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On the Uncertain Future of the Volumetric 3D Display Paradigm

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Abstract

Volumetric displays permit electronically processed images to be depicted within a transparent physical volume and enable a range of cues to depth to be inherently associated with image content. Further, images can be viewed directly by multiple simultaneous observers who are able to change vantage positions in a natural way. On the basis of research to date, we assume that the technologies needed to implement useful volumetric displays able to support translucent image formation are available and so primarily focus on other issues that have impeded the broad commercialization and application of this display paradigm. This is of particular relevance given the recent resurgence of interest in developing commercially viable, general purpose, volumetric systems. We particularly consider image and display characteristics, usability issues and identify several advantageous attributes that need to be exploited in order to effectively capitalize on this display modality.

Keywords: Volumetric display; autostereoscopic systems; volume displays; 3D imaging.

1. Introduction

Volumetric displays have been the subject of extensive research for ~100 years (Blundell and Schwarz 2000, Blundell 2007). Despite the scale of this research effort, when viewed from the standpoint of today's visualisation needs the majority of approaches have limited merit, and although others exhibit a greater level of feasibility, very few possess the fundamental characteristics needed to deliver marketable products. Overall, this research history demonstrates that although it is relatively easy to implement a volumetric system capable of depicting simple and somewhat crude images, the development of scalable interactive technologies able to display content of an appropriate quality to multiple simultaneous viewers is more problematic.

Indubitably much of the early research was thwarted by the lack of readily available electronics needed to support the storage and throughput of appropriate image data. Even when computer technologies became widely available, for some years it remained possible to satisfy the relatively simple requirements of interactive visualisation applications using conventional flat screen displays. However, as applications continue to increase in sophistication it is increasingly evident that in certain situations the conventional display is non-optimal: '*The constriction of the visual bottleneck will continue to increase due to the grossly incommensurate scaling between information technologies and display technologies; 2D display bandwidth has essentially reached a plateau.'* (Chun et al. 2005) This is one of the driving forces behind research into autosteroscopic (glasses-free) systems fundamentally based on the principle of the stereoscope (lenticular, parallax barrier, immersive virtual reality, etc) (Blundell 2010), and has resulted in commercially available products. In contrast, no volumetric display has yet achieved significant commercial success. In the case of technologies researched during the last thirty years or so, this cannot be attributed to a lack of available electronics and computer technologies, and consequently the 'volumetric demise' may be interpreted as indicating inherent weaknesses or limitations in the approach. Here, we suggest that this is not the case, and consider a number of factors which have hampered progress – the most significant being a general failure to identify, fully appreciate, and capitalise on fundamental characteristics of the volumetric tableau which offer to support innovative methods of image depiction and user interaction.

Over the years, volumetric systems have invariably been considered alongside other autostereoscopic approaches and this has tended to result in performance comparisons which fail to take account of fundamental differences which exist between conventional 2D and stereoscopic-based 3D systems (which are both underpinned by image generation on a static surface) and the volumetric approach. In reality, direct comparison is not necessarily meaningful as it fails to take into account the basic nature of the volumetric tableau. Thus whilst, for example, lenticular and parallax barrier techniques can be fundamentally viewed as having evolved from 2D surface depiction techniques which were greatly advanced during the renaissance period, in terms of visual attributes volumetric techniques more closely align with facets of traditional sculpture. This gives rise to approaches which have the capability of supporting distinctly different (and complementary) forms of creative media.

In Section 2, we briefly review general aspects of the volumetric approach and subsequently outline relevant architectural characteristics. It is assumed that the technologies and techniques needed for the implementation of pragmatic volumetric systems capable of depicting translucent images are available and discussed elsewhere (see, for example, Blundell and Schwarz 2000, Blundell 2007). Consequently, implementation issues relating to particular embodiments are generally avoided.

Research to date clearly demonstrates that in order to achieve significant commercial success across a broad range of applications the development of a viable volumetric technology represents only the first step. A number of other equally important issues must be addressed and with this in mind, in Section 4 we outline key factors which have impeded commercialisation (specifically relating to technical, usability and commercial issues).

2. General Characteristics

In general terms, volumetric displays may be described as supporting: '*the generation, absorption or scattering of visible radiation from a set of localised and specified regions within a physical volume. In some cases a volumetric system may support the controlled anisotropic propagation of this radiation from each localised region.'* (Blundell 2011)

Dependent on display architecture, there may be almost complete freedom in viewing position (e.g. in the case of a spherical and completely transparent volume (image space)), or this may be constrained to one or more viewing 'windows' onto the volume. In general terms, constraining viewing position(s) simplifies display implementation but impacts on usability and application opportunities (which are also influenced by the size and form of image space).

Volumetric images invariably comprise a set of light emissive voxels. However, voxel visibility may also be achieved through the re-radiation of ambient light – thereby supporting image opacity and hence allowing natural shadows to be *intrinsically* associated with image content (although this is an area which has received relatively little research attention).

As with traditionally sculpted physical objects, volumetric displays can satisfy a range of near field pictorial, oculomotor and parallax cues to depth in a consistent manner and without the need to track observer location. However, the majority of approaches investigated to date give rise to translucent images and therefore do not incorporate the occlusion cue. This is *not* an inherent limitation of the volumetric paradigm (see, for example, Cossairt 2007, Blundell 2011), and in the case of some applications (e.g. scenarios in which internal structure is of interest) image translucency can be advantageous. Furthermore, the absence of image solidity is often ameliorated by a display's ability to satisfy the accommodation cue (which aids the discrimination of content lying on either side of the fixation distance). In this respect, volumetric systems are aligned with holographic and varifocal (McAllister 1993, Blundell 2007) approaches in terms of their ability to satisfy both the accommodation and convergence cues in a natural way (although this ability is limited to the depth of image space as measured from the vantage point).

As with traditional sculpture, image perspective occurs naturally and vanishing point locations are determined by image scene geometry and vantage point. The synthetic enhancement of perspective (and hence perceived image depth) assumes a particular centre of projection (and hence viewing position). However, the ability of volumetric displays to support multiple simultaneous viewers and enable natural freedom in viewing position precludes such depth enhancement (unless a unique view is delivered to each observer).

The volumetric approach provides natural support for the binocular cues to depth. Motion parallax is derived from both image and observer dynamics (Blundell 2011), and in the case of the latter is not restricted to movement in the horizontal direction.

Image space should ideally support the formation of a 3D set of possible voxel locations which are spaced in regular manner (e.g. a rectangular array), with the total number of available positions being represented by the voxel location capacity. In practice, during each image update period only a small percentage of these voxels will normally be activated (measured by the voxel activation capacity). This reflects an essential aspect of volumetric image depiction and the crucial importance of negative space – comprising the translucent penetrable space in which a collection of spatially separate visible entities reside. This plays a vital role in supporting vivid visual perception of spatial occupancy - the importance of which has long been recognized by artists such as Monet: '*I want the unobtainable. Other artists paint a bridge, a house, a boat and that's the end. They are finished. I want to paint the air which surrounds the bridge, the house, the boat, the beauty of the air in which these objects are located, and that is nothing short of impossible.*' (Barry 2009)

Thus, the effectiveness of the volumetric image is not simply determined by the formation of dynamic image content, but also by the display's ability to effectively support the portrayal of empty space (even non-activated voxels can contribute to the overall information content of an image scene).

3. Architectural Considerations

The general architecture of a volumetric display can be described in terms of four inter-dependent subsystems (Blundell 2011). Namely:

(a) **Image Space Formation:** The technologies and techniques employed in the formation of the physical volume in which images are displayed, and through which light must propagate from the each activated voxel to the observer(s).

(b) **Voxel Generation:** The physical process stimulated by the voxel activation mechanism(s) and which gives rise to visible voxels. Usually, this subsystem should support the isotropic radiation of light.

(c) **Voxel Activation:** The controlled mechanism(s) which stimulate the voxel generation process.

(d) **Re-Imaging/Projection:** The majority of volumetric displays prototyped to date employ only the above three subsystems. However, a re-imaging and/or projection subsystem may also be present and serves to modify the direction of light emitted by the voxel generation subsystem and/or project light such that an image scene appears to exist in free space (see, for example, Kameyama *et al.* 1993, Kameyama and Ohtomi 1993, Blundell and Schwarz 2006). Usually in the absence of this subsystem image content resides within physically bounded image space. This makes it impossible for physical interaction tools to 'contact' image components and so impacts on interaction opportunities (e.g. haptics). However, free-space image formation is not entirely dependent on the presence of a projection subsystem and may be achieved directly without the need for the image space formation subsystem – see, for example, HoloVect[1], and Ochiai et al. 2016.

Volumetric displays are invariably broadly categorized as either ‘swept-volume’ or ‘static-volume’ systems (Blundell and Schwarz 2000, 2002). In the case of the former, image space formation is underpinned by the rapid cyclic motion of a surface or structure. Rotational or translational movement is usually employed, although hybrid motion is also possible. In contrast, static-volume systems place no reliance on mechanical movement for image space formation.

Consideration of image space as an extension of a conventional flat screen display (with a pixel capacity of n^2) into the third dimension suggests the need for a voxel location capacity (N_l) *of* $\sim n^{3/2}$. Any effort to support the activation of a large number of voxels during each image refresh period requires a high degree of parallelism (P) in the voxel activation and generation subsystems:

$$N_a = \frac{P}{fT}.$$

Where N_a denotes the voxel activation capacity, f the image refresh frequency and T the time needed for voxel activation. The use of DLP® technology for image slice projection provides the parallelism needed to support the formation of large numbers of voxels during each image refresh period and allows $N_a \sim N_l$. However, as previously indicated, when used to maximum advantage a large proportion of any volumetric image space is void and this suggests that the voxel activation capacity can be considerably less than the voxel location capacity (which is invariably the case when, for example, a small number of directed beams are used for voxel activation). Unfortunately, in the case of both static and swept-volume displays this often leads to the issue of ‘conditional voxel activation’, in which the ability to activate a particular voxel may be determined by the location and temporal sequencing of previously activated voxels. This frequently reduces the predictability of both static and swept-volume displays exhibiting low parallelism in voxel activation and can only be completely avoided by ensuring that any combination of possible voxel locations can comprise the voxel activation list, provided that the display’s fill factor (Ψ) is not exceeded, where:

$$\Psi(\%) = \frac{N_a}{N_l}.100 .$$

In short, the quest to obtain a fill factor of 100% should primarily be driven by a need to avoid conditional voxel activation rather than by a desire to support situations in which the majority of voxels (as defined by N_l) are simultaneously activated (which results in over-cluttering of image space and a loss of spatial and dynamic clarity).

In the case of swept-volume displays, the sweep efficiency denotes the ratio of the useful image space volume (in which images may be satisfactorily formed) to the volume actually swept out by the cyclically moving component(s) and is expressed as a percentage. From a usability perspective, it is desirable to support a sweep efficiency that is close to 100%, although as indicated below, reducing this value can facilitate display implementation.

Display subsystems should ensure that voxel attributes such as size, light output and definition are invariant with voxel position, time of formation, and/or viewing direction. This places restrictions on the material or arrangements of materials which can comprise image space as, relative to any possible viewing position, they should allow the rectilinear and

[1] Holovect.com

isotropic propagation of light. Boundary refraction can result in an apparent reduction in the sweep efficiency, can cause apparent non-invariance of voxel attributes, and can result in unacceptable levels of image distortion (including the distortion of negative space). This impacts on the usefulness of static-volume systems which employ a solid or liquid media for image space formation.

4. Impediments to Success

In reviewing ~100 years of volumetric display research (see, for example, Blundell 2007) it is evident that interest in the area has been cyclic and although much innovative work has been carried out, literature reveals considerable repetition of effort. Invariably, sooner or later the development of particular architectures has floundered and efforts to commercialise technologies have failed to gain the necessary momentum. Below, we outline factors which have negatively impacted on success from technical, usability and commercial perspectives.

4.1 Technical Considerations

As previously indicated, early efforts to develop volumetric systems were greatly impeded by a lack of appropriate electronic systems. Undeterred, in the 1920's for example, John Logie Baird sought to develop a volumetric system which could directly interface to image capture hardware (Baird 1932, Blundell 2007) and in the early 1940's, Parker and Wallis attempted to develop display technologies which exhibited the same spatial and temporal characteristics as the radar systems to which the displays were intended to interface (Parker and Wallis 1948, 1949). In the 1960's it became possible to implement (at the component level) the data storage and processing hardware needed to operate displays exhibiting low levels of parallelism in voxel activation. More recently, off the shelf hardware has become increasingly available and offers the performance needed to support high speed voxel processing and throughput.

However, in reviewing display architectures researched to date it is evident that almost all exhibit, to a greater or lesser extent, some of the largely negative attributes summarised in Table 1.

Attribute	Possible Impact	Exemplar Cause
Limited and non-scalable image space dimensions.	Impacts on spatial clarity, viewing distance, etc, thereby impacting on applications.	Image space formation using translational motion of a surface.
High density of materials used for image space formation (static-volume).	Boundary refraction (image distortion) and portability issues that ultimately limit image space dimensions.	Image space formation using a solid or liquid (e.g. in respect of the former, heavy metal fluoride glasses doped with rare earth lanthanides).
Major limitations on image space visibility (e.g. a single 'window' onto image space).	Impacts on suitability for multi-user applications and leads to clustering of viewers.	Image space formation using a stack of liquid crystal or photochromic panels.
Presence of image space elements which interfere with the rectilinear propagation of light.	Image distortion. Variations in image quality with viewing position and with changes in image position. Resulting in preferential viewing directions.	Use of a 3D array of voxel generation centers.
Existence of 'Dead Zones' (in which one or more image attributes fall below a given threshold (Blundell and Schwarz 2000, 2002).	Typically limits the placement of image components to certain regions of image space. Seriously impacts on image dynamics and display predictability in general.	Image space formation using the rotational motion of a planar or helical screen.
Variations in voxel attributes.	Variations in image quality with viewing position and changes in image position.	Image space formation using the rotational motion of a planar screen or voxel activation at the intersection of two directed beams.
Limitations on the height to width ratio of a cylindrical image space.	May impact on applications.	Image space formation using the rotational motion of a helical structure (see, for example, Hartwig 1976).
Low sweep efficiency.	Large display apparatus relative to the size	Can reflect efforts to improve display

	of the usable image space.	characteristics such as inter-voxel positioning and variations in voxel attributes.
Low fill factor.	Conditional voxel activation	Voxel activation using a small number of directed beams in conjunction with the swept-volume technique.
Low brightness of voxels.	Suitability for use under stronger ambient lighting conditions.	Voxel generation using the two-step excitation in a low pressure gaseous image space medium.

Table 1: Indicative flaws frequently associated with volumetric display architectures.

The majority of the systems researched have been able to demonstrate the general concept of the volumetric technique by supporting the depiction of lines and curves in 3D space (e.g. Lissajous figures). Others have been able to display simple computer-generated images. However, relatively few have reached the level of depicting more complex multi-colour animated images. It is during these stages in the development process that key visual deficiencies become increasingly apparent to both researchers and potential investors.

For example, in the case of a rudimentary proof of concept prototype, an observer may be quite willing to view an image component from a particular position such that its visual quality is optimal. However, variations in image quality with viewing position become much more apparent when image size is increased and when image dynamics are introduced.

In the case of swept-volume architectures, the translational motion (usually following a sinusoidal speed profile) of a planar screen coupled with DLP® technology for voxel activation has the ability to support regularity in voxel positioning, can eliminate dead zones, and ensures rectilinear propagation of light to the user. With judicious design, it is possible to minimize effects relating to the reduced speed of screen movement which occur towards each end of the screen's travel. Further, this approach has the potential to ensure that the number and spatial distribution of voxels comprising an object remain invariant under translation operations.

Unfortunately, mechanical issues relating to the rapid cyclic motion of the surface constrain image space dimensions, although considerable progress has recently been made in this area (see, for example, Voxiebox[2]). Earlier researchers sought a novel solution in which the advantageous characteristics associated with translational motion could be retained whilst at the same time eliminating the mechanical difficulties (Szilard 1974). In this scenario, a cylinder rotating about its central axis was used (the axis being located in a horizontal plane). A set of screens were attached to the periphery of the cylinder, each being offset in depth from its neighbours in order to be located along a single turn helical path over the length of the cylinder. As the structure rapidly rotated, a series of synchronized images slices were projected from the rear so as to impinge on the appropriate screen as it passed a particular location.

This approach provides an example of an attempt to circumvent problems associated with reciprocating motion whilst retaining the above advantageous characteristics. However, it results in a low sweep efficiency. For example, in the case that height and average width of image space to be formed are equal (denoted *w*), and that the image space comprises *n* depth planes, then the radius (*R*) of the rotating apparatus (comprising cylinder and screens) is given by:

$$R \approx \frac{w}{2}\left[\frac{n}{\pi}+1\right]$$

[2] Voxon.co

Assuming an approximately cubic image space with sides of only 20cm and restricting the number of depth planes to 20, yields an apparatus which has a diameter of ~148cm and which exhibits a sweep efficiency of only ~2%. Naturally, any effort to increase the number of depth planes (which would be required to provide satisfactory depth discrimination) would further reduce this value. Although this provides a simple and low cost approach to the implementation of a basic but operational volumetric display, the low fill factor limits its practicality to experimental work (which applies to other architectures where designers have sought to improve display characteristics through a reduction on sweep efficiency).

Similar issues arise when image space is formed using the rotational motion of an Archimedes spiral (Yamada et al. 1984), and in general terms efforts to improve display performance by reducing the sweep efficiency are unacceptable in commercial systems. The rotational motion of a planar screen provides a mechanically simple and robust approach to image space formation, but can give rise to undesirable characteristics in the region close to the axis of rotation. Further, voxel attributes may vary with radial distance from the rotational axis (for indicative embodiments see Blundell 2007, 2011 and Sun et al. 2014).

4.2 Usability Considerations

The subsystems comprising a volumetric display are usually highly interdependent and this impacts on the extent to which rapid prototyping techniques can be used to resolve weaknesses and quickly evaluate potential improvements. As a result, relatively little work has been undertaken in tuning display characteristics so as to better explore and optimize novel opportunities offered by the volumetric tableau (e.g. comparative studies of different image space sizes, forms, etc). Moreover, since few volumetric systems have emerged from the research laboratory, the creative arts community has had little opportunity to gain experience with this image depiction modality.

Volumetric systems are particularly suited to the depiction of collections of spatially separated dynamic objects, and it appears that the ability to greatly facilitate the visualization of complex 3D movement (e.g. the simultaneous motion of image components over three spatial dimensions) denotes a key advantageous characteristic. Unfortunately, any lack of image space predictability becomes particularly problematic when dealing with dynamic content. For example, as previously noted in early stage proof of concept systems, observers may be willing to accept variations of image quality with viewing position (and in such situations, it is often necessary to manually adjust the position and orientation of images to optimize the visual experience). However, when dealing with dynamic image content this type of manual adjustment serves little purpose and as objects move, variations in the spatial characteristics of image space are usually immediately evident. Consequently, image space predictability is crucial.

Volumetric systems offer to provide novel interaction opportunities (e.g. via pointer-based interaction). As previously indicated, a re-imaging/projection subsystem may be used to project volumetric images into free-space, thereby enabling physical interaction tools to co-exist within the space in which image content appears to reside. This opens up the opportunity for haptic-based interaction and further aligns the volumetric technique with traditional forms of sculpture. However, to date this area has received relatively little research attention (see, for example, Blundell and Schwarz 2006), and at the present time it would appear that the most promising approaches will require significantly more cumbersome display apparatus or will impose viewing limitations which will preclude the all-round viewing scenario.

As previously noted, reducing viewing freedom can facilitate the implementation of volumetric systems. In the case of several architectures researched to date (including the commercialized DepthCube™ systems (Sullivan 2003, 2004), viewing freedom has been limited to a single window onto image space. This restricts multi-viewer opportunities and from a usability perspective is undesirable as it results in a display which takes on an outward appearance (in terms of depth) which resembles the older CRT-based form of conventional display. Furthermore, from the perspective of creative interaction this modality does not encourage the operator to move *into* the third dimension.

Ongoing research and commercialization developments at the Looking Glass Factory[3] provide an example of static-volume displays offering two windows onto image space, thereby providing significantly more flexibility than the single window scenario. This work encompasses the development of small, low cost, 'hand-held' volumetric displays.

4.3 Commercial Considerations

The most widely known efforts to commercialize volumetric systems centered on Actuality Systems' Perspecta display (Favalora et al. 2001, 2002, Favalora 2009), and the DepthCube™. Both were primarily intended for high end visualization applications but neither gained widespread acceptance.

Unfortunately, to date research into volumetric displays has largely been driven by a bottom-up approach in which researchers have attempted to realize interesting (but not necessarily practical) ideas, with little initial consideration of the innovative and demanding nature of the volumetric tableau and how it may *truly* advance visualization processes. Fundamental weaknesses have often been cast to one side – until their growing significance ultimately caused techniques to flounder.

The successful commercialization of volumetric systems can only be achieved by accurately identifying and quantifying the benefits offered by this display modality, and matching these with innovative applications which capitalize on the facets of the volumetric tableau. This recognizes that there are a number of significant hurdles to overcome, several of which are summarized below.

4.3.1 Direct Comparison with Flat Screen Display Modalities

The conventional flat screen display provides strong support for the pictorial cues to depth and, depending on image content, can give rise to stereopsis by default (Blundell 2015), which enhances three-dimensionality through negative space perception. More general support for 3D imaging is achieved by means of coding techniques involving the use of filter glasses, the parallax barrier, lenticular techniques, etc. Support for the oculomotor cues is more difficult to achieve and when such displays are used for extended periods, accommodation/convergence conflict can cause stress to the visual system. Furthermore, supporting motion parallax in a natural way (both vertically and horizontally) is problematic, particularly in multi-viewer scenarios.

All these approaches offer support for the depiction of high quality photorealistic images to which all screen pixels usually contribute. Consequently, as previously indicated, such techniques may be considered to fundamentally draw on and extend methodologies employed by Renaissance artists in their quest to achieve photorealism in painting.

In contrast, the volumetric approach does not purport to support high definition photorealism, and key motivations for the development of volumetric displays centre on (or should centre on) areas which include:

1. **Support for an Innovative Tableau:** Yielding a display modality whose opportunities and limitations have not yet been fully identified and evaluated. This will yield new forms of application and hence new ways of interfacing with the digital domain.

[3] Lookingglassfactory.com

2. **Enhanced Visualization:** For example, the depiction of geometrical objects (of varying complexity) in which image components are moving (often simultaneously) in different directions, and in which the vivid impression of spatial separations is of key importance. The volumetric approach is particularly suited to the vivid depiction of the non-linear motion of image components which are continually changing in size and/or form. Whilst a flat screen display technology (depicting 2D or stereo-based 3D content) can provide an immersive visual experience, the volumetric approach supports a 'third person' view which does not give rise to the same form of immersion.
3. **Alignment with the Visual System:** Support for 3D spatial perception that more closely matches the natural world experience (including the oculomotor and parallax cues).
4. **Support for Multiple Simultaneous Viewers:** Enabling freedom in viewing position and allowing each viewer to obtain a unique view onto an image scene.
5. **Interaction:** Support for innovative interaction techniques including haptics.
6. **Responsiveness:** When linked with appropriate sensory hardware, volumetric systems are ideally suited to scenarios which incorporate the depiction of the spatial occupancy and natural motion in physical space. This provides opportunities for display technologies to adapt to, and visually respond to, the natural surroundings thereby supporting innovative forms of augmented reality.
7. **Group Activity:** Technologies which allow users to be positioned around image space facilitate group activity without the need for 'viewer clustering'.
8. **Cost:** An overarching motivation is to achieve such goals through the development of relatively low cost display technologies.

The volumetric approach does not purport to extend the imaging techniques associated with the conventional 2D screen into the third dimension, nor does it align with the opportunities associated with stereoscopic based displays. As previously indicated, volumetric techniques more closely align with traditional sculpture and, importantly, extend this form of creative expression through the natural portrayal of complex motion.

4.3.2 Identifying Real Applications

Unfortunately, much research into volumetric systems has been handicapped by a failure to identify and exploit key advantageous characteristics and to properly recognize fundamental limitations.

For example, for many decades air traffic control (ATC) has been (and continues to be) mooted as a key area of application for volumetric systems (see, for example, Aviation Week 1960, Soltan et al. 1994, Lasher et al. 1996, together with current suggested applications for the 'CSpace' display[4]). However, the notion that this would significantly enhance the day-to-day work of ATC professionals has little basis in fact. For example:

1. Scaling: For given vertical and horizontal ATC distances scaling is defined by image space dimensions. For example, assuming a cylindrical image space measuring 1m in diameter and 30cm in height and a corresponding cylindrical ATC volume 100km in diameter and 10km in height, 1km horizontal and vertical separations would be represented by 1cm and 3cm respectively within image space. For this type of application, the use of different scaling factors is undesirable.
2. Visibility: Consider the case of two vectors, which from a particular vantage point appear to intersect and that are located on the far side of an image space. Although in reality they may depict trajectories separated by 1km horizontally, this separation is unlikely to be evident

[4] www.3dicon.net/innovation/cspace (last visited November 2016).

to a stationary observer. This suggests a need for the user to continually change viewing position, or for constant image scene rotation.
3. Disorientation: Support for all-round viewing can be advantageous, but in the case of ATC, failing to define operator orientation relative to the flight trajectories has potentially dangerous consequences.
4. Text: In general terms, volumetric displays which offer considerable freedom in viewing orientation are unsuited to the depiction of text (which may not be readily readable from some viewpoints). Meaningfully assigning flight data to vectors is therefore problematic.
5. Quantifiable Benefit(s): The adoption of volumetric systems for professional ATC activity would necessitate significant changes in working practice and to the physical layout of ATC facilities. There is no indication that volumetric displays would provide significant benefit to highly trained ATC staff, and that investment in the technology could be justified by quantifiable benefits.

Whilst undoubtedly volumetric systems could be used advantageously for training purposes in a number of areas (including ATC), such applications tend to be fundamentally based on requirements that are currently fulfilled by conventional display technologies. Proving *a priori* that a proposed volumetric system offers superior, quantifiable benefits which guarantee that the expenditure and entropy (including possible/probable resistance to change) is readily justified is problematic, and is a key factor that has led to commercialization ventures floundering.

In charting a future for volumetric technologies, it is therefore preferable to focus on quite new applications which offer novel opportunities and exploit the true benefits of volumetric tableaux.

4.3.3 Top Down Design

As previously indicated, researchers investigating volumetric systems have invariably adopted a bottom-up design strategy in which potential applications have been hypothesized, but not analyzed from the outset. In order to secure a future for the volumetric approach, it is advantageous to adopt a top-down strategy in which the analysis of potential applications forms a key starting point thereby enabling the necessary display characteristics to be defined at an early stage.

Given the range of approaches that can be adopted in the implementation of volumetric systems (including hybrid methods - although these have received relatively little attention to date), the top-down strategy is suited to volumetric research. However, over the years there have been few opportunities to gain hands-on experience with the volumetric tableau. This has made it difficult for researchers entering the area to gain a clear insight into image quality characteristics, the ramifications of image space deficiencies (including dead zones and predictability), viewing and interaction issues, etc. prior to technology implementation. Consequently, the bottom-up approach, which promotes display implementation at an early stage, has continued. Current developments in volumetric display commercialization offer to make off-the-shelf low cost systems accessible to a broad research base, and so this situation may change.

4.3.4 Intellectual Property

During a century of research into the volumetric approach, numerous patents relating to particular architectures and methodologies have been granted (for a wide-ranging review see, for example, Blundell 2007). Issues arising from the ownership of intellectual property can seriously hamper the introduction of technologies, and the need to navigate a complex patent landscape can force developers to adopt non-optimal approaches. Fortunately, in the case of volumetric systems large numbers of patents have now expired, and consequently most of the general volumetric methodologies are no longer ring fenced by intellectual property issues.

5. Discussion

In its various forms, the flat screen display has gained almost universal acceptance in mediating our interaction with the digital domain. The visual and physical versatility of this form of display tableau enables it to provide commonality across applications involving the use of hand-held, desk based and wall mounted screens. Users have become both confident and adept in capitalizing on the imaging and interaction opportunities which it provides across an extensive range of diverse applications.

Volumetric systems do not purport to represent an alternative form of general purpose interactive display which can replace (or compete with) the flat screen, but rather offer complementary display tableaux possessing markedly different visual, usability and interactive attributes. In order to usefully exploit volumetric systems, ongoing research must identify the strengths and creative opportunities offered in a clear and quantified way. Furthermore, for this form of display to gain widespread acceptance it is necessary to demonstrate in an unequivocal manner that its capabilities do not simply advance particular niche activities, but rather that its usage is advantageous across a broad range of current and emerging applications.

From a practical perspective, it is also important to consider ways in which displays of this type can be accommodated in the workplace, domestic environment, etc. For example, in order to take advantage of a display which imposes little restriction on image space viewing, there is a need to ensure all-round access suggesting that a display would become a central feature in an environment. Other displays which provide one or two windows onto an image space may be more suited to desktop use. To justify a desktop ‘footprint’, the display must be in regular (rather than occasional) use. This in turn implies that the display must have clearly demonstrable ergonomic benefits.

As previously indicated, to date little research has been undertaken in assessing optimal image space form and dimensions (i.e. when considered from the perspective of developing a system which has greatest practical value across a broad range of potential applications). In the case of displays supporting, for example, a spherical image space with a diameter of 20-25cm or less, viewers tend to automatically position themselves as close as possible to the image space boundary for an optimal visual experience. This tends to support an intuitive belief that larger image space dimensions are more suited to facilitating the visualization of spatial information from a comfortable distance and are hence desirable (for an exemplar embodiment see Sawalha et al. 2012). However, without judicious design, larger displays have greater impact on room layout and this is likely to impact on widespread acceptance.

Although more research is needed, it is possible that small hand-held (personal) displays may also offer practical advantages (since, for example, hand rotation of image space allows a user to rapidly and intuitively view content from any orientation).

As in the case of the physical world perception of three-dimensionality, the volumetric tableau is of limited value when used to depict static image content which is viewed from a single vantage point. This situation changes considerably when motion parallax relating to image and/or observer dynamics is introduced (in respect of the latter, see, for example, Yamamoto and Kokubu 2014, concerning the visualization of tangent developables). Advantageous characteristics of the volumetric system are further exploited through support for intuitive interaction (encompassing haptics) which, for example, allows 3D design tasks to be carried out within a 3D space and in a way in which content takes on the solid characteristics associated with real materials. For entertainment and social applications, key characteristics of the volumetric tableau can be further enhanced through the provision of sensory hardware enabling the display to become responsive to its environment and audience.

Current commercialization ventures have the potential to catalyze interest in the volumetric tableau and support the creative exploration of its capabilities and limitations.

Without such vital investigations, the future of volumetric systems is likely to remain uncertain.

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