process involves assigning graphical representations to objects from the model, and the conversion of their positions, defined in the internal format, to the 3D coordinates used by the scene. For example the locations of the objects in a CM may be defined using geographic coordinates, which would need to be translated to a 3D coordinate system of the 3D scene to allow drawing.

The scene, as well as the model, also needs to be kept and managed in memory, and different data structures can be used for that. Watt (2000, p58) describes efficient scene management using hierarchical, or tree, data structures, such as BSP trees, to represent the scene down to object and sub-object level. He also explains the needs that led to the development of hierarchical data structures that represent collections of objects, in which the whole scene is considered an object itself.

A.2 Object representations

The representations of objects that comprise scenes are stored in computer memory. There are several types of object representations. The most common are the *polygon mesh* and the *implicit representa-*

tion (based on a mathematical description), or a combination of both (Watt, 2000, pp39-44).

A polygon mesh (Watt, 2000, p30) is a set of connected planar polygons or *faces*. These polygons are described simply by the sets of points that define them. This is the most popular form of representation because it is simple and allows an efficient rendering. The efficiency of polygon mesh drawing is due to the fact that current graphical systems are capable of using polygons as primitives – the smallest construction blocks used for drawing.

Some objects can be rendered by the graphical system based on their mathematical parameters (Watt, 2000, pp31-32), for example for a sphere defined by the implicit function

$x^2 + y^2 + z^2 = r^2$

it is enough to provide the value of its radius (plus other properties – such as the intended position in the scene, colour or material – as required), to enable drawing.

For more complex objects a combination of both representation types can be used, to describe their different parts.

Other examples of object representations used in 3D graphics are:

- *Bi-cubic parametric patches* – (Watt, 2000, p30, pp125-138), which is a form of representation similar to the polygonal mesh, except that it uses curved surfaces instead of polygons. Each patch is specified by a mathematical formula that determines its position and shape. This type of representation has great possibilities for interactive modelling, because each shape can be modified by changing its mathematical parameters. However the drawback is the high computational complexity of the rendering process. Paradoxically it is quicker to first convert objects stored as patches to their approximations using polygon meshes, and then draw the results, than to draw the patches directly

- *Constructive solid geometry (CSG)* – (Watt, 2000, p31, pp46-50) is an exact representation commonly used in interactive Computer Aided Design (CAD) systems, popular in industrial design. It is a constrained representation, and allows exclusive modelling of shapes which can be constructed from combinations of the primitive elements and shapes included in the system. The combinations of shapes include Boolean operations such as union, subtraction and intersection, performed on sets of objects. CSG is a volumetric representation which contrasts with other methods that represent shapes using surfaces
- *Spatial subdivision techniques* – (Watt, 2000, p31, pp51-53) are 3D equivalents of using raster approaches in 2D. Instead of dividing a 2D plane into a grid of pixels, 3D space is divided into elementary cubes, known as *voxels*. Each voxel is then labelled as empty or containing a part of an object. This approach is very memory expensive, especially when high resolution is required, but it is used in some applications, such as ray tracing. In this approach the whole three-dimensional space used by the object is represented, not just its surface

A.3 Coordinate systems

3D applications and their rendering processes have to work with several different coordinate systems. 1) The first one is used to describe the model, and is entirely in the domain of the application. The model, in which graphical objects are defined, can use any type of a coordinate system (Watt, 2000, p141). For example locations of objects in 3D Cartesian space can be described as points P_i (x, y, z), with coordinates that are relative to the centre of the model, P_c (0, 0, 0). But they can equally well be defined in a spherical coordinate system, for example as geographical locations. There are no restrictions regarding the types of coordinate system used to describe models, and the choice depends entirely on the need and the purpose of the application. For example in GIS, interactive maps, and other systems which are used for the display of geo-referenced data, Latitude and Longitude are often used to describe locations (this is also true for our 3D Map Viewer platform).

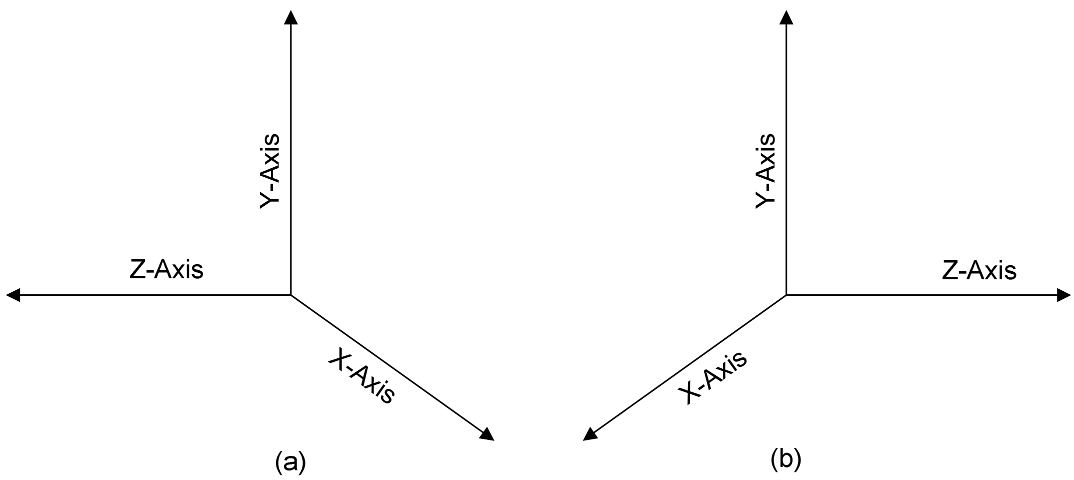

Figure A.1. Coordinate systems: (a) right-handed, (b) left-handed

2) For drawing the model has to be transformed into a 3D scene. This process involves several aspects. First the coordinates of the model are translated into the coordinate system used by the 3D scene. Then the graphical representations of objects are placed in their intended 3D scene locations and several additional properties are applied. The process of scene generation then continues with additional transformations, application of lights and setting of the viewpoint. This is described later – for the moment let us focus on coordinate systems.

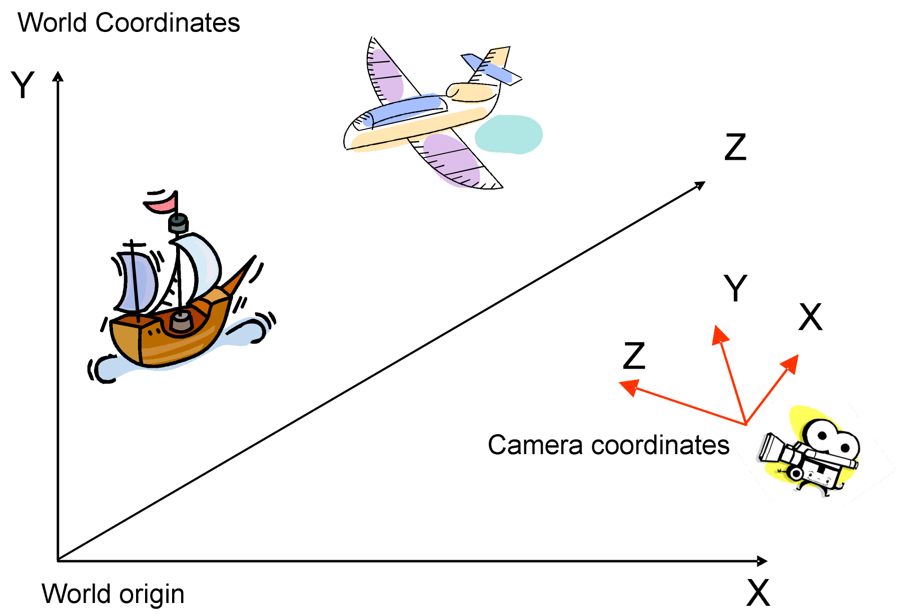

Figure A.2. World and camera coordinate systems

The type of coordinate system used by the 3D scene is arbitrary, and depends on the implementation of the graphics library used for rendering. Normally it describes 3D Cartesian space, where objects' locations are defined as points P_i (x, y, z). There are two basic types of coordinate systems that can be used: left and right-handed (Figure A.1; Watt, 2000, p2). The coordinate system used in our project is right-handed. The process of translation of coordinates between the model and the scene can be more or less complicated, and depends entirely on the specifics of the model.

3) The *scene coordinate system*, known also as the *world coordinate space* (Watt, 2000, p143), is handled by the rendering process. In the rendering pipeline, this coordinate system has to be transformed into yet another coordinate space, called the *view space* or the *camera coordinate system* (Watt, 2000, pp143-144). In the camera coordinate system the positions of the graphical elements are described in relation to the current point of view. These are still expressed in Cartesian 3D space, but the point of origin is moved to the location of the camera, and the directions of the axes are bound to its spatial orientation (Figure A.2).

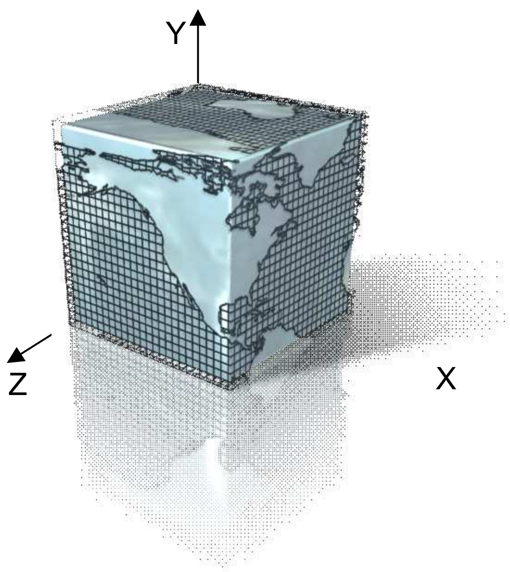

Figure A.3. A cube defined in a local coordinate system, with the point of origin in one of its corners

4) The fourth category of coordinate systems is used internally by the graphic objects that comprise the scene. If a polygon mesh is used for

object representation, the coordinates of the points that comprise the mesh and its faces are expressed in relation to the centre of a local coordinate system, rather than as absolute locations within the 3D scene. This makes sense, because each object can be drawn at many different positions within the scene, using translations, rotations and scaling operations, to adjust it to the current rendering need. Figure A.3 presents a cube defined in its own local coordinate system. This system is a 3D Cartesian space with X, Y and Z axes.

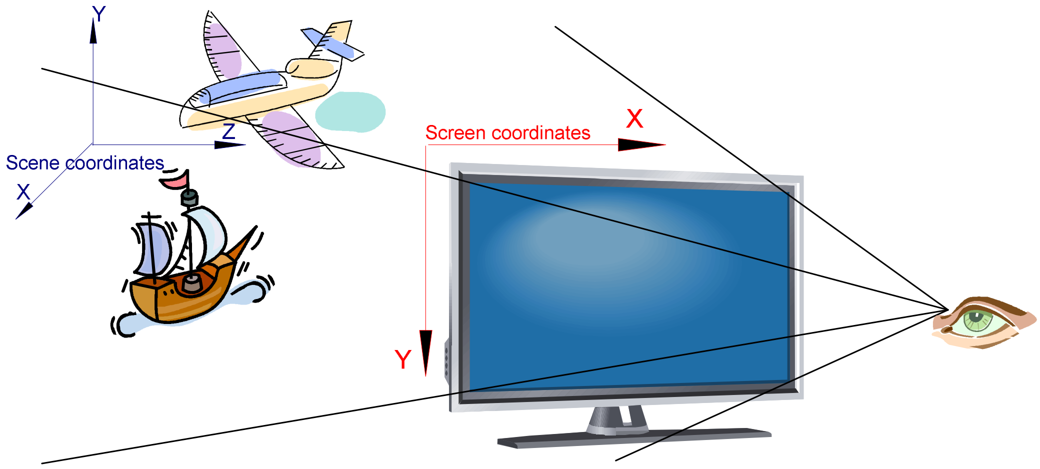

Figure A.4. Projection of the 3D scene onto the 2D surface of the screen

5) The last coordinate system is the 2D surface of the screen, onto which the 3D scene is projected for display (Watt, 2000, p144). The projection is managed by the graphical system, as presented in Figure A.4. In this process the 3D coordinates are translated to x, y coordinates of the display area. Although this process is automatic, it is very important to be able to perform the reversed transformation, when the x, y position of a screen pixel is used to determine the corresponding 3D coordinates within the scene, and further identify the object(s) in the model which correspond(s) to this location. This is necessary to enable any system that uses 3D visualization to perform

selections, queries, and other forms of interaction between the user and the displayed model.

A.4 Camera and view volume

The perspective from which the scene is seen is determined by the viewpoint, view direction and several other properties. The combination of the viewpoint and its properties is often called a camera, as its properties have some analogy to the properties of camera lenses used in cinema and photography. This analogy is, however, only partial and limited.

The properties of a camera include its position within the scene, its spatial orientation defined by the up, right, and forward vectors, the view angle, and the aspect. In addition, two *cutting planes* are present in 3D graphics which do not exist in real photography: the near and the far cutting plane. The analogies to camera shutter speed and aperture do not exist at all.

Based on the camera properties a *view volume* is defined (Watt, 2000, pp147-149). It has the shape of a pyramid, which in most systems is additionally constrained by the near and far clip planes. The clip planes are cut-off planes normal to the view direction. Any objects closer than the near cutting plane, or beyond the far cutting plane, cannot be seen. The cutting planes are extremely useful to reduce the number of polygons that need to be processed and drawn during the rendering of complex scenes.

The view pyramid with its cutting planes, and the resulting view volume, are illustrated in Figure A.5.

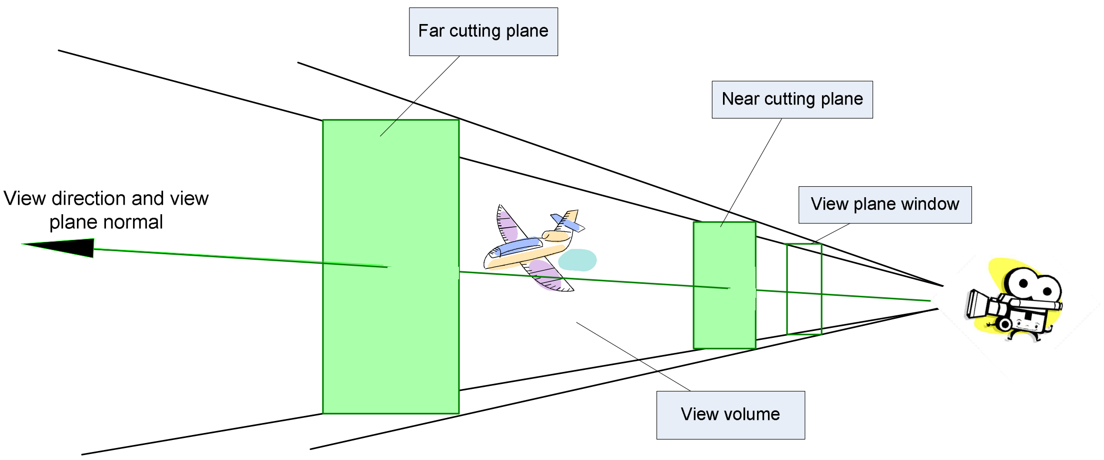

Figure A.5. View volume, restricted by the near and far cutting planes

A.5 Basic 3D affine transformations

Transformations are necessary for the creation of 3D scenes. These are used for the movement and modification of the objects within the scene. There are three basic types of affine transformations: *rotation*, *translation* and *scaling*. Technically speaking an affine transformation is made by any combination of linear transformations (rotation, scaling) preceded or followed by translation, if required.

When an object is to be placed within the 3D scene, the coordinates of all its primitives must be translated from the local coordinate system to the global system used in the scene. This is done by the application of affine transformations. The transformations are described in computer graphics using the four-dimensional matrix notation, where points or vectors are represented as column matrices, preceded by the transformation matrix.

Using the matrix notation, a point P (x, y, z) is transformed with translation, scaling and rotation as:

$P' = T\,P$

$P' = S\,P$

$P' = R\,P$

where T, S and R are respectively the translation, scaling and rotation matrices (Lengyel, 2002, pp57-60).

The matrix notation allows the combination of different types of transformations, and the simple computation of affine transformations. The inverse operations can easily be calculated by the use of inverse matrices T^{-1}, S^{-1} and R^{-1}.

A.6 Lights and materials

Lights and *materials* are metaphors used to enable realistic shading within the scene (Watt, 2000, pp171-183). They are used for defining the sources of light within the scene, and the object surface's response to their different types and colour components. The interaction between the combined light and an object's surface is used to calculate an appropriate shade, or colour, following the analogy to the process known from the real world.

In most graphical libraries a light can be defined as a global ambient source, or as a light source placed in a specified location within the scene. Lights usually have multiple properties, such as the colour and intensity of its different components (diffuse, specular and ambient). These interact with the properties of the materials set for the polygons within the scene. Polygons can have defined colours and intensity with which they reflect different components of the combined light available at their location in the scene. The surfaces may also be transparent, or translucent, in which case the appropriate order of polygon drawing – from back to front – has to be maintained, to achieve the intended effect. In addition materials can emit light to imitate the effect of glowing.

Lights are as important components of scenes, as materials are important properties of objects that populate them. The definitions of lights, combined with light-material simulation of the interaction process, allow the rendering system to determine which parts of the scene should be displayed, and with what intensity. Most graphical systems use the local reflection model by Phong (1975) for this calculation.

A.7 Textures

Textures are two-dimensional maps that can be placed on a surface of a 3D object. There are several types of textures used in different ways, but all are used to increase the realism of a visualisation. Example types of texture are light maps, used for the description of light on a surface of an object, or bump maps.

Bump mapping, developed by Blinn (1978) is a technique that enables a flat surface to appear geometrically complex, without the need to model the complexity of its shape. It cheats the eye by introducing modifications to the local values of surface normal vectors, causing the light to be reflected in different directions, as if the surface had the shape described by the bump map.

The most common type of a texture is the one used for mapping the distribution of colours on the surface of an object. For example an aerial photograph of a land area can be draped on the surface of the corresponding 3D terrain model to draw it with a high level of realism.

The textures are usually stored in the form of bitmap files. This causes several problems. Firstly, the sizes of such files are large, and thus their resolutions are limited. This matters because the application of a small-resolution bitmap on a large surface may not be as visually compelling as required, due to the visible pixelization effect. Secondly, the bitmaps have to be prepared in advance for each object, limiting the possibility of dynamic shape generation.

These limitations are bypassed by the new texturing technique, called *procedural textures*. This technique enables dynamic, per-pixel texture generation, based on the source code written in a special shading language. Procedural textures are also called *fragment* or *pixel shaders*.

A.8 Optimization of drawing

The complexity of the rendering process is strongly correlated to the number of polygons present in the scene. The more polygons to be drawn the more loaded the graphical system gets, and the longer the rendering of each frame takes.

Hence, to draw a 3D scene effectively several basic optimisation operations are performed. These include *culling*, or back-face elimination, *clipping* to the view volume, and application of *Level-of-*

Detail (LOD) algorithms. The idea behind all these is to minimise the number of polygons that will be drawn.

Culling (Watt, 2000, p147) is an operation in which the orientations and positions of complete polygons are compared with the viewpoint, to determine and remove the polygons that cannot be seen. On average, half the polygons of a polyhedron are back-facing and do not have to be rendered. Special tests are performed to determine and remove the hidden faces, and in their result the number of total polygons in the drawing pipeline is reduced.

Clipping (Watt, 2000, pp168-171) is a process of calculation and removal of all polygons that, for the current scene transformations and viewpoint, are located outside of the view volume.

Level-of-Detail (LOD) is a family of techniques that can be implemented in many different ways, according to the common principle. The principle is that depending on the distance to the viewer, graphical objects can be drawn with different numbers of polygons. The bigger the distance the smaller the number that can be used to approximate the represented shape without a negative impact on the realism of the scene. This is based on the observation that the limitation of the view resolution usually prevents us from noticing too many details of distant objects. LOD techniques are more complex than culling and clipping, as they involve special algorithms to facilitate dynamic change to the number of polygons used for the object's representation, while keeping a possibly good approximation of its original shape. A detailed description of existing techniques can be found in (Luebke et al., 2003).

Luckily, modern graphical libraries, such as the OpenGL, lift the burden of most of the basic optimisation procedures, such as culling and clipping, from the graphical application developer's shoulders. This, however, does not apply to the LOD techniques.

A.9 Animation

Animation, which is described in detail in (Watt, 2000, pp473-535), is a very broad subject on its own, and can mean different things to different people. The understanding varies, from simple updates of the rendered objects or scenes, occurring over time, to description of the process of computer-generated movie scene creation.

In interactive graphics the world 'animation' is often used in the first meaning, where a scene has to be frequently redrawn, either due to pre-programmed changes of the objects' positions – to create an illusion of motion; or in reaction to manipulation operations performed by the user – which effect in modification of the view. The main point regarding animation is that it is not good enough to draw the scene once. In interactive systems which involve kinetic objects and allow user interaction the whole scene has to be constantly redrawn.

The frequency of the redrawing process is described as the *frames-per-second* rate (FPS). The value of the FPS gives the number of redrawing operations performed each second. The higher the FPS value, the more ergonomic, smooth and fluent the animation seems to the user. Typically 24 frames per second are considered to be a threshold above which the human eye is no longer able to distinguish between animation and real movement. This is traditionally the number of frames of film used per second for a movie in the cinema.

The FPS produced by a computer system varies, depending on the complexity of the scene and the efficiency of the machine used for rendering. For many applications the illusion of smooth animation is not crucial, and lower values of FPS can be used. In some systems such as CAD, the FPS is a side issue, and is less important than the precision and accuracy of the visualization. FPS requirements in the context of 3D mapping are discussed in Section 4.2.3.

A.10 The rendering pipeline

The process of transforming 3D scenes stored in memory into 2D pictures drawn on the computer screen is called the *rendering pipeline* (Watt, 2000, 142-143; Angel, 2006, pp29-34; Akenine-Moller and Haines, 2002, pp9-24). The process involves several steps, which can be described by the block diagram shown in Figure A.6.

The process starts with objects, comprised of graphical primitives, defined in their local coordinate space. These coordinates are transformed into the world coordinate space, and the scene is composed. Shading is performed: lighting is applied, illumination and reflectance are calculated. Then the scene is transformed into the view-specific coordinate system. Optimisation operations, such as clipping, are applied. Then the camera space is projected onto the 2D plane, called the display space. This involves culling – hidden surface removal (Watt, 2000, pp189-201). The last step is called *rasterization* (Watt, 2000, pp183-187). In this process graphical elements are translated into a raster grid which matches the pixels of the screen. Textures are applied, and colours are calculated and assigned to particular pixels. The set of computed pixels is then passed to the hardware graphics accelerator for drawing.

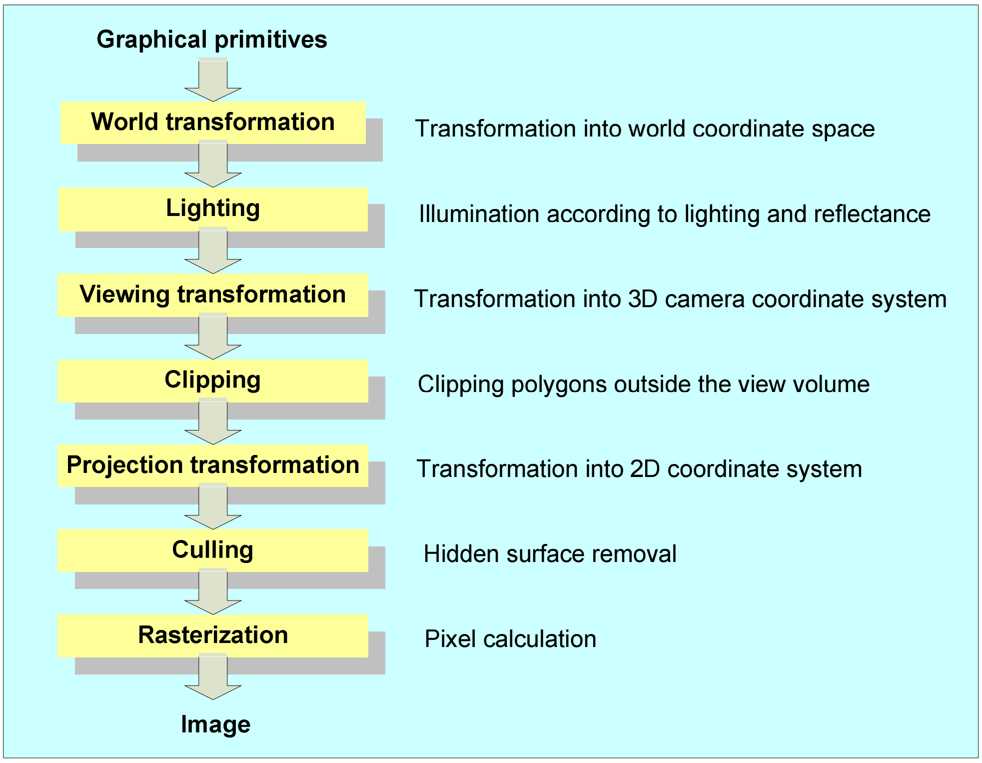

Figure A.6. 3D graphics rendering pipeline

At the end of the pipeline, on the hardware accelerator side, additional operations, such as per-pixel shading (procedural textures), can be applied to the output set of pixels, before these are finally drawn on the screen.

A.11 Hardware and software support

To enable the generation of 3D visualization, the software designer needs to program the graphical system of the computer. In modern computers the tasks related to display are usually handled by a specialized graphical controller, called a *Graphics Processing Unit* or a *GPU*. GPUs are designed and optimised to handle basic graphical operations efficiently. GPUs have their own low-level language, but the creation of complex scenes using it directly would be a very difficult and counter-productive endeavour, that would have to be repeated for each particular type of graphical hardware.

Luckily, higher level graphical libraries, that isolate the programmer from the hardware and simplify the graphics programming process, have been invented. Such libraries operate on generic 3D graphical primitives and concepts. These are capable of handling objects, lights, and cameras, performing calculations for transformations and various display optimisations, and they greatly simplify the creation of 3D scenes. The libraries are hardware independent, which means that a library-compatible program can be run on different computers with diverse GPUs. One such library is the Open Graphics Library, known as OpenGL. Another example is Microsoft Direct3D. The process of communication between an application and the hardware is illustrated in Figure A.7.

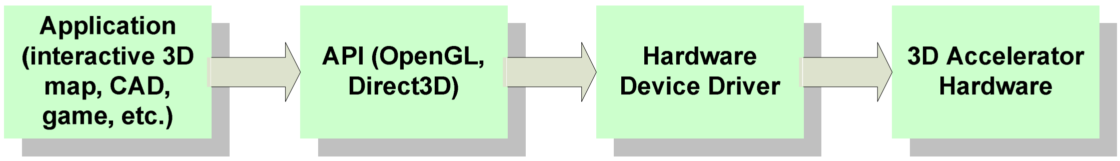

Figure A.7. The process of communication between 3D application source code and graphical hardware

Our project is based on OpenGL. Simply speaking OpenGL is a specification of a high-level Application Programming Interface (API) that consists of over 250 function calls, and is managed by the not-for-profit technology consortium, the Khronos Group, Inc. OpenGL is not only hardware-independent, as all hardware providers have to provide their own implementations, but is also platform-independent, as these implementations can be provided for different operating systems. When used by a programmer, OpenGL basically translates its high-level function calls that deal with 3D primitives, to a low-level API of the computer display hardware. For more details on OpenGL refer to Shreiner et al. (2007).

For more complex projects and big complicated scenes, the use of plain OpenGL API can still be not enough to ensure a satisfactory productivity. Basic graphical primitives and procedures can be grouped and organized into higher-level software libraries and APIs, for example to enable the use of an object-oriented approach. Examples of such libraries are *scene graphs* which use hierarchical tree-based data structures to manage multiple objects and scene settings; and *gaming engines* that provide more games-specific functions, such as handling of controllers and sounds (see Section 4.3.10).

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