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Applications and Benefits for the Development of Cartographic 3D Visualization Systems in support of Maritime Safety

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ABSTRACT: Maritime shipping is among the world's most important industries and is vital to the global economy. With growing levels of traffic marine accidents pose a danger to health and lives of ship crews, environment, and have a strong impact on profitability of shipping and port operations. This underlines the urgent need for the development of maritime navigation systems whose objective will be to contribute to a safer sea. Amongst many technical and methodological issues to address, there is a need for more efficient electronic charting and radar display systems for use in navigation, traffic monitoring and pilotage, to improve the level of situational awareness of ship navigators, Vessel Traffic Services (VTS) operators and marine pilots. Cartographic 3-dimensional visualization (3D chart) facilitates fast and accurate understanding of navigational situations in ports and at open sea, decreases mental overload and minimises fatigue, this supporting better decisions for either sailors at sea or maritime authorities in charge of traffic monitoring. This leads to a reduction of human error which is the main cause of marine accidents. This paper presents the latest developments and applications of cartographic 3D visualizations (3D charting) in marine navigation, VTS and pilotage.

1 INTRODUCTION

Maritime shipping is among the world's most important industries. It can be compared to a cardiovascular system of the global economy – for thousands of years ships of different types and sizes are transporting goods between different countries and continents, facilitating world trade by enabling some routes and making other economically viable.

The risk of marine accidents has always be a major consideration, as a factor which not only determines the economic viability and profitability of shipping, but also directly endangers health and lives of ship crews. Moreover, ships carrying hazardous loads pose serious threats to the environment, as well as to the lives, health and wellbeing 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. Collisions of even small craft often lead to serious consequences, often including casualties.

Over the years huge efforts have been directed towards improving the level of maritime safety, including areas as diverse as ship design, certification, training, fire safety, radio-communications, navigation rules, electronic chart systems, identification systems, life-saving equipment, ship operation and maintenance procedures and requirements, port operations, pilotage and accident investigation. International treaties such as the International Convention for the Safety of Life at Sea (SOLAS) (International Maritime Organisation 2004) have been introduced to prevent accidents by regulating those and other maritime safety-related areas. A huge progress has been achieved.

However, with the level of shipping constantly growing in the long term, and reaching its historical peak levels in the late XX and early XXI centuries, the risks of accidents from categories as diverse as equipment faults and breakdowns, fires and explosions, personal injuries, collisions and groundings are also growing, with the last two categories responsible for the majority of fatalities (Talley et al. 2006).

According to research by the U.S. Coast Guard Research & Development Center (Rothblum 2006) about 75-96% of marine casualties are caused, at least in part, by some form of human error, with this being the case for 84-88% of tanker accidents, 79% of towing vessel groundings, 89-96% of collisions and 75% of fires and explosions. Those numbers show clearly that human error ranks as the major contributor to different types of marine accidents, including the most dangerous categories such as collisions and groundings.

As shipping lanes are increasingly becoming crowded with larger and faster craft, ship crews are getting smaller. This puts a growing pressure on the navigators, as well as on the on-board systems that are required to provide them with decision-making and navigation support.

Human errors can also come from control centre (Vessel Traffic Services, VTS) on shore where people might have difficulties to appreciate and anticipate a given situation due to the traffic load. Also marine pilots, despite their excellent knowledge of navigation and local expertise are not immune to errors. Investigation of accidents such as the grounding of Vallermosa (Marine Accident Investigation Branch 2009) indicate insufficient level of support from ship crews, mental overload, inability to comprehend and control the developing scenario, the lack of situational awareness, and the absence of coordination and support from VTS operators among main causes of accidents involving pilot-led vessels.

The latest technological breakthroughs including radar, electronic charting (Electronic Chart Display Information Systems, ECDIS), traffic control and management (VTS) and automatic identification and communication (Automatic Identification System, AIS) brought a significant improvement to the problem of maritime navigation safety, contributing greatly to improved navigational awareness, collision-avoidance information and guidance available to navigators. However, they have not eradicated the problem and marine accidents still happen frequently, often due to fatigue, mental overload and limited awareness of the navigational situation.

This can be improved by offering more visually efficient and both easier and quicker to understand chart display systems based on cartographic 3D visualization to navigators, pilots and VTS operators. Three-dimensional charts are proven to dramatically reduce the number of human mistakes and improve the accuracy and time efficiency of navigational operations, compared to traditional 2D charts (Porathe 2006), including Electronic Chart Display Information Systems (ECDIS). To minimise human error, and in consequence reduce the number of accidents, they could be applied at several stages of the maritime safety management process, including on-board ship navigation, vessel traffic monitoring (VTS) and pilotage. They also can be used in training and provide significant insight in accident investigation.

2 NAUTICAL ELECTRONIC CHARTS

Maps are among the oldest forms of graphical communication, and are the most effective and efficient mean for transfer of spatial and geographical information (Kraak 2001). Over the years, different types of maps have been developed with different cultural and application backgrounds, and used for many aspects of our everyday lives. More recently, maps have moved from paper to digital formats and are becoming more popular than ever.

From the navigational perspective electronic charts offer a number of benefits over their paper equivalents, allowing for dynamic analysis of vessel position and chart data for alerting about potential groundings, integration with bridge equipment and presentation of combined information from sensors such as GPS, radar and AIS, and automation of typical navigational tasks, such as plotting the course or calculating different parameters of the planned route. This integration and automation helps in reduction of navigators' workload, and offers more accurate understanding of the navigational situations.

2.1 *State-of-the-art*

Due to its obvious benefits electronic charting is fully supported, and encouraged, by the International Maritime Organization (IMO), International Hydrographic Organization (IHO) and member state regulators, who developed a standard for Electronic Chart Display Information System (ECDIS), with an objective to replace maritime maps on the decks of commercial ships with automated and electronic charts. An ECDIS system comprises the official nautical chart data (International Hydrographic Bureau 2000) stored in the vector IMO/IHO Electronic Navigational Chart (ENC) format produced by national hydrographic offices (Fig. 1), a type-approved real-time 2-dimensional display conforming to performance and display standards associated with the current position of a vessel obtained from GPS, a user interface to perform basic navigational tasks, with optionally integrated information from AIS, radar, and other bridge instruments.

The carriage of type-approved ECDIS will become mandatory on all merchant and passenger ships with a transitional schedule for the implementation of this requirement for different types of new and existing ships starting from July 2012 (new passenger ships of 500 gross tons or more, and new tankers above 3000 gt) to July 2018 (retrofit on existing dry cargo ships of above 10000 gt).

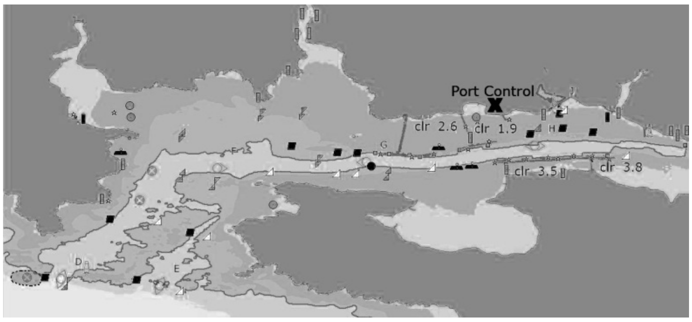

Figure 1. ENC chart no GB50162B – the Port of Milford Haven – as viewed in an ECDIS, with additionally marked location of the Port Control (VTS operations centre)

VTS centres and pilots usually use non-approved chart display systems based on official ENC charts (Electronic Chart Systems, ECS), offering special functionality for situation analysis and tracking of port operations.

Leisure boating enthusiasts have a broad selection of chart plotters, which do not have to conform to regulations, available on the market, and these are constantly gaining in functionality and popularity.

2.2 *Supporting technologies*

The main purpose of a charting system, or an ECDIS, is to display the relevant chart and navigational information and to automatically present the ship in this context. This is done by overlaying the ship's position as received from a satellite navigation transponder on a digital chart.

However, one of the most appealing functionalities of digital charts is the possibility of easy integration of additional information received from other systems or on-board sensors and devices. This may include meteorological data (from weather station, or from weather forecasts), digital compass, and other, but most importantly the information about surrounding obstacles and traffic which is very helpful in avoidance of dangers. This information may come from radar (drying features, obstacles, other ships), sonar (bathymetry), but also from Automatic Identification System (AIS) which is one of the most significant recent technological developments, allowing for reliable and easy detection and identification of ships within a range of up to 35 NM. An AIS transponder generally integrates a transceiver system, a GPS receiver and other navigational sensors on board such as a gyrocompass and a rate of turn indicator. It runs in an autonomous and continuous mode, regardless of its location (e.g., open sea, coastal or inland areas). The transmitted information is broadcasted through VHF communications, to surrounding ships and to VTS systems operated by maritime and port authorities.

The International Maritime Organization has made the AIS a mandatory standard under the Safety of Life at Sea (SOLAS) convention for all passenger and international commercial ships, and these are now equipped with AIS transponders.

2.3 *Limitations*

Despite the progress brought with the shift towards digital charting and introduction of ECDIS and other technologies, 2-dimensional maps are sometimes difficult to interpret from a cognitive point of view. Users have to generate a mental model of a map, rotate it and match with real world and translate the symbols and map features towards some abstract concepts. This explains why so many people have difficulties with the interpretation and understanding of 2-dimensional maps, this often resulting in errors and sometimes leading to fatal mistakes.

This is true even for trained navigators, especially when they are tired or under pressure, with high levels of stress and mental overload, which are typical for marine navigation. The time and mental effort required for understanding of 2-dimensional 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 situation changes quickly, and available time 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 death casualties. All these collisions were caused by poor understanding of the situation or temporal loss of orientation by navigators, despite being guided by modern digital 2D chart displays.

3 3D VISUALIZATION IN MARITIME SAFETY

3.1 *State-of-the-art*

The application of 3D visualization to maritime safety is not a new idea. 3D presentations are widely adopted, extensively used and highly regarded in some areas of the maritime safety management process, such as for example in marine navigation training, where realistic 3D simulators are a safe, cheap, convenient and reliable way of gaining navigational experience, or in ship building, where three-dimensional Computer Aided Design (CAD) systems are extensively used for design and modelling.

However, for some reasons, 3D visualization has not been successfully adopted in real-time 3D navigation, VTS or pilotage. There are no professional 3D charting systems available on the market, with very limited success of adoption of 3D perspectives in chart plotters offered to the leisure market. The same situation is true in the VTS or pilotage operations where ECDIS-like 2D chart displays are commonly used. The possible reasons for this are discussed in Section 4.2.

3.2 *Cartographic vs. photorealistic 3D*

It is important to stress the importance of the distinction between photorealistic and cartographic 3D presentations. The representatives of the first group are meant for realistic representation, or mimicking of the real world, and are known from computer games and navigation training simulators. The goal in simulation is clear: to recreate the situation and conditions of navigating at sea with greatest possible accuracy, to offer a trainee as much practice time as possible in diverse nautical conditions, without the risk, time and cost of going into the sea. As such, simulators have to be built to represent the realism of the situation with all its negative aspects, such as inability to see more than the view out of the window and of what typical bridge instruments would present, which offers a limited situational awareness.

Just as a well-designed 2D chart differs from a photograph, cartographic 3D presentations are different from their photorealistic counterparts. Cartographic 3D visualizations (3D maps) enhance and facilitate the understanding of the presented situation, by clarifying and tailoring the presentation to user needs, and are designed for the highest possible efficiency of information transfer. As outlined in more detail in Section 5.1, to achieve that purpose they use cartographic principles equivalent to or extrapolated from 2D cartographic rules.

3.3 *Potential and benefits*

Despite the observation that 3D visualization is currently not present at all or used only to a very limited degree in maritime navigation, research and experiments indicate that the application of 3D in marine charting may offer significant benefits, including faster and more accurate understanding of the portrayed situations and higher level of operational comfort, when compared to their 2D counterparts.

This potential is based on the inherent ease of understanding of 3D representations which is a consequence of the way we see the world, and how 3-dimensional representations appeal to our brains (Van Driel 1989). The process of perception in three dimensions has been perfected by millions of years of evolution, because prompt recognition of potential dangers was, and still is, crucial for survival. According to estimates, about 50% of brain neurons are used in the process of human vision. 3-dimensional views stimulate more neurons and hence are processed quicker (Musliman et al. 2006). 3-dimensional maps resemble the real world to a greater degree than their traditional 2D counterparts, and are more natural to human brain (Schilling et al., 2003). Another advantage is that 3D symbols can be recognized very quickly even without special training or referring to a legend.

Based on experiments conducted with different types of maps, Porathe (2006) argues that 3-dimensional maps are not only quicker to understand but also provide improved situation awareness, and have strong potential of helping to minimize human error in marine navigation and the resulting marine accidents. In his experiments Porathe asked a group of participants with different characteristics (age, sex, navigational experience) to perform a simulated navigational exercise using four different types of charts: paper, digital 2D north-up, digital 2D heads-up and interactive 3D chart. The efficiency of navigation using each map type was measured as the time required to complete the task, the number of mistakes (groundings) made during its execution, and the perceived difficulty of use. The results showed that the use of 3-dimensional maps led to up-to 80% reduction in the number of navigational mistakes, as well as more than 50% reduction in the time required for the completion of the simulated navigational task, when compared to 2D charts. Three-dimensional maps were also voted by the participants as the most friendly and easy to understand.

A very important finding was that the patterns of the results were similar in every participants group, regardless of their navigational experience level. While on average experienced navigators completed their tasks faster and caused less groundings a similar increase of efficiency and reduction of error was observed for their group, as for inexperienced users. And just as inexperienced group trained navigators appreciated the perceived friendliness of and ease of navigation using 3D charts.

It is our belief that this benefits can and should be transferred from the experimental research domain into the world of real navigation, to offer the benefits of 3D charting to navigators, and reduce the number of accidents in ports and at sea. The improvements to maritime navigational safety can be gained by application of 3D visualization to navigational charts for use in real-time in navigation, VTS operations and pilotage, or for analysis, training and accidents investigation with use of historical data recordings.

4 NAUTICAL 3D VISUALIZATION

4.1 *Previous work*

The idea of 3-dimensional navigational charts was initially introduced in (Ford 2002) with the conclusion that 3-dimensional visualization of chart data had the potential to be a decision support tool for reducing vessel navigational risks. A prototype charting system was based on custom-prepared 3D model of the selected area.

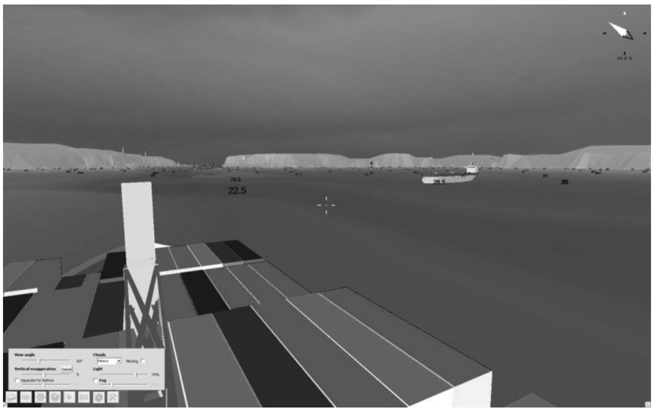

Figure 2. Bridge view in the "3D ECDIS" prototype

Arsenault et al. (2003) presented a prototype 3D visualization system that used an overlay of a scanned paper navigational chart over a 3D bathymetry, and served as a platform for research on concepts that might be used in the "chart-of-the-future," including merging tidal and bathymetric information and simultaneous display of multiple linked views.

Gold et al. (2004) proposed a prototype of an interactive 3-dimensional "pilot-book" for the East Lamma Channel in Hong Kong, with 3D model (map) of the area derived from the corresponding ENC cell, and manually converted into a 3D presentation with the use of satellite DTM and orthoimagery.

Porathe (2006) introduced a prototype charting system, with custom-built visual vocabulary of guidance symbols, comparable to virtual signs on a motorway, for use in navigation. The system worked on manually prepared 3D model of the selected area.

Goralski & Gold (2008) proposed a "3D ECDIS" prototype based on a custom-designed 3D visualization engine, kinetic spatial data structures and ergonomic manipulation interface (Fig. 2). The system used official ENC charts to automatically create real-time 3-dimensional display associated with the current position of vessels.

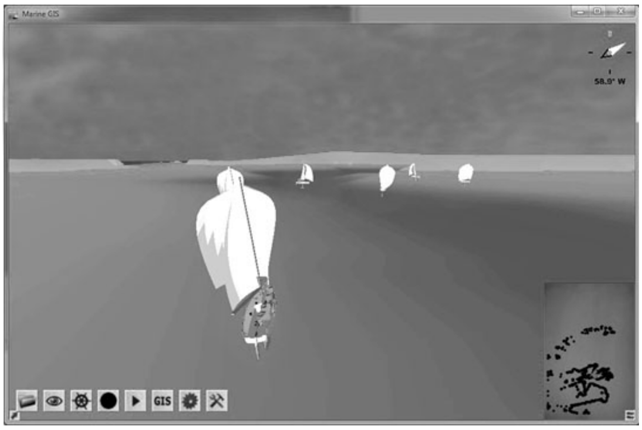

Figure 3. Immersive real-time 3D visualization of a sailing regatta (Brest Bay)

Ray et al. (2011) presented a 3D virtual environment based on an interactive 3D chart for tracking of marine vessels and visualization of a sailing regatta competition for a wider public in real-time (Fig. 3). The system was based on a real-time tracking and dissemination platform introduced by Bertrand et al. (2007, Fig. 4).

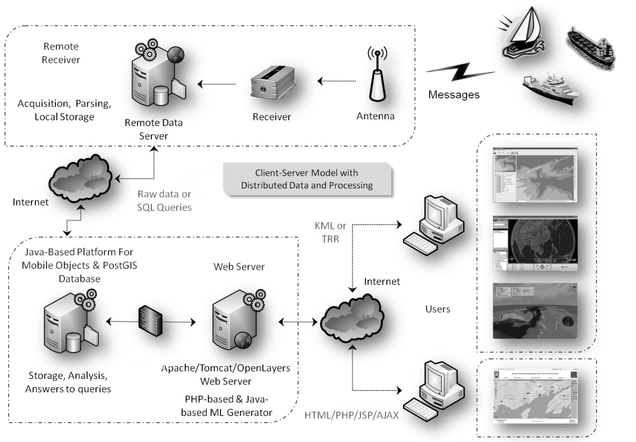

Figure 4. Real-time data recording and dissemination architecture

Ternes et al. (2008) proposed a prototype 3D visualization system developed with the Port of Melbourne, for support of navigation during hydrographic surveys. System works with manually-prepared 3D models and proved to be very effective in helping to maintain accurate survey track with the use of virtual boys and markers.

4.2 *Inhibiting factors*

After analysing the benefits of 3D visualization to maritime navigation safety, including the results of experiments, and reading about various prototype developments proposed in the last decade an important question occurs. If 3D charts have been proven to be so efficient and have been proposed by a number of researchers, why they have not become popular and are not used widely for navigation? Why they seem to never have moved beyond research prototypes stages? And why, unlike hugely popular 3D marine navigation simulators, they are not commercially successful and available on the market? These are complex questions, and our experience suggests that there are several combined reasons for this situation.

The first reason is in technical complexity. Building a robust, reliable and usable 3D charting product that is designated for constant real-time use in a very important and responsible function, upon which the safety of people relies (which an aid to navigation certainly is) is a much more demanding task than is the case for either digital 2D chart or a training simulator.

This is combined with well-meant and fully justified conservatism and scepticism of the regulators and the industry. It took years for the industry to acknowledge and appreciate the benefits of 2D charting and to develop and embrace standards such as ECDIS. The regulators, shipping operators and navigators have to be cautious in entrusting any new technologies which have not been fully validated and tested in practice.

The technical complexity and industry conservatism make development of professional 3D charting a costly and relatively risky endeavour, which requires more resources and a longer development time, with significantly more difficult quality control, while not necessarily leading to gains which would compensate for it.

On top of that, but partially resulting from the above problems, are the legal limitations. We cannot really have a 3D ECDIS at the moment, because it would not fulfil very strict and precise standards of information presentation set out by the regulators. 3D is not an option for type-approved ECDIS displays and it seems unlikely that this will change for many years to come.

Another consideration is the cost of data acquisition and the availability and coverage of 3D charts. In all prototype systems listed above, with the exception of the prototype “3D ECDIS” by Goralski & Gold (2008), 3D charts had to be manually created in a laborious process, which restricted their usability to the selected areas of interest.

Apart from the other reasons, there is the conceptual difficulty and lack of experience, tradition and know-how in efficient presentation of cartographic information in 3D. Unlike 2D cartography which has been practised and developed for hundreds or even thousands of years, 3D cartography is rather new and is a largely uncharted territory. Several researchers in the area, including Haeberling (2002) and Meng (2003) complained about the lack of available research in the field, and the situation has not improved since. That leads to a situation where very little knowledge and guidance is available to potential producers of 3D mapping systems.

Part of the above refers to the difficulty of building efficient presentations of data in 3D, while another part concerns the complexity of design of ergonomic user interfaces for efficient operation of (or navigation within) 3D charts, which with the addition of the extra dimension becomes an incomparably more difficult task than in 2D.

All the above factors combined contribute to the delay in adoption of 3D charting, but in our opinion none of the discussed reasons should stop this beneficial process, providing that the requirements for successful 3D charting products will be fully understood, and the identified difficulties solved.

4.3 *Requirements*

From the analysis of the difficulties inhibiting and delaying the popularisation of 3D charting in marine navigation it seems clear that successful 3D charting products should fulfil a number of requirements.

Firstly, they should be at least as robust and reliable as their 2D counterparts are, to be able to overcome the reservation and scepticism with which the regulators and maritime industry rightly treat all new technologies.

Secondly, 3D charts should be applied first where legal regulations do not preclude them. There are no reasons why they could not be used in VTS or pilotage, and in professional navigation they can be used as add-ons to, or alongside, rather than instead of, type-approved ECDIS.

Thirdly, to tackle the problem of costly data acquisition and availability they need to be universal. Ideally they should work with existing, approved and widely available standards of chart data, such as ENC charts, and generate 3D models of the covered areas automatically.

Fourthly, they need to be user-friendly and ergonomic. Their operation and manipulation has to be effortless, natural and intuitive, and cannot be cumbersome or distracting.

Finally, they have to use cartographic principles to maximise the efficiency of information presentation and transfer.

Fulfilling all the above requirements may require extra cost and time for research and development, but is necessary to produce 3D charts that can be used and relied upon even in the most demanding conditions, and should be worthwhile due to benefits that well-designed 3D charts would bring to marine navigation.

5 NAUTICAL 3D CHARTS

5.1 *3D Cartography*

Cartography is the discipline dedicated to study and practice of production, interpretation and use of maps, and includes all related scientific, technical and artistic activities and aspects (Edson 1979). The expertise of cartographers involves the knowledge of visual design – to make maps as readable as possible – as well as diverse related areas such as the process of map production and distribution, different forms of map use and applications but also the underlying technologies and algorithms, as well as the psychological mechanisms of human perception and cognition.

The scope of 3D cartographic knowledge is an extension of the traditional cartography, but includes areas and aspects which either need to be adapted for the use with the additional dimension, or are completely new.

Visual design is one of the examples from the first category. Cartographic presentations, i.e. maps, require carefully designed symbols and methods for presenting different types of information. They use the principles of symbolism, generalisation and abstraction. In 3D some symbols, texts and numbers may be presented using methods similar to those known from 2D. Other may need to be represented differently – for example as self-explanatory 3D models of the real-world objects, including the 3D model of the terrain (and bathymetry) of the presented area. The 3D representations do not have to be photo-realistic to be easily understandable. In fact non-photorealistic 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). Desirable are dynamic algorithms for the optimisation of the chart display, to assure that the important information is always presented efficiently.

Interactivity and manipulation interfaces are among the examples of aspects which are completely new, or incomparably more important and complex in 3D. Static 3D (perspective) presentations have been known for years, but never gained much popularity. This is due to their inherent limitations, including the distortion of the perspective and the problem of hidden regions. It is with the introduction of the ability to interact with or within the presented environments when 3D maps become truly beneficial. A user of a 3D map needs to be able to freely move in the represented area and test different perspectives to be able to fully understand the presented situation. For that reason the design of highly interactive and ergonomic interfaces emerges as a new area of interest for 3D cartography. The use of typical "arrows" (pan left, right, up and down) and "zooming" (zoom in and out) buttons in a 3D map is not a satisfactory option. Preferred are direct manipulation interfaces which allow for constant and fluent control of all the required levels-of-freedom in an ergonomic, effortless and intuitive manner.

The trouble with 3D cartography is the already mentioned lack of sufficient research results, resources and know-how which would guide producers in their efforts of the development of truly usable and efficient 3D charting products.

5.2 *State-of-the-art*

The deficiency of 3D cartographic research means that each 3D chart development effort has to be based not only on the existing body of knowledge, but also add a significant amount of original work into the subject.

This paper proposes a 3D charting (cartographic 3D visualization) system for marine navigation, VTS and pilotage, using best practices and the scarce research available on 3D cartography, as well as our experiments conducted and experience gathered during over the decade of its development at the Hong Kong Polytechnic University, University of Glamorgan, French Naval Academy and GeoVS Limited. The system was designed based on the requirements described in Section 4.3.

The navigation, VTS and pilotage systems are built around the common 3D charting platform "C-Vu" and are called respectively "C-Vu 3D ECDIS" (add-on to type-approved systems), "C-Vu Surveillance 3D VTS" and "C-Vu 3D Pilot" (for pilot boat navigation, as well as pilot carry-on units.)

Apart from highly efficient 3D cartographic engine the systems integrate with port and on-board infrastructure and sensors (GPS, AIS, radar, tide gauges, weather stations, digital compass, ship register, networking equipment) and offer robust recording and distributed information dissemination architecture for real-time remote multiple-display monitoring as well as analysis and evaluation of historical data – for training or accident investigation. Different elements of the system integrate with each other, allowing a pilot with a carry-on unit to see the complete picture of the situation in the port as recorded by the VTS, or for a mobile radar installed on a pilot boat to feed into the main system, thus increasing the local clarity of the radar picture or covering blind spots. The architecture allows for redundancy of all system elements for increased reliability.

In terms of usability "C-Vu" 3D charts offer a global coverage with automatic generation of fully-fledged 3D models from official ENC charts, with the use of advanced Voronoi algorithms for terrain and slopes reconstruction (Dakowicz & Gold 2003). The user interface is kept simple and ergonomic – it is tailored for the purpose of each system version – and employs our original metaphor for navigation in the 3D map area, which is coupled with a hardware 3D controller to allow efficient direct manipulation in all directions with a single hand.

The 3D cartographic engine is built around a set of custom-designed 3D models of navigational objects and different ship types, with dynamic algorithms for optimisation of sizes, colours and spatial orientations, to assure the highest possible level of visual efficiency.

Underneath the visual layer are GIS-type kinetic Voronoi-based algorithms that maintain spatial relationships between different objects in the model (including the bathymetry), and may be used for prediction and avoidance of collisions and groundings.

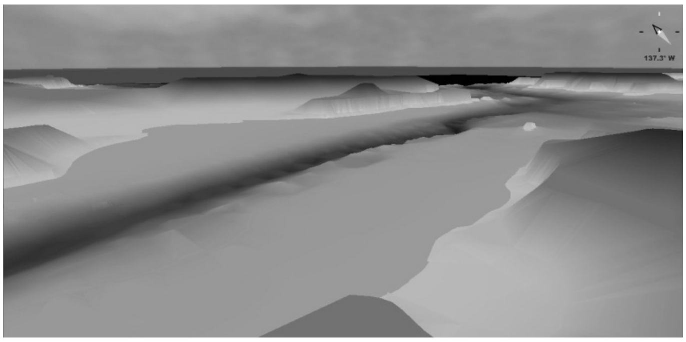

Figure 5. C-Vu Surveillance 3D VTS - bathymetry and terrain model of the Port of Milford Haven as seen from the location of the Port Control (traffic information not displayed)

All systems from the "C-Vu" family are in their final development stage. "C-Vu Surveillance 3D VTS" is currently being used and trialled for 24/7 VTS operations, and is being improved with the operators feedback, in the Port of Milford Haven in Wales, UK (Fig. 5). It is expected to be commercially available in the summer 2011 from GeoVS Limited, with "C-Vu 3D ECDIS" and "C-Vu 3D Pilot" following later that year.

5.3 *Future work*

Future work will include the finalisation of the development of the navigation and pilotage systems from the "C-Vu" family, improvements of the distributed platform, as well as continued research work on 3D cartography, visual efficiency, user-chart interaction, decision support, and 3D charts' applications.

Special focus will be placed on providing users with efficient decision support, through employment of the underlying spatial algorithms to the avoidance of accidents, and the use of advanced behavioural models for prediction of dangerous behaviour from the participants of marine traffic (Le Pors et al. 2009).

Once a sufficient user base is built a team of occupational psychology researchers from the University of Glamorgan will undertake a formal assessment, including qualification and quantification, of the occupational comfort and efficiency benefits attained by the use of 3D charts in VTS and navigation.

6 CONCLUSIONS

Although current maritime systems are relatively successful, thanks to the development of digital charting, vessel traffic systems and automated information and communication systems, there is still a need for innovation in minimising human error and reducing the number and severity of accidents at sea.

With advances in cognitive science and psychology comes a better recognition of the strengths and limitations of human perception and natural abilities of our brains. New charting products should use this knowledge and be designed to support the strengths and minimise the limitations, to reduce errors made by navigators, VTS operators and pilots.

3D charts were proposed and tested as a very efficient medium for fast and accurate transfer of navigational information and enhancement of situational awareness of ship crews, VTS operators and pilots, even when working under pressure or when fatigue significantly limits their cognitive capabilities. 3D charts reduce mental overload and improve overall occupational and operational comfort and efficiency.

The research presented in this paper explains the benefits of 3D visualization in maritime safety, presents the state-of-the-art of 3D charting and introduces a universal 3D chart display system based on official ENC charts and integration with bridge or port infrastructure.

The proposed system generates fully-fledged cartographic 3D models of any area from standard ENC charts and is being prepared for use in marine navigation, VTS and pilotage, where it provides a better sense of the environment for many situations at sea, this being an asset for safer navigation. The interface developed can be used either in real-time for navigation monitoring and control, or for the analysis of maritime navigation behaviours. The system is currently being trialled in the Port of Milford Haven for its VTS operations, and has a potential to become the first fully-functional commercial implementation of a 3D VTS.

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