Perspectives for Using Virtual Reality to Extend Visual Data Mining in Information Visualization

Rubén Jesús García-Hernández[1] Christoph Anthes[1,2] Markus Wiedemann [1] Dieter Kranzlmüller[2,1]
[1] Leibniz Supercomputing Centre, Bavarian Academy of Sciences
Boltzmannstr. 1
85748 Garching bei München, Germany
[2] Ludwig-Maximilians-Universität
Oettingenstr. 67
80538 München, Germany
+49 - 89 / 35831 - {7826, 8744, 7834, 8703}
{garcia, anthes, wiedemann, kranzlmueller}@lrz.de

Abstract—**Although virtual reality (VR) has a huge success in increasing the quality of scientific visualization applications, there is a considerable lag in the development of VR applications in the case of information visualization (InfoVis). Some researchers in InfoVis claim that 2D representations are enough for data analysis; however, in the case of multi-dimensional datasets, other researchers indicate that studying multiple dimensions simultaneously is advantageous [1], [2], [3].**

The first studies with low quality stereoscopic devices showed no advantages when performing simple tasks on simple datasets [4]. However, recent experiments using higher quality devices and more complex datasets show a huge improvement in performance [5]. Still, designing an effective 3D representation remains a complex endeavour. Brath [6] provides a list of things to take into account.

This paper shows how a CAVE-like[2] environment can allow the study of multi-dimensional datasets while keeping multiple 2D representations available, using genome comparisons as a usecase. Parallel coordinate plots and non-planar graph representation in 3D space are also described.

Some potential applications in aerospace are also listed (this is by no means a complete listing of applications; readers are encouraged to suggest new ones).

Table of Contents

1. Introduction

Virtual reality interfaces have been used successfully for many years in the field of scientific visualization, with hundreds of both commercial and academic software systems created in the field of astronomy, physics, chemistry, biology, medicine, and engineering. The use of these interfaces provides well known benefits: easier understanding and manipulation possibilities for the data, yielding a more efficient and complete analysis. In the field of information visualization, in contrast, most approaches use a 2D visualization system, although a couple dozen systems do use virtual reality interfaces to evaluate complex datasets. Examples of such virtual reality systems include on the one hand studies of large non-planar graphs which arise from complex problems in different application domains, and on the other hand different visualizations dealing with gene expression data (and some systems show gene expression by means of graphs). Also, some 3D visualizations, which currently use standard 2D monitors for rendering, may in the future be applied inside virtual reality paradigms.

Some researchers have reported that no increases in performance were obtained by the use of stereo monitors versus monoscopic [7], when studying simple datasets. However, in the case of complex datasets the use of stereo and immersion does provide a definite advantage, as long as care is taken to provide a sensible interface [6].

Currently, some established researchers in the field of information visualization still express strong objections against 3D visualization [1], [2], [3] citing concerns about occlusion and distortion due to perspective projection; however, we expect that, with time, these objections will mitigate as more and more reasonable approaches are discovered (another possibility is the split of the information visualization community into 2D and 3D sub-fields).

Nevertheless, some results indicate that immersion seems to be beneficial in applications where spatial knowledge about an environment is useful, with head tracking providing greater user satisfaction and increasing task performance (head tracked users build a cognitive map of space more quickly, avoiding redundant searching) [8].

The visualization community takes the view that the use of immersive virtual reality techniques and proper interaction procedures can in most cases yield measurable increases in ease of use and productivity of systems, for a wide variety of application domains.

Interestingly, in the field of genomics, we do find a surprisingly high fraction of papers using VR for information visualization; it may be that this is due to the relatively small number of directly-representable concepts, but in any case, the success in this field is encouraging that other fields will benefit from applying VR techniques.

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This article presents a few techniques to easily create 3D visualizations to explore multi-dimensional data, which can be then explored by the use of stereoscopic, immersive visualization devices.

The paper is organized as follows: We start by describing the uses of virtual reality in information visualization (the review is, to the best of the author's knowledge, complete). Then, we show how commonly used 2D scatterplots of 3D data may be integrated into a 3D object. Later, we describe common 3D extensions of parallel coordinate plots. After that, we show how complex, non-planar graphs can benefit from 3D displays. Section 4 describes possible applications of the different techniques in the aerospace domain. Finally, some conclusions are shown, with some directions of future work mentioned. An appendix describes 3DScover, a successful usecase for displaying abstract three-dimensional data.

2. RELATED WORK

In contrast to the hundreds of successful uses of virtual reality in scientific visualization, there seems to be comparatively few uses in information visualization. We have performed an extensive search in the most relevant conferences and journals [9], [10], [11], [12], and further web-based searches; however, only a couple dozen papers show uses of VR in information visualization.

In the aerospace field, a virtual reality system for optimizing the design phase of satellites which uses 3D scatterplots and 2D parallel coordinates exists [13]. Immersive displays have also been used to visualise the parametric space of transfer orbits [14].

Outside of the aerospace field, VR has most often been applied in graph visualization and in genome analysis tools. A description of the applications follows.

A generic framework [15] introduces information rich virtual environments, supporting both immersive (specifically head mounted displays) and non immersive (desktop) 3D worlds. In these environments, a virtual world is enhanced with abstract information. The problems of text visualization are discussed in detail, and methods to avoid occlusion are also described.

Another general setup uses particle systems [16] to visualize time-varying datasets. The data-driven movement of the particles is guided by simulated forces or swarm simulation at the small scale, and the large scale views show aesthetically pleasant patterns; emergent behaviours and visual clues which map to higher level evolution and dynamic tendencies of the dataset. Interaction and navigation possibilities are provided.

Experiments have been performed to compare VR versus desktop environments for statistical visualization of multidimensional datasets.

One example is the C2 system. The design [17], the VR details [18] and the benefits for statisticians [19] have been published. The performance of users in detection and selection of clusters, intrinsic dimensionality and radial sparsity were tested, using the brushing and grand tour techniques. The use of VR produced improvements in performance for clustering and radial sparsity, which according to the error rate seem to be the most complex tasks. In the case of intrinsic dimensionality, the results were equally good in both platforms. A small learning curve is present for the VR system, so interaction was slower than with the desktop version for people with no previous experience in VR (though this might be due to a non-optimal selection of interaction gestures by the software developers).

The response times for statistical tasks regarding scatter and surface plots of 3D data have been measured in small pilot studies. The effect of field of regard (FOR), head-based rendering (HBR) and stereo were investigated by Raja [20]. The usefulness of high FOR, HBR and stereo was strongly dependent on the type of visualization and the task performed. While higher quality VR often produced lower response times and higher ease of use, the results were inconclusive at the sample sizes in the study (additionally, in one study, the floor projector was broken, so users could not use the top-bottom view, further skewing the results). Scatterplots in particular were particularly promising [8], although we think the low quality Gouraud shading used may have had an influence on the poor responses in surface plots.

Nagel et al. [21] shows the design of a VR system supporting extended scatterplots (in which each point in 3D is rendered as a glyph encoding more information from other data dimensions), 3D histograms and combinations of surface and 3D scatterplots. Initial informal tests of the system indicate that it can be useful to find non-linear relationships among variables [22].

3D self-organizing-maps (SOM) have also been proved to be useful in CAVE environments [23]. The main benefits with respect to 2D SOM are natural and intuitive interaction and exploration, and smaller size of the generated maps.

In the software engineering field, VR was used to visualize the architecture and design of software systems [24], and particularly object-oriented designs [25].

Immersive visualizations of general graph-based data have also been created. Osawa et al. [26] describes a general system, which includes direct manipulation using hand gestures. Smith [27] presents a variety of layouts and applies them to visualization of coupled differential equations, network intrusion detection data, processor interconnect data, or forces among atoms. Debugging data mining algorithms and exploring the generated trees is also facilitated by VR techniques [28].

3D stereoscopic monitors have been used for enhancing the visualization of 2D layout graphs. AlTarawneh [29] changes the depth of the nodes with which the user is interacting, raising them towards the user, to provide an optical zoom. Compound graphs are also separated by depth clues. The parent-child relationships can also be encoded in depth, displaying children nearer. Alper [5] compares traditional colour highlighting of nodes with depth-based highlighting. Both provide similar benefits in task completion, and their combination provides higher decreases in task completion time than either technique alone. Occlusion and perspective problems in general 3D layout of graphs are mentioned as reasons to stick with 2D layouts.

Studies related to gene expression are also common; VR was used in gene expression studies: to study relationships within a gene family and networks of gene expression data [30], to find relationships between gene expression and illnesses [31], to display relationships between gene expres-

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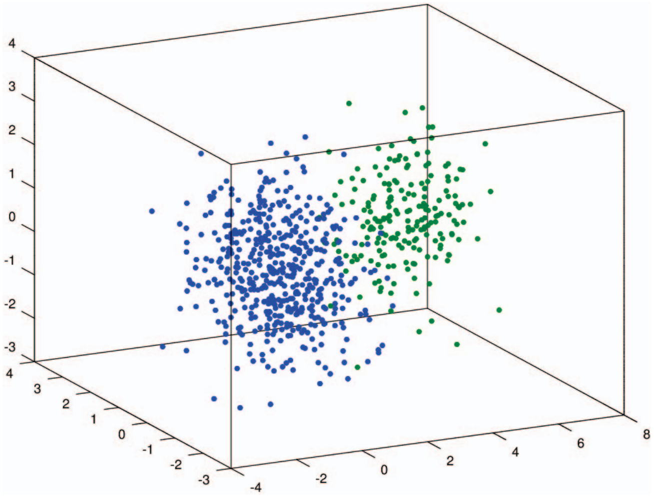

Figure 1. Example visualization of a 3D scatterplot. Two clusters, following normal distributions N([0,0,0], [1,1,1]) and N([4,0,1],[1,0.5,1]) are shown.

sion and metabolic pathways [32], and to display gene expression to help select suitable genes for drug discovery [33], [34], [35]. It was also used to establish correspondences between genes according to different criteria [36], and to display interactions among loci within the human genome [37].

With respect to the visualization techniques used in these genome studies, exploration of graphs was used by Ferey et al. [36], Stolk et al. [30] and Yang et al. [32]. A dividing road metaphor to symbolize decision taking and a lab bench metaphor for information display was used by Nishimura et al. [33], [34], [35]. 3D dotplots and sets of vectors were used in Kanou et al. [31]. A visual landscape based on a relation matrix is found in Aiden Lab's Juicebox [37].

3. General Approaches Particularly Suited for Aerospace

We now describe in some detail the three approaches which we consider that show the best promise for successful application in the aerospace domain: integration of multiple 2D graphs for 3D data, 3D parallel coordinates and visualizaton of complex graphs.

Integrating Classical 2D Plots into a More Informative 3D Object

3D scatterplots have been used for a long time to study three dimensional datasets. Most often, rotation by mouse-drag is used to let the brain recover the 3D information. However, the quick, small rotations interfere with the data analysis, so a better method is the use of 3D monitors or immersive environments. See figure 1 for an example; if the techniques are not available, understanding is greatly hampered.

A novel approach [38] takes three well known 2D visualizations in the field of genomics and notices that they can be seen as 2D projections of an underlying 3D structure. They use a CAVE-like[2] immersive environment to display this 3D structure. At the same time, the three projections are put on the walls, taking care that everything is correctly aligned. This approach allows easier understanding of the data (see appendix for details). The approach can be reused in many other fields where multi-dimensional data has until now been studied by pairwise comparison of different variables, in order to extend previous methods to three way comparisons, which will yield a more complete, study. If five variables are studied, the number of combinations is ten in both cases. For fewer variables, there are fewer 3D graphs than 2D graphs. For more than five variables, there are more 3D graphs, but each provides more information, so it may make sense to choose some of these 3D graphs if the relevant 2D projections show interesting interrelationships.

Still, there are many datasets with a dimensionality between three and five, so this approach is worth investigating. For n variables, there are $C_n^2 = \frac{n!}{2(n-2)!}$ 2D graphs and $C_n^3 = \frac{n!}{6(n-3)!}$ 3D graphs. In particular,

$$C_3^2 = 3; \quad C_3^3 = 1; \tag{1}$$

$$C_4^2 = 6; \quad C_4^3 = 4; \tag{2}$$

$$C_5^2 = C_5^3 = 10; \tag{3}$$

$$C_6^2 = 15; \quad C_6^3 = 20. \tag{4}$$

Care must be taken to provide a 3D structure that highlights the meaning of the data, and the interrelationships among the variables, while preserving the correspondences with the 2D projections to enable seamless switching between the already internalized meaning of the often-used 2D graphs and the 3D data structure.

The device used should match the mapping used for graphing the different variables. Cartesian mapping is optimal for CAVE displays, while cylindrical or spherical mapping can be best viewed in displays of corresponding shapes (see figure 2 for example hardware configurations). Some work has also been performed on using general surfaces as projector screens (using Microsoft Kinect [39] or 360° cameras [40]). If the data should be projected into a more complex 2D manifold embedded in 3D space, and the manifold can be constructed, these techniques can be useful. Single, planar screens are not very convenient for this use, as they only provide stereo to account for the third dimension.

In addition, the result can be generalized to more than three dimensions [41]. Methods exist to navigate and display a 4D world by letting the user move and rotate within it, and using the position and orientation of the user to generate 3D cross-sections which are then re-projected into a 2D monitor, and which can be generalized to an n-dimensional world. In the case of immersive, stereoscopic virtual reality devices, we can obtain a more realistic view of the 3D cross section, avoiding some of the ambiguity created by the monoscopic 2D projection. The possibility to walk and look around also help better understand this 3D slice of the 4D world.

Hollasch [42], section 4.3 uses a double projection from 4D to 3D and from 3D to 2D, each with different parameters, to view the 3D projection from different angles while maintaining a constant 4D view. While the resulting 2D views are not "physically plausible", in the sense that no direct 4D to 2D projection can achieve the views, this false perspective can aid in object understanding.

[2] CAVE^{TM} is a trademark of the University of Illinois Board of Trustees. We use the term CAVE to denote the both the original system at Illinois and the multitude of variants developed by multiple organizations.

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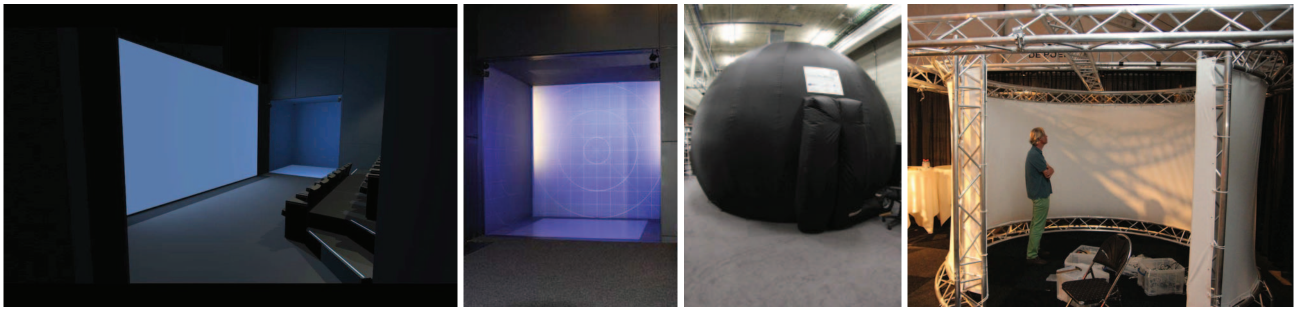

Figure 2. Immersive devices: Planar, cubical, spherical and cylindrical VR. The first two images correspond to the V2C at LRZ. The next image is in BLOOM, while the rightmost image belongs to EDM. See acknowledgments for full attribution.

The extension of the system to general, n-dimensional worlds should take into account the added stress on the users when they need to navigate, remember and orient themselves in a high-dimensional landscape; often, it will be better to use multiple projections into lower-dimensional worlds, and explore these in succession, than to try to understand the high dimensional world in one go.

There is furthermore considerable reluctance to the use of 3D solutions by some established researchers in the information visualization field, as mentioned earlier, so these 4+ dimensional worlds remain early experimental prototypes at the moment.

3D Parallel Coordinates

Another possibility to harvest the power of immersive displays is to combine Parallel coordinates [45] with 2D scatterplots. Parallel coordinates display multi-dimensional datasets by displaying parallel vertical lines, each of them corresponding to a dimension in the original data. A datapoint becomes a polyline. However, often some of these dimensions are actually projections of a 2D variable (such as longitude / latitude). If we keep these 2D subspaces, we can create a 3D, parallel coordinates representation, in which parallel planes are used in addition to vertical lines. Data points become polylines in 3D space, and each plane is effectively an scatterplot showing these dimensions. This provides a simplified display, in the sense of fewer segments needed. The use of stereoscopy enables the user to always see the correct positioning of the data points, and avoids the ambiguity of planar monoscopic displays.

Parallel coordinates have also been integrated with star glyphs to obtain 3D parallel coordinates [44]. The data can also be unrolled along the third dimension instead of in the glyph, as Honda and Nakano [43] show. Figure 3 provides an example of the techniques; from a hidden, $A0 \rightsquigarrow N(0,1)$ variable, we obtain $A1 = A0 + N(0, 0.2)$, $A2 = (1 - A0) + N(0, 0.1)$, $A3 = A0^2 + N(0, 0.2)$, $A4 = N(0, 1)$, $A5 = A2 \cdot A4$. The inverse and quadratic relationships can be seen directly on the second graph, while rearrangements would be required in the first graph. Star glyphs readily provide quick impressions of the data. Transparency helps in minimizing the problems of occlusion.

The use of immersive, stereoscopic displays would be useful to help understanding in these visualizations as well. Multirelational parallel coordinates also uses a 3D representation [46]. 3D parallel coordinates have also been used to add line density information to standard parallel coordinates, using monoscopic displays [47]. Depending on the data complexity, the use of immersion can also help understanding. As we mentioned earlier, a virtual reality system for the design phase of satellites which uses parallel coordinates already exists [13].

Understanding Complex, Non-planar Graphs

Complex graphs arise often when studying the relationships among multiple interrelated concepts. There have been many studies which indicate that immersive, stereoscopic systems aid in understanding and navigating these graphs (e.g. [32], [30]). Figure 4 shows an example visualization of a graph in an immersive environment.

A survey of techniques is provided by Herman et al. [48]; section 2.4 has a collection of 3D techniques which may benefit from stereoscopic displays. Most of the techniques are generalizations of 2D placement algorithms. The availability of extra space needs to be traded off with the occlusion added, but the use of transparency and interactivity means that often there is a large net gain.

4. Potential Applications in Aerospace

This section provides a quick example of some areas where the techniques described above might be of interest in aerospace research. It does not intend to be exhaustive; comments from experts in aerospace about further application areas are welcome.

Exoplanet Research

Exoplanet.eu [49] contains a database of exoplanet data, and allows the creation of 2D scaterplots to compare two of the following dimensions: Angular Distance, Argument of Periastron, Calculated and Measured temperature, Conjonction Date, Epoch of Periastron, Geometric albedo, Hottest point longitude, Impact Parameter b, Orbital Eccentricity, Inclination and Period, Planetary Mass and Radius, Primary and Secondary Transits, Velocity Semiamplitude K, Year of Discovery, Zero Radial Speed time, log(g), H, I, J, K and V magnitudes of a host star, Distance, Mass, Radius, Metallicity, Age and Effective temperature of a host star, RA and Dec (J2000) of a star, Semi-Major Axis, Sky-projected angle between the planetary orbital spin and the stellar rotational spin.

Being able to do 3-way comparisons would provide more insights into the relationships among the variables.

The use of parallel coordinates can also be interesting, es-

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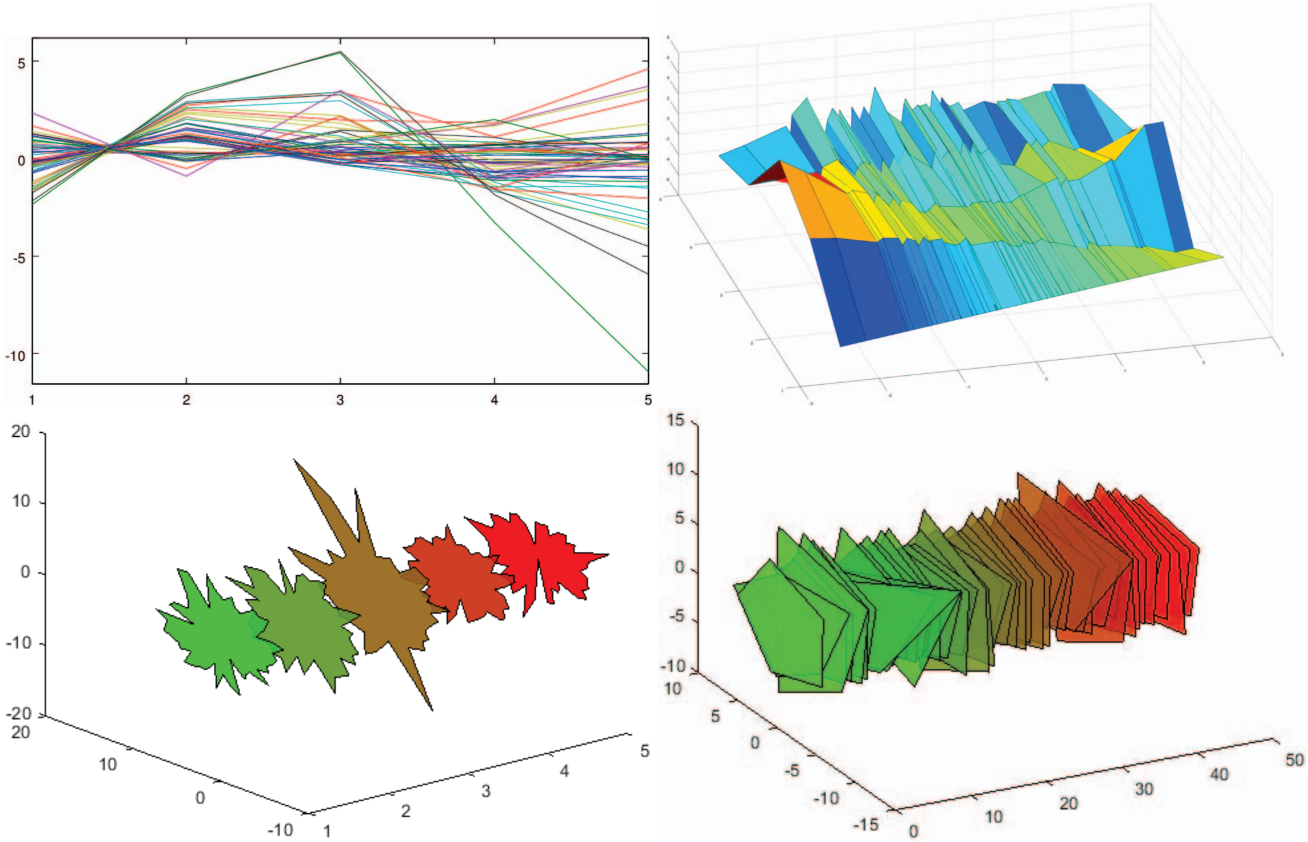

Figure 3. **Example visualization of a parallel coordinate plot and some 3D extensions: Top left: standard 2D parallel coordinate plots. Top right: 3D extension following Honda et al [43] figure 2. Bottom row: Visualizations following Fanea et al [44], figures 4 and 5.**

pecially since some of the variables can be integrated in 2D planes, as mentioned previously.

Spacecraft Design Optimization

As mentioned earlier, Stump et al. [13] have successfully used immersive virtual reality to visualize graphs related to optimization parameters in the design phase of satellite creation. The use of more advanced visualization techniques will allow better decision making in the case of especially complex spacecraft.

Spacecraft Optimal Path Analysis

Often, spacecraft orbit manouevres, gravity assists and insertion burns are plotted using two spatial dimensions plus time. The use of 3D displays allows us to graph time in a spatial dimension, showing all the information in one go.

In the case of craft leaving the solar system plane (e.g. Ulysses [50], Solar Orbiter [51], Solar Polar Orbiter [52]), the three spatial dimensions are needed to show the orbital path. However, a 3D plus time representation will benefit from stereo, immersive displays (immersive displays have already been used for choosing transfers to Earth-Sun L2 halo orbits [14]).

See figure 1 from Wenzel et al. [50] for the equivalent 2D drawing; if multiple assists and complex manouevres had been needed, the image would not be readable. See also figures 1-3 from Muller et al. [51] and figure 1 from Macdonald et al. [52]; a 3D representation would greatly benefit understanding, especially for non-experts.

The advantages of these displays will become more apparent as longer missions take place, which will probably use more complex orbit adjustments and gravity assists to reduce costs.

Depending on the parametrization used, these visualizations may be classified as either scientific or information visualization.

Aerodynamic Design

3D scatterplots are already used for visual data mining in aerodynamic design [53]. The use of immersive, stereoscopic devices can help when the number of datapoints increases to the point where standard monoscopic displays become too crowded for image understanding.

Launch Abort Decision Making

Massive time series are used to detect anomalous behaviour in order to decide if rocket launches should proceed or be aborted [54]. Multiple variables are monitored simultaneously. The use of immersive 3D displays can be used to study the relationships between pairs of these variables, and help detect failure conditions which depend on the interaction among various variables.

Mission Planning

When designing complex, multi-objective, multi-spacecraft missions, many constraints must be simultaneously taken into

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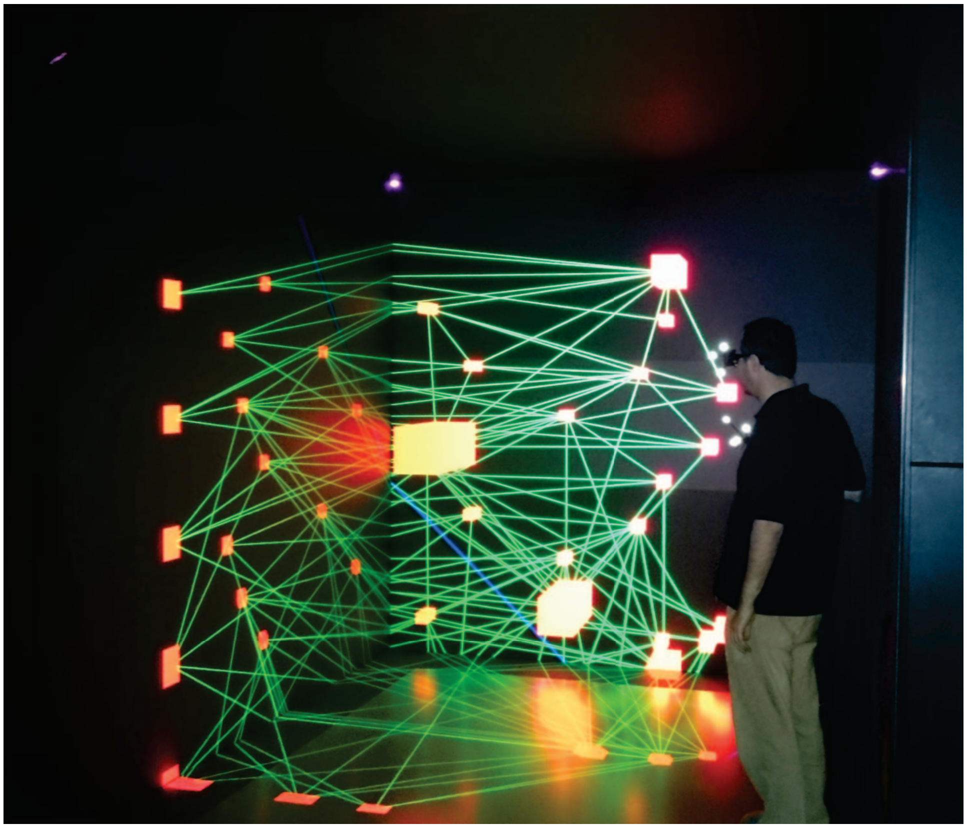

Figure 4. **Example rendering of a complex, non planar graph displayed on a CAVE, in the spirit of Stolk et al. [30]. Stereoscopy has been disabled to ease image understanding in written media. In normal use, head tracking, stereoscopy and pointing possibilities allow for easier understanding of nodes and relationships.**

account. Decisions restrict later available courses of action, and delays propagate into the different subsystems.

Often, the best way to obtain an overview of how concepts are interrelated is to create a graph. However, with complex missions, these often non-planar graphs can be difficult to visualize in a 2D screen. The use of the 3D, immersion aware visualization systems for complex graphs can aid in understanding the workflow for these missions.

Graph theory has been used to study the design space of multiple, interrelated space missions [55] (in essence a full space program). Visualization of the analysis may also benefit from immersive displays.

Space Debris, Asteroid and Near Earth Object (NEO) Orbit Analysis

3D scatterplots are used in space debris analysis, for example for orbital parameter distributions (see Anz-Meador [56], figure 2 for an example). As the problem of space debris worsens and the debris population increases, immersive techniques will be needed to make sense of increasingly complex graphs.

In the case of studies of asteroid and NEO families, the same techniques may be of use. As more asteroids are discovered, the scatterplots will become more crowded and difficult to understand. The use of 3D graphs can simplify some studies (for example, Warner et al [57], figures 5, 7 and 8 and Stokes et al [58], figure 2-1 each show two 2D scatterplots using excentricity and inclination in the vertical axis against different variables in the horizontal axis; these might benefit from a 3D scatterplot if stereoscopic visualization is available).

Citizen Science in Aerospace

Citizen science is a research technique which takes advantage of laymen interested in scienticic topics, by having them perform data analysis tasks. The internet is used to provide potential citizen scientists with a description of their expected task and the tools required to perform it. Their contributions are then aggregated for review by the scientists providing the data [59].

Up to now, citizen science projects have used simple 2D representations for displaying the information to be analyzed. Exoplanet search, for example, uses light curves [60]. However, many current televisions and monitors have 3D capabilities, and in the near future, we expect low-cost immersive displays to popularize. The use of stereoscopy and immersion will allow researchers to prepare more data-rich representations, increasing the feasibility of higher-level science return from final users.

5. Conclusions and Future Work

Creating effective 3D interfaces can be complex and time consuming. We have shown here how, by using a combination of 2D graphs, a simple way to create a 3D interface presents itself. This interface keeps the original 2D graphs, to ease the transition to the new system, and adds a 3D structure to show 3-way interrelationships. A usecase is presented (see

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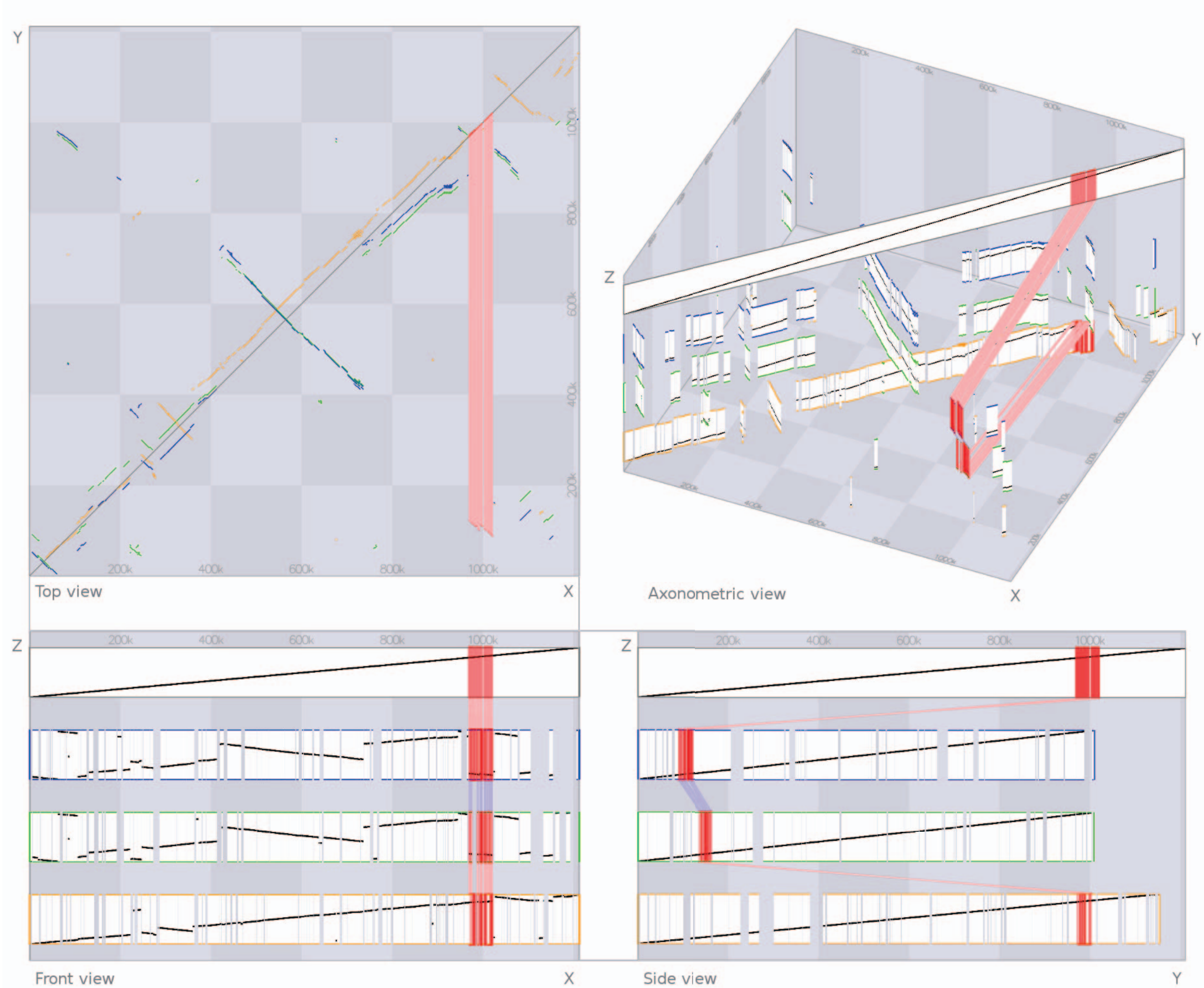

Figure 5. **2D representations of genome comparison 3DScover and monoscopic 3D view**

appendix).

We also highlight a few 3D parallel coordinate visualizations, and describe how complex, non-planar graphs can be more easily studied using 3D displays.

We also mention how the three types of interfaces can be of application in multiple areas within the aerospace community, and the fact that the use of virtual reality displays can greatly aid in data manipulation and understanding.

For future work, we would like to investigate what other general techniques for information visualization can benefit from virtual reality interfaces. Low cost immersive devices such as head-mounted displays might also be of interest. We would also like to investigate applications in other domains.

Appendix: 3DScover Usecase

3DScover [38] integrates three well known bi-dimensional representations of genomic comparison data:

- **top view**, or **dot plot**: Used to show genome alignment.
- **front view**, or **gradient view**: Used to perform multiple whole genome comparisons.
- **side view**, or **linear representation**: Used to highlight inter-genome connections.

Geneticists need to use all views and switch among them to perform an analysis of the evolutionary events which create, from a single original species, a multitude of different organisms, each adapted to a different niche.

Figure 5 shows the different 2D views. The 3D structure of which the 2D views are orthogonal projections can be used as cognitive anchor, as Brath [6] suggests, or it can be used directly to easily visualize evolutionaty events.

Figure 6 shows the use of a CAVE environment to display concurrently the three projections and, optionally, the 3D data structure. Analysis is simplified by the possibility of using locomotion and gaze to switch fast and intuitively among projections and 3D structure. A small-scale 3D object is also available to support direct manipulation paradigms.

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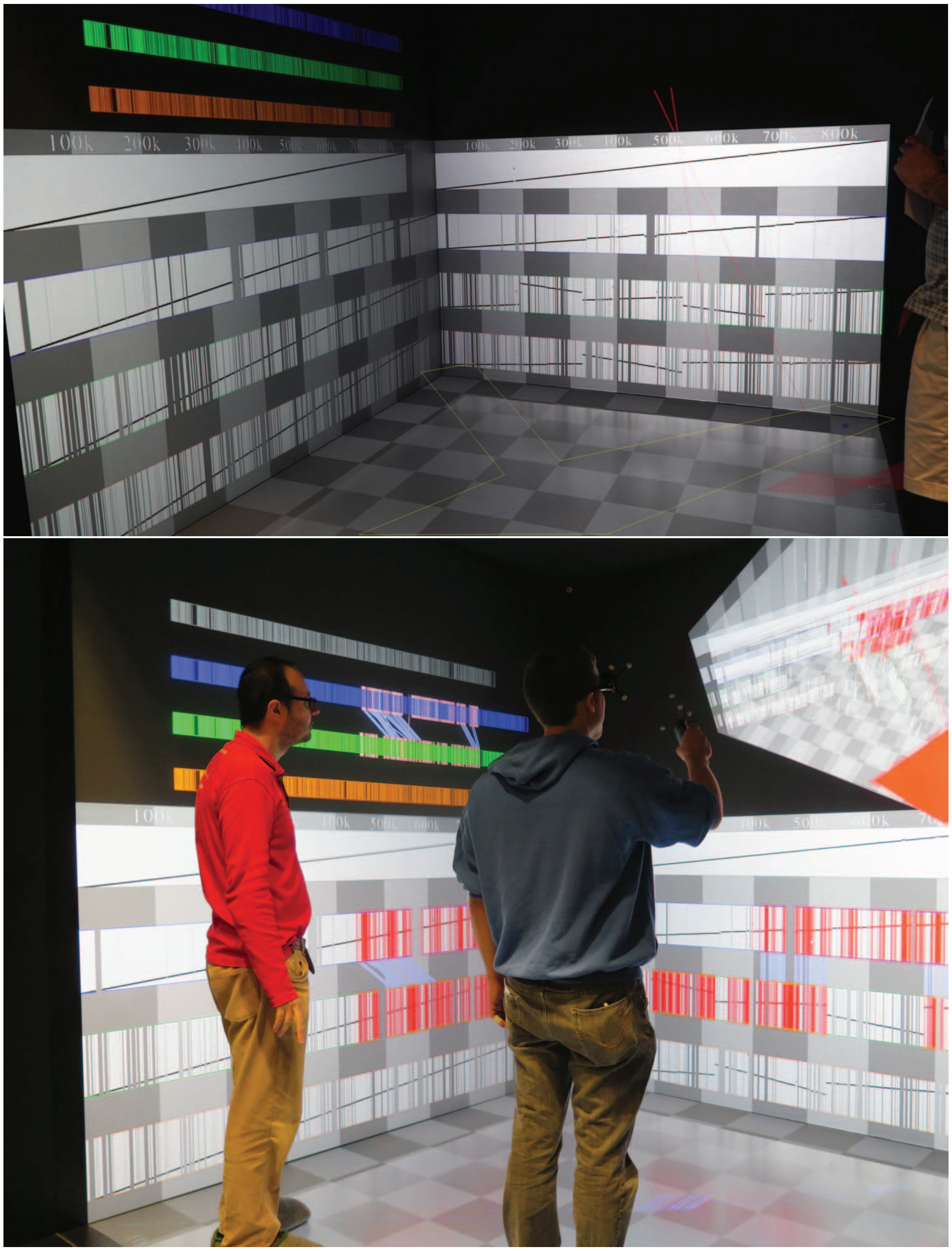

Figure 6. **CAVE views. Top: 2D projections (the graphs in the floor –red, green and blue lines– are difficult to see due to the camera angle, but they can be seen quite clearly when standing within the CAVE; a yellow polygon was added to ease finding them in this image). Bottom: showing the 3D structure. While the screens show a monoscopic view with the projections, a fully stereo, 3D representation can be manipulated to highlight the relationships among the projections.**

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Figure 2 shows installations at the Leibniz Supercomputing Centre, Bavarian Academy of Sciences (Munich, Germany), the BLOOM Centre 3D i Tecnologies Emergents (Girona, Spain), and the Expertise centre for Digital Media of Hasselt University (Hasselt, Belgium).

REFERENCES

[1] T. Duval, P. Kuntz, J. Royan, W. Stuerzlinger, and G. Venturini, Eds., *2014 IEEE VIS International Workshop on 3DVis: Does 3D really make sense for Data Visualization?* Paris, France: IEEE, Nov 2014.

[2] R. S. Laramee, C. Hansen, S. Miksch, K. Mueller, B. Preim, and C. Ware, Eds., *2014 IEEE VIS Panel: 2D vs 3D*. Paris, France: IEEE, Nov 2014.

[3] C. Chen, *Information Visualisation and Virtual Environments*, C. Chen, Ed. Springer, 1999.

[4] J. McIntire and K. Liggett, "The (possible) utility of stereoscopic 3d displays for information visualization:

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The good, the bad, and the ugly," in *2014 IEEE VIS International Workshop on 3DVis: Does 3D really make sense for Data Visualization?*, T. Duval, P. Kuntz, J. Royan, W. Stuerzlinger, and G. Venturini, Eds. Paris, France: IEEE, Nov 2014.

[5] B. Alper, T. Hollerer, J. Kuchera-Morin, and A. Forbes, "Stereoscopic highlighting: 2d graph visualization on stereo displays," *IEEE Transactions on Visualization and Computer Graphics*, vol. 17, no. 12, pp. 2325–2333, Dec. 2011.

[6] R. Brath, "3D InfoVis is here to stay: Deal with it," in *2014 IEEE VIS International Workshop on 3DVis: Does 3D really make sense for Data Visualization?*, T. Duval, P. Kuntz, J. Royan, W. Stuerzlinger, and G. Venturini, Eds. Paris, France: IEEE, Nov 2014.

[7] Y. Jansen, P. Dragicevic, and J.-D. Fekete, "Evaluating the efficiency of physical visualizations," in *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, ser. CHI '13. New York, NY, USA: ACM, 2013, pp. 2593–2602.

[8] D. Raja, D. A. Bowman, J. Lucas, and C. North, "Exploring the benefits of immersion in abstract information visualization," in *8th Int'l Immersive Projection Technology Workshop (IPT '04)*, 2004, pp. 61–69.

[9] *IEEE Virtual Reality Conference*, 1993–2016.

[10] *IEEE Symposium on 3D User Interfaces*, 2006–2016.

[11] *ACM Virtual Reality Software and Technology*, 1994–2015.

[12] *Presence Journal*. MIT Press, 1998–2015.

[13] G. Stump, M. Yukish, T. Simpson, and J. O'Hara, "Trade space exploration of satellite datasets using a design by shopping paradigm," in *Aerospace Conference, 2004. Proceedings. 2004 IEEE*, vol. 6, March 2004, pp. 3885–3895 Vol.6.

[14] K. Museth, A. Barr, and M. Lo, "Semi-immersive space mission design and visualization: case study of the "terrestrial planet finder" mission," in *Visualization, 2001. VIS '01. Proceedings*, 2001, pp. 501–599.

[15] D. A. Bowman, C. North, J. Chen, N. F. Polys, P. S. Pyla, and U. Yilmaz, "Information-rich virtual environments: Theory, tools, and research agenda," in *ACM Symposium on Virtual Reality Software and Technology (VRST '03)*, Osaka, Japan, 2003, pp. 81–90.

[16] A. Vande Moere, *Infoticles: Information Visualization Using Data Driven Particles*, ser. Selected readings in vision and graphics. Hartung-Gorre, 2004.

[17] J. Symanzik, D. Cook, B. D. Kohlmeyer, U. Lechner, , and C. Cruz-Neira, "Dynamic statistical graphics in the C2 virtual environment," in *Second World Conference of the International Association for Statistical Computing*, Pasadena, California, USA, Feb 1997.

[18] L. Arns, D. Cook, and C. Cruz-Neira, "The benefits of statistical visualization in an immersive environment," in *IEEE Virtual Reality (VR '99)*, March 1999, pp. 88–95.

[19] L. Nelson, D. Cook, and C. Cruz-Neira, "XGobi vs the C2: Results of an experiment comparing data visualization in a 3-D immersive virtual reality environment with a 2-D workstation display," *Computational Statistics*, vol. 14, no. 1, pp. 39–51, 1999.

[20] D. Raja, "The effects of immersion on 3D information visualization," Master Thesis, Virginia Polytechnic Institute and State University, Blacksburg, VA, USA, May 2006.

[21] H. R. Nagel, E. Granum, and P. Musaeus, "Methods for visual mining of data in virtual reality," in *Proceedings of the International Workshop on Visual Data Mining, in conjunction with ECML/PKDD2001, 2nd European Conference on Machine Learning and 5th European Conference on Principles and Practice of Knowledge Discovery in Databases*, 2001, pp. 9–12.

[22] H. R. Nagel, M. Vittrup, E. Granum, and S. Bovbjerg, "Exploring nonlinear data relationships in VR using the 3D visual data mining system," in *Proceedings of the International Workshop on Visual Data Mining, in conjunction with The Third IEEE International Conference on Data Mining*, 2003.

[23] D. Wijayasekara, O. Linda, and M. Manic, "CAVE-SOM: Immersive visual data mining using 3D Self-Organizing Maps," in *Neural Networks (IJCNN), The 2011 International Joint Conference on*. IEEE, Jul. 2011, pp. 2471–2478.

[24] J. I. Maletic, J. Leigh, and A. Marcus, "Visualizing software in an immersive virtual reality environment," in *in Proceedings of ICSE'01 Workshop on Software Visualization*. Society Press, 2001, pp. 12–13.

[25] J. Maletic, J. Leigh, A. Marcus, and G. Dunlap, "Visualizing object oriented software in virtual reality," in *9th IEEE International Workshop on Program Comprehension (IWPC'01)*, Toronto, Canada, 2001, pp. 26–35.

[26] N. Osawa, K. Asai, and Y. Y. Sugimoto, "Immersive graph navigation using direct manipulation and gestures," in *Proceedings of the ACM Symposium on Virtual Reality Software and Technology*, ser. VRST '00. New York, NY, USA: ACM, 2000, pp. 147–152.

[27] S. Smith, "Immersive information visualization (demo)," in *High Performance Computing, Networking and Storage Conference (SC 2004)*, november 2004.

[28] J. Leigh, A. E. Johnson, T. A. DeFanti, and M. D. Brown, "A review of tele-immersive applications in the CAVE research network," in *IEEE Virtual Reality 1999 Conference, VR'99, Houston, Texas, USA, March 13-17, 1999, Proceedings*. IEEE Computer Society, 1999, p. 180.

[29] R. AlTarawneh, S. R. Humayoun, and A. Ebert, "Expand: A stereoscopic expanding technique for compound graphs," in *Proceedings of the 20th ACM Symposium on Virtual Reality Software and Technology*, ser. VRST '14. New York, NY, USA: ACM, 2014, pp. 223–224.

[30] B. Stolk, F. Abdoelrahman, A. Koning, and P. Wielinga, "Mining the Human Genome using Virtual Reality," in *Eurographics Workshop on Parallel Graphics and Visualization*, D. Bartz, X. Pueyo, and E. Reinhard, Eds. The Eurographics Association, 2002.

[31] M. Kanou, S. Tsutsumi, K. Nishimura, H. Aburatani, K. Hirota, and M. Hirose, "Visualization for genome function analysis using immersive projection technology," in *IEEE Virtual Reality Conference 2002, VR '02, Orlando, Florida, USA, Proceedings*. IEEE Computer Society, 2002, p. 224.

[32] Y. Yang, L. Engin, E. S. Wurtele, C. Cruz-Neira, and

Authorized licensed use limited to: COLORADO STATE UNIVERSITY. Downloaded on December 02,2023 at 23:44:32 UTC from IEEE Xplore. Restrictions apply.

J. A. Dickerson, "Integration of metabolic networks and gene expression in virtual reality." *Bioinformatics*, vol. 21, no. 18, pp. 3645–3650, 2005.

[33] K. Nishimura, S. Ishikawa, S. Tsutsumi, H. Aburatani, K. Hirota, and M. Hirose, "Gene selection using gene expression data in a virtual environment," *Genome Informatics*, vol. 13, pp. 276–277, 2002.

[34] K. Nishimura, S. Ishikawa, K. Abe, S. Tsutsumi, H. Aburatani, K. Hirota, and M. Hirose, "Virtual environment design for gene selection using gene expression data," in *10th International Conference on Human - Computer Interaction*, 2003, pp. 1213–1217.

[35] K. Nishimura, K. Abe, S. Tsutsumi, H. Aburatani, K. Hirota, and M. Hirose, "Virtual environment design guidelines for gene expression analysis: the utility of a lab bench metaphor and a road metaphor," in *Virtual Reality, 2004. Proceedings. IEEE*, March 2004, pp. 247–248.

[36] N. Férey, P. E. Gros, J. Hérisson, and R. Gherbi, "Visual data mining of genomic databases by immersive graph-based exploration," in *Proceedings of the 3rd International Conference on Computer Graphics and Interactive Techniques in Australasia and South East Asia*, ser. GRAPHITE '05. New York, NY, USA: ACM, 2005, pp. 143–146.

[37] Aiden Lab, "Juicebox VR," 2014, https://play.google.com/store/apps/details?id=com.visor.JuiceboxVR.

[38] B. Tukora, C. Anthes, P. Heinzlreiter, and D. Kranzlmüller, "Large-scale dynamic visualization of multiple comparative genomic data," in *IEEE VIS 2014 Poster Program*, November 2014.

[39] B. R. Jones and R. Wa, "Illumiroom: Peripheral projected illusions for interactive experiences," in *In Proc. CHI 2013, ACM Press*, 2013.

[40] R. J. García, A. Rodríguez, J. M. García, M. Magdics, P. Bekaert, and M. Sbert, "Implementation of an immersive videogame: Legends of Girona," *International Journal of Creative Interfaces and Computer Graphics*, vol. 6, no. 1, pp. 1–20, 2015.

[41] M. D'Zmura, P. Colantoni, and G. Seyranian, "Virtual environments with four or more spatial dimensions," *Presence*, vol. 9, no. 6, pp. 616–631, Dec 2000.

[42] S. R. Hollasch, "Four-Space Visualization of 4D Objects," Master's thesis, Arizona State University, 1991.

[43] K. Honda and J. Nakano, "3 dimensional parallel coordinates plot and its use for variable selection," in *Compstat 2006 - Proceedings in Computational Statistics*, A. Rizzi and M. Vichi, Eds. Physica-Verlag HD, 2006, pp. 187–195.

[44] E. Fanea, S. Carpendale, and T. Isenberg, "An interactive 3D integration of parallel coordinates and star glyphs," in *Information Visualization, 2005. INFOVIS 2005. IEEE Symposium on*, Oct 2005, pp. 149–156.

[45] A. Inselberg and B. Dimsdale, "Parallel coordinates," in *Human-Machine Interactive Systems*, ser. Languages and Information Systems, A. Klinger, Ed. Springer US, 1991, pp. 199–233.

[46] J. Johansson, M. Cooper, and M. Jern, "3-dimensional display for clustered multi-relational parallel coordinates," in *Information Visualisation, 2005. Proceedings. Ninth International Conference on*, July 2005, pp. 188–193.

[47] M. Streit, R. C. Ecker, K. Österreicher, G. E. Steiner, H. Bischof, C. Bangert, T. Kopp, and R. Rogojanu, "3D parallel coordinate systems—a new data visualization method in the context of microscopy-based multicolor tissue cytometry," *Cytometry Part A*, vol. 69A, no. 7, pp. 601–611, 2006.

[48] I. Herman, G. Melancon, and M. Marshall, "Graph visualization and navigation in information visualization: A survey," *Visualization and Computer Graphics, IEEE Transactions on*, vol. 6, no. 1, pp. 24–43, Jan 2000.

[49] J. Schneider, C. Dedieu, P. Le Sidaner, R. Savalle, and I. Zolotukhin, "Defining and cataloging exoplanets: the exoplanet. eu database," *Astronomy & Astrophysics*, vol. 532, p. A79, 2011.

[50] K. P. Wenzel, R. G. Marsden, D. E. Page, and E. J. Smith, "The ULYSSES Mission," *Astronomy and Astrophysics Supplement*, vol. 92, p. 207, Jan. 1992.

[51] D. Müller, R. Marsden, O. St. Cyr, and H. Gilbert, "Solar orbiter," *Solar Physics*, vol. 285, no. 1-2, pp. 25–70, 2013.

[52] M. Macdonald, G. Hughes, C. McInnes, A. Lyngvi, P. Falkner, and A. Atzei, "Solar polar orbiter: A solar sail technology reference study," *Journal of Spacecraft and Rockets*, vol. 43, no. 5, pp. 960–972, 2006.

[53] S. Jeong, K. Chiba, and S. Obayashi, "Data mining for aerodynamic design space." *JACIC*, vol. 2, no. 11, pp. 452–469, 2005.

[54] J. Lin, E. Keogh, S. Lonardi, J. P. Lankford, and D. M. Nystrom, "Visually mining and monitoring massive time series," in *Proceedings of the Tenth ACM SIGKDD International Conference on Knowledge Discovery and Data Mining*, ser. KDD '04. New York, NY, USA: ACM, 2004, pp. 460–469.

[55] D. C. Arney, "Rule-based graph theory to enable exploration of the space system architecture design space," Ph.D. dissertation, Georgia Institute of Technology, 2012.

[56] P. Anz-Meador, "A review of space environment implications of cubesat traffic, 2003-2014," *Orbital Debris Quarterly News*, vol. 19, no. 3, pp. 4–6, july 2015.

[57] B. D. Warner, A. W. Harris, D. Vokrouhlický, D. Nesvorný, and W. F. Bottke, "Analysis of the Hungaria asteroid population," *Icarus*, vol. 204, no. 1, pp. 172 – 182, 2009.

[58] G. H. Stokes, D. K. Yeomans, J. William F. Bottke, S. R. Chesley, J. B. Evans, R. E. Gold, A. W. Harris, D. Jewitt, T. Kelso, R. S. McMillan, T. B. Spahr, and S. P. Worden, "Study to determine the feasibility of extending the search for near-Earth objects to smaller limiting diameters," National Aeronautics and Space Administration, Tech. Rep., 2003.

[59] R. Bonney, C. B. Cooper, J. Dickinson, S. Kelling, T. Phillips, K. V. Rosenberg, and J. Shirk, "Citizen science: a developing tool for expanding science knowledge and scientific literacy," *BioScience*, vol. 59, no. 11, pp. 977–984, 2009.

[60] D. A. Fischer, M. E. Schwamb, K. Schawinski, C. Lintott, J. Brewer, M. Giguere, S. Lynn, M. Parrish,

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T. Sartori, R. Simpson, A. Smith, J. Spronck, N. Batalha, J. Rowe, J. Jenkins, S. Bryson, A. Prsa, P. Tenenbaum, J. Crepp, T. Morton, A. Howard, M. Beleu, Z. Kaplan, N. vanNispen, C. Sharzer, J. DeFouw, A. Hajduk, J. P. Neal, A. Nemec, N. Schuepbach, and V. Zimmermann, "Planet hunters: the first two planet candidates identified by the public using the Kepler public archive data," *Monthly Notices of the Royal Astronomical Society*, vol. 419, no. 4, pp. 2900–2911, 2012.

BIOGRAPHY

Rubén García *studied Computer Science at the University of Granada (Spain) where he obtained his PhD in Computer Graphics in 2009. He has worked in the Universities of Granada, Girona and Hasselt, and in the Allegorithmic firm. He is currently at the Leibniz Supercomputing Centre at the Bavarian Academy of Sciences in Munich. His current research focuses on virtual reality and Immersive Visualization.*

Christoph Anthes *received his PhD from the Johannes Kepler University Linz, Austria in 2009. He is specialised in virtual reality and Collaborative environments and the responsible contact for the Virtual Reality and Visualisation Centre (V2C) at the Leibniz Supercomputing Centre, Munich. His research focuses on real-time interactive and collaborative environments, scientific and information visualisation as well as multi-user game environments.*

Markus Wiedemann *obtained his Bachelor's and Master's Degree in Electrical and Computer Engineering at the Technische Universität München. He currently is with the Leibniz Supercomputing Centre at the Bavarian Academy of Sciences in Munich. His current research focuses on scientific visualisation using virtual reality and immersive visualisation technologies.*

Dieter Kranzlmüller *is full professor of computer science at the Ludwig-Maximilians-Universität (LMU) Munich and member of the board of the Leibniz Supercomputing Centre (LRZ) of the Bavarian Academy of Sciences and Humanities. He has worked in parallel computing and computer graphics since 1993, with a special focus on parallel programming and debugging, cluster and especially grid computing.*

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