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Holographic data visualization: using synthetic full-parallax holography to share information

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ABSTRACT

This investigation explores representing information through data visualization using the medium holography. It is an exploration from the perspective of a creative practitioner deploying a transdisciplinary approach. The task of visualizing and making use of data and "big data" has been the focus of a large number of research projects during the opening of this century. As the amount of data that can be gathered has increased in a short time our ability to comprehend and get meaning out of the numbers has been brought into attention. This project is looking at the possibility of employing three-dimensional imaging using holography to visualize data and additional information. To explore the viability of the concept, this project has set out to transform the visualization of calculated energy and fluid flow data to a holographic medium. A Computational Fluid Dynamics (CFD) model of flow around a vehicle, and a model of Solar irradiation on a building were chosen to investigate the process. As no pre-existing software is available to directly transform the data into a compatible format the team worked collaboratively and transdisciplinary in order to achieve an accurate conversion from the format of the calculation and visualization tools to a configuration suitable for synthetic holography production. The project also investigates ideas for layout and design suitable for holographic visualization of energy data. Two completed holograms will be presented. Future possibilities for developing the concept of Holographic Data Visualization are briefly deliberated upon.

Keywords: Data Visualization, Holography, 3D imaging, Full-parallax, Information Visualization, Computational Fluid Dynamics, Solar irradiance, Practice-based Research.

1. INTRODUCTION

This research project focuses on the possibility of using synthetically generated holography in combination with Data Visualization. The question arose when observing a copy of Zebra Imaging's pivotal hologram of downtown Seattle.[1] This full-color reflection hologram features a three-dimensional map with models of the buildings.[2] It is displayed horizontally and lit with an overhead white light. The viewer looks down over the cityscape from above. The spectacle of the buildings towering above the surface of the hologram formed an emerging vision of how the medium could be developed for the exchange of information and ideas. Would it be possible to develop a language of Holographic Data Visualization?

1.1 Data Visualization

By placing data in a visual context viewers can be supported in gaining access to patterns, trends and correlations that may not be apparent when presenting data as a set of numbers. Data Visualization aims to convey information clearly and excellently using graphic elements such as charts and tables. Tufte wrote in 1983, a time when visualizations were generally printed on paper and stated: "Graphical excellence is that which gives to the viewer the greatest number of ideas in the shortest time with the least ink in the smallest space".[3] Contemporary information graphics are often viewed directly on computer screens, and may be interactive; saving ink is not a high priority but the aim remains to generate ideas and understanding through comprehensible visual form. Tufte defined further Graphical Excellence, which is the well-designed presentation of interesting data - a matter of substance, of statistics, and of design. It also consists of complex ideas communicated with clarity, precision, and efficiency. Good visualization supports users in understanding and analyzing complex data.

Contemporary Data Visualization is undergoing intense development. The current condition in which rapid technical development is enabling mankind to collect and store increasing amounts of data, forms new challenges. Big data sets

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can deliver insight into previously unknown patterns and correlations, and in order to unearth significant information these need to be extracted and understood. High Performance Computing is also rapidly increasing the size of data sets routinely produced by scientific and engineering calculations. Contemporary Data Visualization enhances the human capability to extract meaningful evidence from sources that will appear abstract when presented as large series of numbers. What kinds of new interfaces need to be developed in order to efficiently familiarize viewers with what the data represents? Which new tools and methods can be created in order to aid our use and understanding? There has been recent excitement about the use of 3D visualization in this quest, one area of accumulating research is visualization through 3D printing, and the emergent area of Data Physicalization.[4] Here the focus is on the use of holography.

1.2 Synthetic Display Holograms

"A synthetic hologram is an optical system made of hundreds of images amalgamated in a structure of holographic cells"[5] writes Desbiens in 2013. These holographic cells have also been described as a holographic element, a hogel[6], or a holopixel[7]. During the print process each hogel is exposed with a laser through an LCD mask encoding the directional information and intensity of the light in the pre-calculated model of the 3D image to be produced onto the holographic medium. When the synthetic hologram is played back the hogels present a particular point of view per angle to the onlooker, and when the onlooker changes position to the hologram a different view is presented. In this way the onlooker perceives a three-dimensional image. Desbiens describes the viewer's interaction with the synthetic hologram "When observers move freely and change their viewing positions, they travel from one field of view division to another. In synthetic holography, metamorphoses of image content are within the observer's path." This inherent invitation to active viewership by the onlooker forms one of the aspects of the vivacity behind the idea of Holographic Data Visualization, where the aim is both to engage and inform the audience.

A multitude of different terminologies are used by researchers and manufacturers in the field to describe holograms with computer generated imaging, created with the intention of being viewed as images (display holography), and printed using an array of diffractive holographic elements performing the function of the refractive lenslets in integral photography.[8] Klug and Holzbach uses the term "Holographic Stereogram" in in Benton and Bove's book Holographic Imaging,[9] Bjelkhagen and Brotherton-Ratcliff writes about "Digital Colour Holography" in Ultra-Realistic Imaging.[10] The process is described as Direct Write Digital Holography (DWDH) in the Saxby and Zacharovas book Practical Holography, Fourth Edition.[11] Producer Geola uses the description "i-Lumogram",[12] Zebra Imaging Inc "3D Holographic Prints"[13] and Ultimate Holography uses the term "Holoprint".[14] In this paper "Synthetic Display Holography" will by used as to make the method described readily distinguishable from other forms of digital holography. Following the example of Desbiens: "Synthetic holograms simulate continuous parallax by combining hundreds of computer generated images".[15]

The experiments described in this paper are printed as color reflection holograms with horizontal and vertical parallax by Zebra Imaging Inc. There are only a small number of manufacturers of synthetically generated display holograms active globally at present. Here the choice was made due to the researcher's experience of holograms manufactured by Zebra Imaging Inc. using similar design structures. The Lithuanian manufacturer Geola also produces synthetic display holograms, but does not offer a full-parallax option at this point in time. Ultimate Holography based in France also print full-parallax synthetic display holograms. Additional accessible production facilities would be welcomed for future research in the area.

In order to test the theoretical concept of using synthetic display holography to visualize data a collaborative project was set up. The De Montfort University Imaging and Displays Research Group lead by Prof. Martin Richardson provided 3D imaging expertise and the Institute of Energy and Sustainable Development contributed computational 3D models which were suitable for testing the project brief. Dr. Simon Rees suggested the models based on his current research into visualization of solar irradiation and fluid flow data sets. The author, Creative Technologist Tove Dalenius, who initiated the idea of using synthetic display holography for Data Visualization was employed as researcher to materialize the concept. This project was transdisciplinary in nature and there was an instrumental continuous exchange of ideas throughout the process. The investigation was carried out in the first 6 months of 2014.

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1.3 Subject of the visualizations

Two different main subjects were selected for visualization, a model which features Solar irradiation data on the facades of a building, visualized through color variations and a model of a racing car using streamlines and colors to visualize fluid dynamic calculation outputs. These models offered suitable characters for assessing the concept, as well as depicting content accessible to a wider audience. The Solar irradiation model was created to visualize the amount of solar energy that falls on a building over the whole year. Architects are interested in the solar irradiation in order to identify where shading may be required and also to recognize where ideal places for solar panels may be. The modeling method used in the calculation takes account of the shading effects of the building components and surrounding objects over the whole year.[16] This is not possible to see with a physical model or a simple calculation.

The racing car model used in this study visualizes Computational Fluid Dynamics (CFD) data. CFD makes use of numerical methods to solve the partial differential equations that define fluid flow problems and produces large data sets that can be used to visualize how a gas or liquid flows, as well as how the gas or liquid affects objects as it flows past.[17] Such tools can calculate spatially varying velocities, turbulence and the pressures created by a moving object. In the automotive industry improvement of the aerodynamics of a car's design can increase the performance significantly and application of CFD tools and High Performance Computing resources has become routine practice. The flow of air around the car determines how much drag and down-force the car experiences and these quantities can be optimized through use of CFD methods during the design process. A wide range of visualization techniques and algorithms have been developed to allow filtering of the large data sets, formation of abstracted 3D polygon visualization objects and mapping of data to color and other visual attributes.[18] A number of such techniques have been tested in this study to generate examples of visualization objects that may be of interests to technical and non-technical audiences.

1.4 Practice-based Research method

This paper is presented with a methodological base in Practice-based Research (PBR). "Practice-based Research is an original investigation undertaken in order to gain new knowledge partly by means of practice and the outcomes of that practice" states Linda Candy who has a longstanding experience of establishing PBR at the groundbreaking the Creativity and Cognition Studios (CCS) at the University of Technology Sydney.[19] Many of the envisaged possible developments for Holographic Data Visualization combine understanding and skills from diverse academic fields. Physics and Optics, Big Data research, Data and Information Visualization, Cognitive science, Arts, Design, Creative Technologies, and numerous other relevant fields are often separated in terms of academic research areas. An approach that does deliberately encourage transdisciplinary collaboration is therefore desirable.

The research project at hand was made possible through the collaboration of investigators from a background of Mechanical and Architectural Engineering, Modern Holography, Fine Arts and Creative Technologies. Within a PBR situation creative output can be produced as part of the research practice, and "claims of originality and contribution to knowledge may be demonstrated through creative outcomes in the form of designs, music, digital media, performances and exhibitions."[20] However the work should also be supported by textual analysis to place it within a context and evidence critical reflection. In this investigation it was deemed of high relevance to produce tangible proof-of-principle holograms. The clear aim is to learn by doing, and to disseminate both practical procedural learning and a larger context of conceptualization.

1.5 Holographic Data Visualization

To encourage a searchable trail of research using the term Holographic Data Visualization was suggested by Dalenius in 2014.[21] Although a term following on from the established terminology Data Visualization and Information Visualization, and the newer and less established Data Physicalization, Data Sonification and Data Haptification[22] might have been most appropriate, it was felt that a suitable and good combination could not be made in the same way using the term holography.

2. TECHNICAL PROCESS

The CFD calculation that is initially expressed as numerical data (volumetric scalar and vector data fields) was first processed through use of the software ParaView. ParaView is an open-source application for data analyses and visualization.[23] The software has been developed to investigate large datasets, which can be explored interactively in 3D

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on a two-dimensional screen. This software interprets the data and generates streamlines, which are visualized as points, tubes, lines or ribbons. The visualization can be tuned using various filters to focus attention on the aspect under investigation. Particle paths can also be extracted. By applying glyphs such as arrows, cones or lines vector fields can be examined (Figs. 1 and 2). Color can be used to represent pressure or magnitude of velocity. In the case of the solar irradiation data (Fig. 1) the data sets consisted of unstructured polygons with scalar vertex data only. ParaView exports visualized data objects as X3D files - visualization objects consisting of polygons and vertex data. X3D is an open standards file format that represents 3D objects using Extensible Markup Language (XML). The format X3D is developed for use in scientific visualization and engineering.

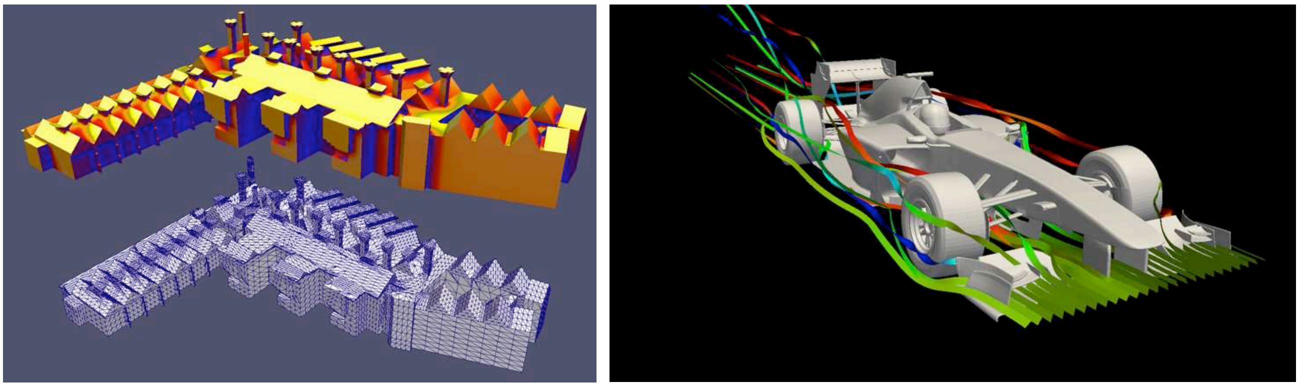

Figure 1 and 2. Visualization of Annual solar irradiation data and CFD data through ParaView

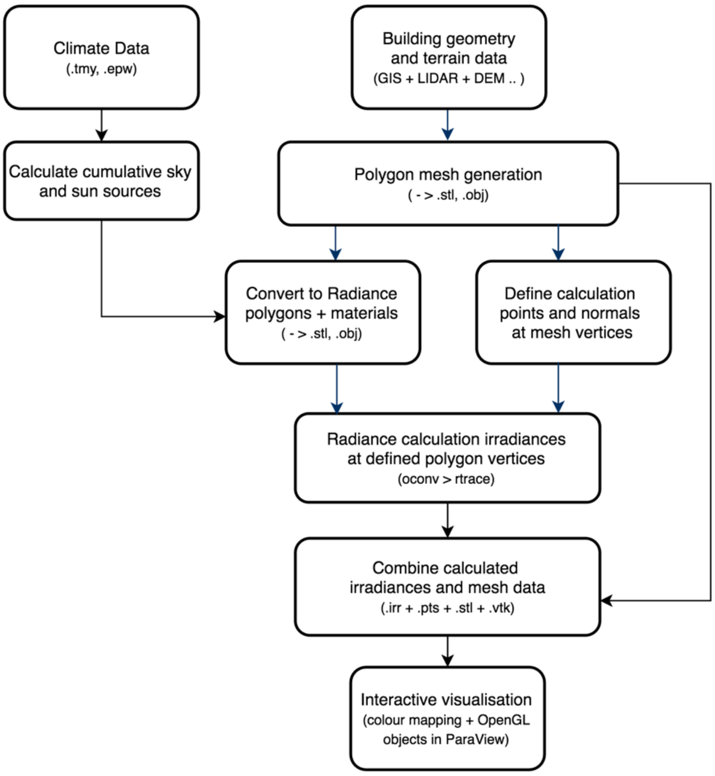

Figure 3. Schema for solar irradiation Data Visualization process.

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2.1 Initial challenges

To print the synthetic hologram Zebra Imaging Inc had been selected. The company provides a software tool "ZScape Preview" which allows the user to import their model in order for it to be constructed in a format suitable for the creation of a full-parallax hologram. The import file structures accepted by the software are polygon formats such as ZSM, STL and the most frequently employed OBJ. However the data was exported from the Data Visualization program expressed in the X3D format. It was not possible to import the X3D format visualization models directly into the selected manufacturer's pre-production software without converting them into a format that the pre-production software could read. The challenge was now to find an expedient method of doing this within the limited time scope of the research project. At first efforts were made to find a direct conversion tool to import the X3D and export as OBJ, but no such tool was readily available.

Attempts were made using MeshLab, an open source system developed to process unstructured 3D triangular meshes. It is mainly utilized for models generated by 3D scanning to edit and repair meshes. All though this program both imports the X3D format and export OBJ the color information of the initial model was lost. The color information in the X3D files exported by the visualization software is stored as vertex data and this was found to be lost in the conversion process. New attempts were made using the more complex versatile software package Blender. Blender is an open source 3D modeling tool used for developing animation movies, visual effects and 3D models. Although we were able to open and independently edit different elements of the Data Visualization models exported from ParaView, we still did not manage to export our project retaining the color information with the OBJ geometry definition file.

Eventually a solution was established through learning from 3D printing practice. In 3D printing a photographic image can be wrapped around a 3D mesh. A method describes as "vertex color baking" was identified for the software program MeshLab. Vertex Colors from the mesh generated in ParaView could also be baked to a UV texture map in Blender. The process of UV texturing pastes color from an image, a UV texture map, onto a 3D object. In Blender this process is called "render baking". A 2D bitmap image is created from a mesh object's rendered surface. This image is re-mapped onto the UV-unwrapped object using the object's UV coordinates. In this way the color expressing the computational information could be exported as an OBJ together with a material library file, which was compatible with ZScape Preview. The rendered bitmap image showed some artifacts that were additionally cleaned up in Photoshop. This process is illustrated in Fig. 4.

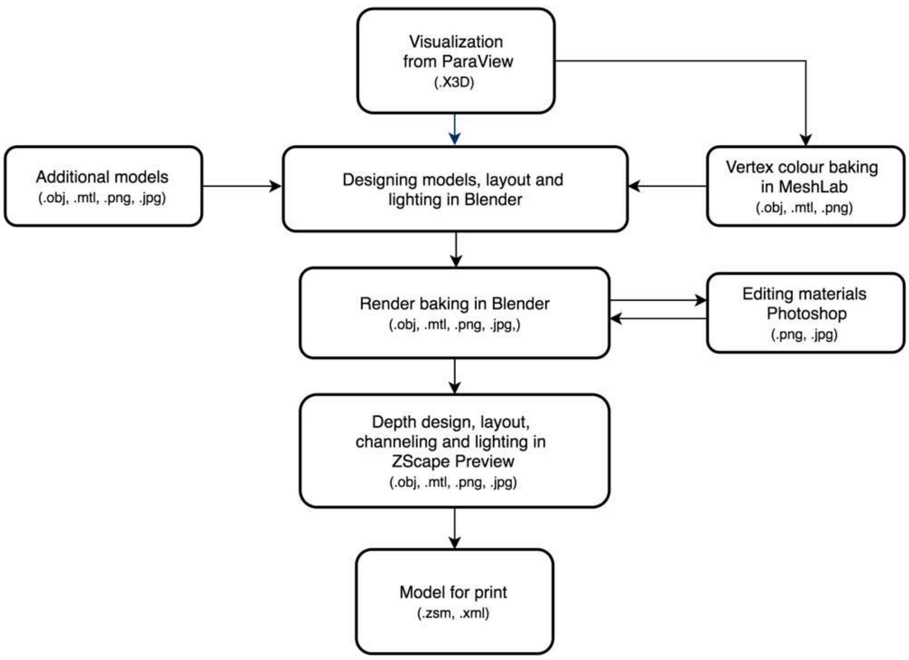

Figure 4. Schema for path from initial Data Visualization model to synthetic display hologram.

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The majority of the models were render baked in Blender, but the pressure model was vertex color baked in MeshLab. The final data sets are polygon surface meshes with texture mapped images. This final form also allows the possibility of combining the visualization data with other textured surface data – for example details of the underlying car surface, labels and logos.

3. DESIGN

Approaching the creation of the two holograms from a Practice-based Research perspective, allows giving importance to, and describing, the practitioners process. The intent here is to share struggles and success in order to support researchers, practitioners and artists. Sharing the issues encountered is taking place with the hope that a larger base of literature and accessible support information will be built through the exchange of experience and ideas.

The objective of creating these holograms was to investigate if synthetic display holography could be used to display Data Visualization in 3D. The team spent some time considering how this could be achieved to the best effect producing holograms that were engaging and interesting for a mixed audience. The designs were reworked several times, including and removing design elements and details in model materials and so on. It was agreed that the design would be kept as clean and simple as possible as to not distract the viewer, and to allow potential audiences to imagine their own designs and for example branding for the car model.

The Solar irradiation hologram was manufactured at a size of 450 by 450 mm. Both holograms are of a full-parallax horizontally displayed "table-top" design. In the CFD hologram channeling was introduced, the viewer can see a different Data Visualization design depending on the direction the hologram is viewed from. Four channels are used in the hologram with the model of the car remaining in the same location in each view. Each channel contains visualization data of different forms: surfaces, ribbons, streamlines, and vectors. The CFD hologram was manufactured at 450 mm by 600 mm.

3.1 Resolution, Color and Depth

The manufacture of the holograms is costly and there was little opportunity to try out more complex design details. Working out how much detail can be fitted in the full-parallax synthetic hologram's resolution, whilst not losing features due to the "pixelation" due to the hogel size, whilst not making flat and uninteresting surfaces, had to happen by estimation, as real life test-prints were not an option. The hogel size in The Zebra Imaging Inc holograms is 0.71mm.[24] Here there is a need for further research and sharing of experience between holographers.

The color sets were chosen to be bright and strong. Again the research team had to estimate what would work well, with some indications from Zebra Imaging to aim for saturated colors with a high degree of contrast values and to avoid pastels and subtle colors.[25] A chart of colors which may work well in synthetic full-parallax holograms could have been useful, as testing is not available.

Another issue was how to establish the best use of the "depth" and "height" available in the medium for the intended design. There is a lack of clear accessible guidelines. Zebra imaging provides the tool ZScape Preview where the practitioner can import the 3D models to frame, light, and export them for production. The software includes a tool, which visualizes the effect of depth blur, however these indications are only advisory. Written advice provided states a height and depth of 150mm to 200mm above and below the image plane is likely to work well, but that there is an increased risk of blurring.[26] In the holograms produced these limits were adhered to with caution. As budgets were limited there was no space for experimenting on this point. As with the cases above it would have been good to have a printed test hologram to refer to in person, where the limits and effect of depth blur can be experienced by the practitioner.

3.2 Design detail for the two holograms.

Color mapping for the Solar irradiation model hologram was designed as follows. Mapping from the numerical data input (the scientific data sets) to colors applied to the graphical objects is something of an arbitrary choice, but is more meaningful if there is a pre-defined false coloring correlation. False coloring refers to rendering methods where the natural/photographic color of an image is replaced with a color that is relaying some other form of information. The choice of mapping may be sensitive to the viewing context and type of data. A customized mapping has been constructed

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for the Solar irradiation data. In this case the extreme low end of the scale is mapped to black and the extreme high end to white. The lower third of the range is mapped from black to dark blue and the upper third is mapped from yellow towards white. The mid-range includes orange, red and a small band of green. In this mapping the dominant bright yellow corresponds to high insolation values and is intended to convey the dominant natural sunlight colors. This mapping is not a "recognized" standard but has been used by authors in a number of studies, for example by John Mardaljevic.[13, 27] A corresponding legend is included in the design of the hologram to inform the viewer.

The building featured in the Solar irradiation hologram is orientated so that it is aligned north to south, with a compass included in the design to inform the viewer. It is a model of an existing construction, the Queen's Building at the De Montfort University campus. Several different options were considered as to how the building should be related to its physical situation. A detailed 2D map was included for the building to "stand on", but it was felt that this was distracting from the issue portrayed. Trees were added around the building to give a sense of scale to the viewer, but again it was decided that this may distract from the point. In the end it was agreed that simplified outlines of roads close to the building would be put in place to indicate the building's setting and to mark a ground level (Fig. 5). This reduced map was created in Photoshop.

A minor detail noticed was that the compass was not "render baked" in the modeling software before exporting to the preview software. "Baking" it would have set any directional lighting information from the modeling software instead of relying on the lighting facilities in the preview program. Due to the cost involved it has not been possible to test both options, but an initial supposition is that the compass would have been more visually defined if it had been render baked, as the building model was. In the final hologram the compass is somewhat undefined and blurred compared to the rest of the composition.

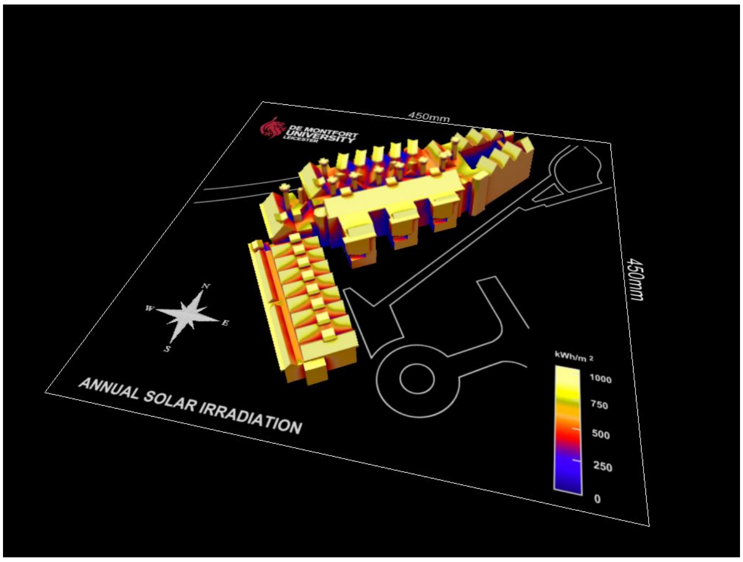

Figure 5. Solar irradiation design , screen captured in ZScape Preview.

In the CFD data hologram of the racing car a number of different indicators were used to visualize data. The CFD data sets contain information about the magnitude and direction of the air flow at points in a dense three-dimensional mesh (approximately 15 million data points). The data sets also contain scalar data representing quantities such as pressure. This volumetric data is supplemented by surface data sets that contain calculated pressures and derived variables such as drag and lift forces. Vector graphical objects created using a sub-set of the volumetric velocity data (e.g. points on a cutting plane) are the classical method of visualizing the flow patterns in CFD data - often coloring the objects by air speed or other quantities. Vector representations are a useful way of visualizing a sub-set of the flow field and allow spatial variations in the flow to be evaluated and structural features such as eddies to be identified. Streamline data (and derived tube and ribbon objects) identify particular paths through the flow field starting at a small selection of points.

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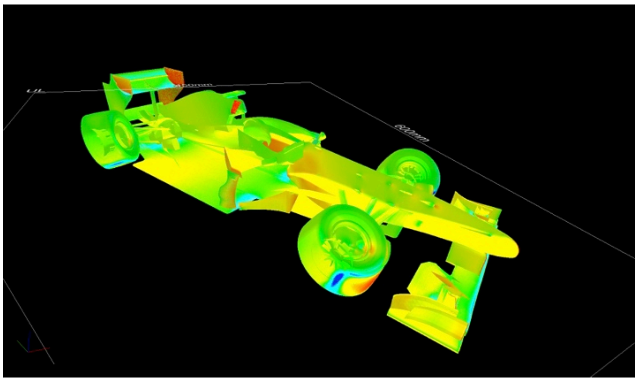
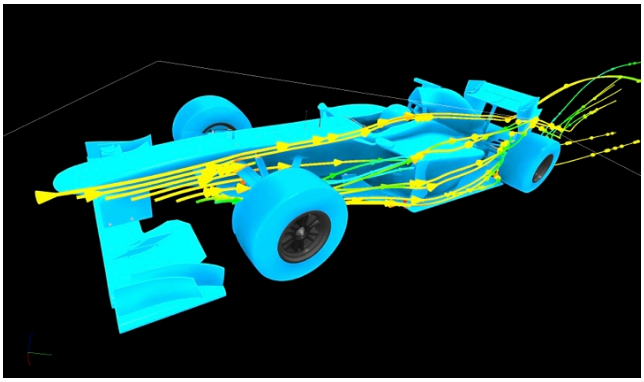
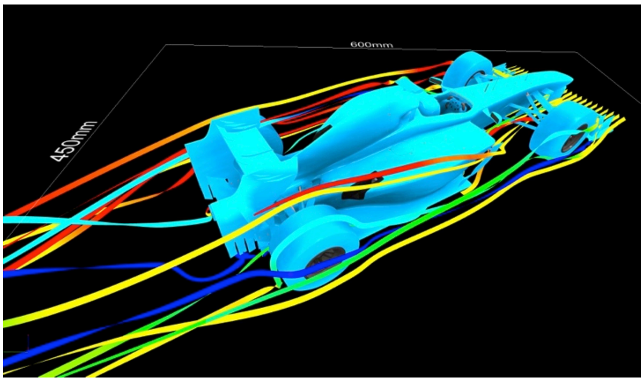
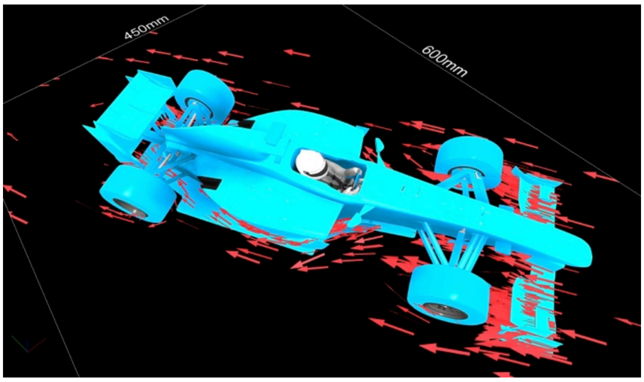
A common type of *generic mapping* uses a full range of hues in a blue to red spectrum (yellows and greens corresponding to mid-range data values). This form of mapping is meaningful for many audiences in the case of temperature data as red is often associated with higher temperatures and blue with cold temperatures. This generic mapping has been used to visualize pressure data in one of the views of the hologram (Fig. 6).

Figures 6 and 7. Generic mapping using false color visualize pressure data. Tubes visualize velocity data.





Figures 8 and 9. Colorful Ribbons visualize velocity data and Arrow Glyphs visualize flow field data.

Streamlines are created by post-processing the flow data by picking starting points in the flow and integrating the velocity data to find the path followed by a hypothetical particle released from that point. Additional post processing in the ParaView tool allows the streamline data to be translated from lines to polygons in the form of ribbons or tube objects that, in turn, can be colored according to other variable values or derived quantities. In the hologram presented two of the views visualize data using *tubes* and *ribbons* respectively (Figs. 7 and 8). The coloring of the tubes and ribbons is chosen to illustrate the capacity of holography to present a wide variety of detail, and is not in this hologram intended to primarily illustrate a specific point important to the automotive industry. In a fourth view the hologram visualizes CFD data using red *arrow* glyphs to illustrate flow fields (Fig. 9). Here the red was chosen to contrast with the blue car, the color does not carry a specific measure. Figures 6 to 9 are screen captures from ZScape Preview.

The pressure data is visualized as a transparent surface model of the car and its driver. In this view observers occasionally perceive that the model, in particular the wheels, are incorrectly inside out, others do not perceive this optical illusion. Interestingly this occurs both with the 3D model viewed on a two-dimensional screen and when the model is viewed as a hologram (Fig. 10).

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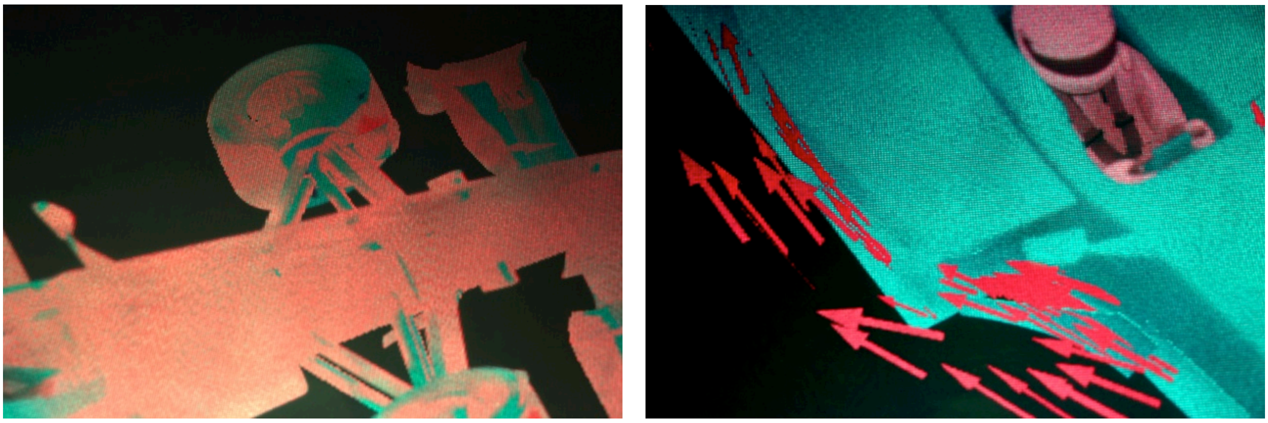
In the initial idea for the hologram the model of the car was intended to be white, but as large white surfaces in this type of hologram tend to tint in a green color a decision was made to make the car blue. This was a creative design choice, and the color contrasts well with the CFD Data Visualization. The blue color translates to a blue/green hue in the manufactured hologram (Fig. 11)



Figures 10 and 11. Close up photographs of the printed hologram: Wheel in pressure data visualization, Glyphs and driver detail.

4. RESULTS

We found that it was possible to make effective synthetic display holograms visualizing data through three-dimensional modeling. These holograms demonstrate in an initial way that the concept is viable, through concretizing a transformation of models from the 2D screen based 3D Data Visualization software ParaView, to a full-parallax holographic medium. Visual information about Solar irradiation and Computational Fluid Dynamics data could be shared through Holographic Data Visualization (Figs. 12 and 13), (Video 1 and 2).

"I think the main points would be that they form a permanent record of the visualization and a subset of the quantitative data. They also allow the visualization to be shared in situations like occasional meetings. They could be for use in the design and development phases of a project and they could be used to 'define' the final result i.e. some characteristic of its performance or behavior that would not otherwise be obvious from viewing the object without the false coloring and visualization objects added" commented researcher Dr. Simon Rees, when having experienced the manufactured holograms in person.

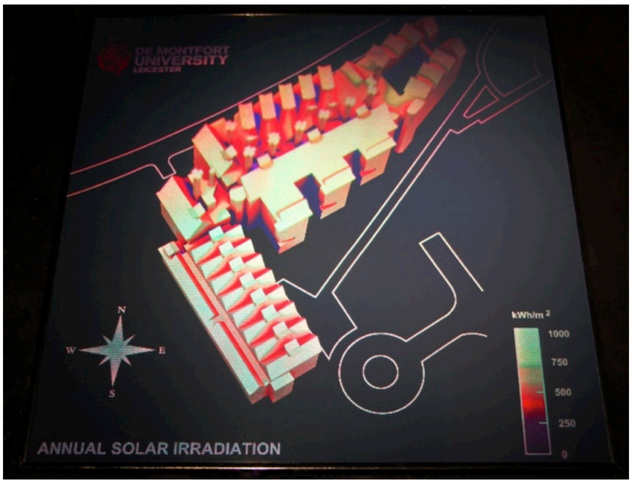


Figure 12. Photograph of Solar irradiation data visualization hologram

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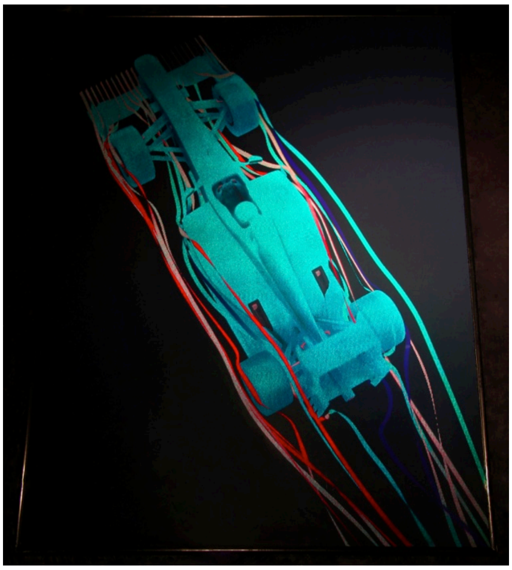
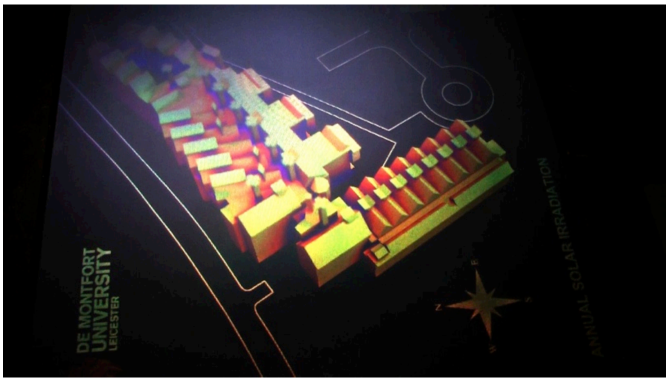
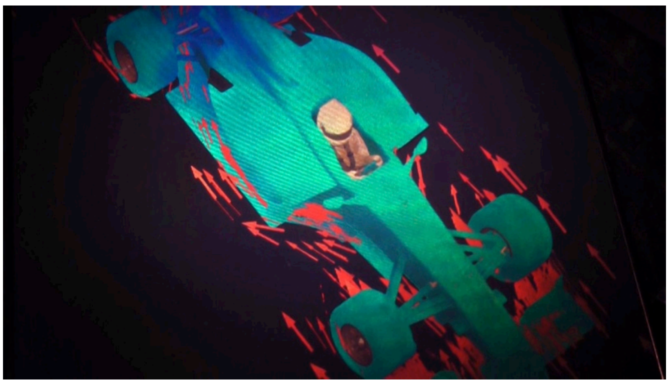


Figure 13. Photograph of CFD data visualization hologram

Links to video recordings of rotating display of the completed holograms. Video 2 exhibits the four channels.



Video 1. Holographic Data Visualization of Solar irradiation: http://dx.doi.org/doi.number.goes.here



Video 2. Holographic Data Visualization of CFD: http://dx.doi.org/doi.number.goes.here

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5. DISCUSSION

The concept of using holography for Data Visualization is in a very early stage. Future research projects where Data Visualization researchers work together with holographers to explore which kind of data sets could be expressed with most benefit through the three-dimensional medium which does not require the audience to wear glasses or headsets would be exciting. Are there any patterns, concepts or shapes that can be expressed in a particularly valuable way, to aid our understanding of the issues explored in the data sets? Are there any aspects of human 3D cognition that are not fully employed when visualizing 3D models on 2D screen technology or in print? How can the holography technologies be developed to make them more useful tools for Data Visualization?

Many of these themes and questions are discussed in the corresponding emergent research field of Data Physicalization, where the use of physical data representations to aid people in exploring and communicating data are investigated. In the formative paper "Opportunities and Challenges for Data Physicalization" Jansen et al. define the area as follows "A data Physicalization (or simply physicalization) is a physical artifact whose geometry or material properties encode data."[28] Examples of Data Physicalization include 3D printed sound wave visualizations where the sounds data 3D model can be seen, but also held and touched. Juan Manuel de J. Escalante and Realität created "Microsonic Landscapes" a representation of an algorithmic exploration the music.[29] Doug McCunes crafted a data sculpture describing housing prices ripping San Francisco apart, mapping the physical area and the price per square for recent house sales. The sculptural map twists and contorts the familiar 2D map of the city.[30] Nathalie Miebach creates woven sculptures combining colorful reed and wood with weather data.[31] Jansen et al. created physical 3D bar charts to compare to the use of 3D bar charts visualized on a 2D screen.[32]

However one of the criteria that distinguish Data Physicalization from Data Visualization is the production of material form as distinct from a display method that is exclusively visual, and holography is a visual medium and so does not fit neatly in the Physicalization field. The overlap in both concepts and inquiries are significant, and to build on common exploration is more expedient than attempting to develop Holographic Data Visualization in isolation.

Jansen et al. identifies potential benefits of Data Physicalization, whilst stating clearly that more research and evidence is needed to explore and evaluate these potentials. Benefits mentioned include: the utilizing of perceptual exploration skills such as active perception and spatial perception skills, cognitive and educational benefits, engagement and bringing data into the "real world" allowing audiences to relate to data in new ways. Data exploration through art and crafts also allows further means of engagement. The paper proposes that Data Physicalization is a research area that "examines how computer-supported, physical representations of data (i.e., physicalizations), can support cognition, communication, learning, problem solving, and decision making."

In terms of evaluation of Holographic Data Visualization many common aspects are found with Data Physicalization. Methodologies share challenges with the Data and Information Visualization and the Human–Computer Interaction field regarding how the benefits could be evaluated, and indeed in identifying what to evaluate. Jansen et al. categorize criteria such as: How do audiences engage with data? How do we evaluate understanding gained, the promotion of engagement and behavior change, memorability, and the affective responses elicited? The paper also points to the importance of exploring "methodologies for understanding how people reason, collaborate and communicate with physicalizations". It invites further joint research by visualization researchers to explore "novel contexts to apply their knowledge on the design of data representations", psychologists to "contribute methodologies and studies for understanding how physical interactions influence cognition", and Human-Computer Interaction researchers to "contribute knowledge on how to best design and implement interactions for physical data representations". Jansen et al. envisioned numerous "application domains to be explored for both serious data exploration with physicalizations, as well as more casual use."

The development of Holographic Data Visualization in terms of technology, visual 3D language, data and information visualization and concept can be of wider benefit for other three-dimensional display technologies. Multiview 3D, Volumetric 3D, and digital hologram 3D display technologies are continually capturing the imagination of both technologists and public audiences. Stereoscopic displays and Head-Mounts, Virtual Reality displays, Autostereoscopic 3D displays and Eye-tracking displays are becoming familiar.[33] The different media has various benefits and limitations, and continuing research can contribute to future iterations.

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Jens Shröter writes of the Transplane Image in his book "3D History, theory and aesthetics of the transplane image" (2014). He portrays the history of the differing 3D technologies such as "stereoscopy, photo-sculpture, integral photography, lenticular images, holography, volumetry and a series of sub types and hybrids". Shröter discusses the cultural context through which we understand these forms of image, and states "any planocentric limitation of the concept of "image" should be avoided by every future scholarly discussion in the theory of images."[34] It is much beyond the scope of this paper to expand on this reflection. However it could be conceptualized that we are still on the doorstep on what transplane imaging might be and mean for the forthcoming generations.

The possibilities of developing and exploring Holographic Data Visualization are at this moment in time wide open. This research project and paper has made a concrete start, through producing two holograms created with the intention to be data visualizations. A future and a history of the concept will be formed and evidenced through potential forthcoming research. It is hoped that this paper will stand as an open invitation to further investigation.

6. RECOMMENDATIONS

6.1 Procedural and design practice aides

To follow up on the practical experience of creating the holograms it would be expedient to support holographers and designers in directly understanding the possibilities and limitations of the full-parallax synthetic display holography medium, many of the issues are also transferable to HPO (Horizontal Parallax Only) synthetic display holography. As each hologram is costly to manufacture it is difficult for the researcher or practitioner to access the facility to test-print ideas.

A shared resource testing and describing practical challenges specific for the medium would have been beneficial to this research project and could be useful for the future. Although onscreen estimated depth blur visualization and vague guidelines are available none of these can replace the experience of viewing a real life hologram. A "test chart" hologram showing the results of depth and height blur could be created, using a variety of 3D shapes, and different materials and color options. As the distribution of these test holograms may be too costly for some research settings an online video of the hologram, with comments by holographers about their real life experience of the model could be added.

The use of color is at the moment slightly arbitrary, it is to a large extent reliant on estimation by the designer when imagining what the screen-based model's colors will look like in the printed hologram. Although there are many issues which have an effect on the final outcome, including the lighting situation when the hologram is played back, it would be useful to provide a test hologram. An array of colors could be printed, including both colors which work well and colors which are more difficult to achieve successfully in synthetic holography. Then a Hex Color Code number could be provided to the designers. Although these may change with different holographic methods and materials, a base code would be useful for holographers, designers and arts practitioners to work from.

A similar approach could be taken to detail in the model design. What are the smallest details in form that can be effectively visualized considering the size of the hogel? What are the finest details in patterns and imaging for 3D modeling materials that will be translated to visual information perceivable to the viewer? Carrying out such experimentation and sharing the outcomes would be a useful resource for an emergent community of Data Visualization holographers, practitioners and artists.

Direct export scripts for synthetic display holography could be created for commonly deployed Data Visualization software.

6.2 History of Data Visualization and Information Visualization using holography

Analogue and synthetic display holography has been used for information visualization with instances of for example architectural imaging, engineering imaging, design imaging, cartographic imaging and medical imaging. Examples in synthetic holography include human anatomy illustration holograms produced by Holoxica,[35] Desbiens "Simulation of the 1999 total eclipse over Europe" which visualizes astronomical information,[36] and holograms of urban growth and density predictions for urban development presented by the Environmental Systems Research Institute (Esri).[37]

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Commonalities and distinctions between Data Visualization and Information Visualization could be explored and defined. A historical overview would be of significance, to form a base for further research.

6.3 Future uses for holography in Data Visualization

Synthetic holography has proven to be a viable format for Data Visualization. Now research is needed to explore which types of data and data sets are best explored through using holography. Are there any unique aspects of holography that fits specifically well with certain visualization requirements? Are there particular human cognition characteristics that could be matched to expressing datasets in 3D, and in particular through the holographic format? Which types of collaborative projects between 3D visualizers in different fields and holographers could be most useful?

Here it is also important to give space for blue sky research, artistic investigation and play. An engaged community of researchers in the field could quickly build from where we stand today.

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