SPAROGRAM: The Spatial Augmented Reality Holographic Display for 3D visualization and Exhibition

Minju Kim, Jungjin Lee, Kwangyun Whon

Abstract—While the 3D graphics technique has found its place for the scientific visualization, especially for medical and biological applications, it has long been speculated that the 3D may not be so much effective as far as the conventional information visualization is concerned. We agree upon this view that the naive extension of the 2D visual forms to 3D is not a way to go. Instead, the computer-generated 3D virtual world will serve best when the virtual world is seamlessly integrated with the real 3D space. For an example, a physical automobile model surrounded with various kinds of virtual visual forms such as texts, images, sounds and 3D models will offer the user (or the audience) another level of appreciation and experience on the subject being presented.

In this paper, we present our on-going developmental efforts toward the above framework which calls for the tight integration of the 3D visual forms and the 3D real space.

The Spatial AR Hologram (SPAROGRAM) is capable of manifesting augmented three-dimensional information by making full use of the real 3D space that encompasses the surroundings of the real object comprehensively and simultaneously. To accomplish this, a multiple layer of stereoscopic images was implemented. Stereoscopic images enable spatial visualization using the physical and virtual third dimension. Furthermore, ensuring the continuity of the spatial experience, we made the use of spatial exploration with user interaction in real-time. We describe the whole process of system design and prototyping. Our initial investigation suggests that the newly conceived holographic display produce not only continuous 3D space perception, but also the better spatial awareness and realism. Furthermore, it is a promising way to present information in three-dimensional display and help the users understand information effectively and efficiently.

Index Terms—spatial data visualization, augmented reality, holographic display, 3D visualization

1 Introduction

Going beyond the text-based 1D and flat 2D configuration, there has been countless number of attempts to revolutionize the way to construct virtual 3D space as close as to the reality and realistically represent 3D information. In particular, over the past few decades, 3D graphics techniques has been utilized in scientific visualization field to simulate and navigate dataset, especially for visualizing complex 3D visual objects, hierarchical information structures and so on. Even though it is regarded as 3D by rendering perspective 3D image providing greater spatial flexibility, image is displayed on a 2D single layer offering a limited depth effect. As a result, there are limits and restrictions on a perfect 3D visualization, depriving the users an opportunity to gain a more complete of complex 3D information.

Accordingly, previous research has explored realistic 3D representation technologies to better support spatial memory such as stereoscopic display, holographic display, volumetric display, and so on [9, 13]. However, they do not have the capacity to provide three-dimensional experiences which actually evoke physical depth cues. Especially, it is difficult and inefficient in displaying additional information on the physical object with the flavor of augmented reality.

In this paper, we present Spatial AR Hologram (SPAROGRAM), a new visualization system that produces three-dimensional information that makes the best use of the real 3D space. First, we make a continuous 3D space that is not subject to a space limit. It allows the system to create augmented information in the way of using real 3D space and physical object as a display area simultaneously. To implement this, we organize the system with using 2-layer display and apply the stereoscopic image at both front and back displays. Second, we enable viewers to experience the information consistently by incorporating 3D user interaction. Depth camera faces the viewer and tracks the position in real time to enable the interaction between the system and the viewer.

We describe the SPAROGRAM implementation, including hardware configuration, system design and prototype for offering spatial experience. We illustrate application prototypes where SPAROGRAM could be applied efficiently including scientific visualization, especially for medical and biological applications and displaying exhibit information in museum environments. Finally, we evaluate the user on how effective the system is in creating the 3D spatial perception and spatial awareness. Our system is significantly different from the general three-dimensional visualization method in the way that we use both the real space surrounding the physical object and the object itself as a display area at the same time. As the final outcome, we discovered the possibility of SPAROGRAM for three-dimensional information visualization overcoming the limitation of conventional 3D information visualization.

2 Related Work

2.1 3D visualization

Over the past few decades, there has been attempts to visualize the three-dimensional information that simulate the richness of 3D reality. Smallman et al. mentioned that 3D visualization is ecologically plausible than 2D since our retinal images are perspective projections of the world. Also it is preferable because it integrates all three dimensions of space into a single display, so people may be spared the mentally demanding process of observing back and forth to gauge spatial relationship [24]. Accordingly, it has been believed that closer the information resembles the real world, easier the usage. Nevertheless, it has been considered as a way to avoid using in general information visualization. Cockburn et al. also claimed that adding a third dimension to computer displays does not aid users spatial memory. Therefore it is difficult to recognize the accurate space perception and it resulted in loss of information [3]. Jason also mentioned that even with the help of 3D rendering software, complex data or 3D objects displayed on 2D screen are still unable to offer depth information effectively and correctly [9]. Moreover, there is no significant difference between task performance in 2D and 3D, causing clutter, occlusion, and low efficiency [23, 4]. However, the strong utility of pure three-dimensional interfaces for scientific visualization [20], medical, mod-

• *Minju Kim is with Graduate School of Culture Technology, KAIST. E-mail: minjukim@kaist.ac.kr.*

2014 IEEE VIS International Workshop on 3DVis (3DVis)
9 November, Paris, France
978-1-4799-6826-8/$31.00 ©2014 IEEE

eling 3D surfaces, architectural as ever means that interface design for pure 3D remains an important and challenging issue [22, 21, 26]. We propose the new space visualization system that helps presenting and delivering three-dimensional information effectively.

2.2 3D display technologies

The ultimate goal of display technology is to show a realistic three-dimensional image that appears to float without a screen frame. Beyond the general 3D graphics that show only two-dimensional flat images that lack depth information [8], there has been a lot of research on exploiting the third dimension, including the opportunity to present realistic three-dimensional information [9]. The concept of the stereoscope, which works based on binocular disparity, allows people to observe different perspectives of an object. So the illusion of depth can be created from two 2D images. Then, the brain merges those two images into a single 3D perspective. Stereoscopic technique has been widely used for simulating data, exploring and manipulating information using the three-dimensional graphics in diverse fields such as medical training [27], scientific visualization [17], education [12], movies and so on, aiding viewers understanding of spatial relationship [16]. As spatial display techniques, holographic display and volumetric display are 3D visualization techniques that form the representation of an image in three physical dimensions rather than 2D screen [14, 6]. It provides a natural depth perception, and it prompts viewers to focus on an image itself rather than on a frame of screen [18]. Both offer all the physiological depth perceptions without any conflict [13]. In this paper, we propose a system that can produce 3D information effectively by utilizing the advantages of both stereoscopic displays and multi-layer display.

2.3 AR Holographic display System

When representing 3D graphic information, integrating graphical augmentations into the real environment is effective with the form of augmented reality (AR). Many approaches have taken augmented reality utilizing special devices such as head-attached and hand-held displays, and many others [2]. Of those, transparent screen, or hologram, has the ability to reconstruct a complete and seamless media space generating 3D image in physical space. It enables viewers to see virtual images that appear to coexist in the same space as the real world. Starting with the hologram performance, Peppers Ghost (1869) [25], it has been expanding its application into telepresence [10], presentation, medical training [7], and desktop workspace for a long time. Recent research has shown that it has ability to enable viewers to rapidly mix real and virtual associated information and create the 3D illusion that viewers have visual integration naturally [11, 15]. However, it still has a problem to evoke physical depth cues and limits on displaying perfect 3D information because it uses only the frontal flat area. Proposed Spatial AR Hologram completely reconstructs the physical three-dimensional display area surrounding the real object, so it effectively enables visualizing 3D image on the mid-air. In addition, it allows viewers to experience 3D information spatially.

3 Design and Prototype of SPAROGRAM

3.1 Design of SPAROGRAM

The ultimate goal of 3D visualization is to reproduce the images generated by a real-world physical object realistically, while helping people explore and navigate data easily and effectively. Apart from general 3D graphics, stereoscopic 3D graphics, holographic display, and other 3D visualization methods have provided viewers three-dimensional experiences by fully utilizing the available resources. Nevertheless, there exists a limit on these techniques in expressing and delivering the spatial relationship and depth information like the real physical object does(Figure 1-(1), (3)). The limit grows even more apparent in situations like AR which visualizes the virtual additional information along with the physical object (Figure 1-(2)). Figure1 shows the table that classify 3D visualization techniques under two heads; one is whether the method provides 3D spatial perception or not, and the other is the existence of the physical objects.

3D Vis Techniques		existence of the physical objects	
		X	O
provide 3D spatial perception	X	(1) 3D Graphics	(3) AR Hologram
	O	(2) 3D Stereoscopic	***(4) Spatial AR Hologram***

Fig. 1. Table of the classification of 3D visualization techniques

In order to overcome the limitations of conventional 3D representation, we propose a new visualization system, SPAROGRAM (Figure 1-(4)) that can help the creation of three-dimensional information effectively. This system uses both front and back space surrounding the physical object and the object itself as a display area, so it enables not only reproducing real three-dimensional information through taking advantage of the real space possible, but also leading to better spatial understanding of the scene as well through especially using the front semi-transparent display. To achieve this, we need to solve the spatial visualization and the spatial exploration problems.

In order to express spatial visualization, we installed multi-layer display, and applied 3D stereoscopic technologies. Multi-layer displays offer spatial impression by increasing the number of displays and arranging them separately in the physical space. Stereoscopic technologies enable the creation of the continuous space between two layers possible by adding the third dimension. In this study, we applied stereoscopic image in the front display. It allows the virtual information to be merged around the physical object naturally and accurately (Figure 4(a)). In addition, for the spatial exploration, it is important to offer additional information with visual consistency according to the viewers physical point of view. The camera faces the viewer and tracks the positions to visualize information by guaranteeing their spatial experience in real-time. As a result, it creates active interaction between the system and the viewer (Figure 4(b)).

3.2 Prototype of SPAROGRAM

The proposed SPAROGRAM uses two displays, a semi-transparent film and a monitor, placed in parallel and 1 meter physically apart from each other. The space in between is used to place the real object which serves as physical information (Figure 3(c)). The semi-transparent film reflects the virtual image which is emanated from the projector underneath, manifesting a virtual image on the mid-air (Figure 3(d)). Another display, placed in the back, serves as the backdrop scene at this moment, but will produce stereoscopic 3D images later, as it will be described in the following section. With this configuration, the system enhances the viewers spatial perception and experience by allowing them to look at the physical objects as well as the displayed digital information on the front and back displays at the same time (Figure 3(a),(b)). Our physical configuration for SPAROGRAM is illustrated in Figure 2.

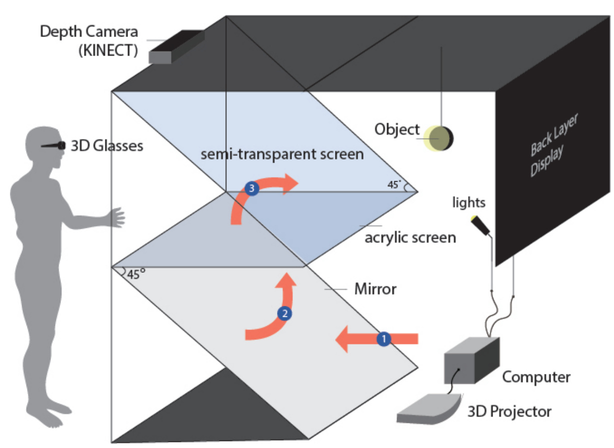

Fig. 2. Prototype of SPAROGRAM

For the front display, we use Musion Eyeliner 42 inch semi-transparent display with 40% light transmission [5]. The physical object and the back layer display are viewed by the user and through the semi-transparent front display. This front display reflects light toward the viewer from a projector mounted under the system. The projector displays a 1024×768 pixels images at 4000 ANSI LUMEN. A 50 inch Samsung LCD displays (1920×1080 pixels images) is used as the back layer. We installed the controllable lights inside the system that switch the scene between virtual reality and augmented reality information naturally and improve the visibility of the real object. The light system is controlled by using ARDUINO [1]. A depth camera which is installed in front of the system faces the viewer and tracks their movements in real time. To block the light and enhance usability, we covered the entire system with a black cloth except for the front which serves as the interaction space with the viewer.

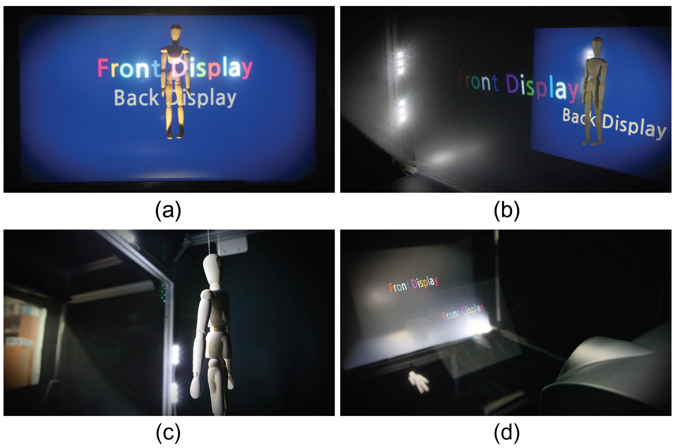

Fig. 3. SPAROGRAM configuration: (a)front view of the system, (b)side view of the system, (c)physical object, (d)projector

3.2.1 Spatial Visualization: multi-layer display with stereoscopic imaging

To visualize 3D spatial images, we applied a stereoscopic image at the front display and a 2D image at the back display respectively(Figure 4(a)). Polarized 3D system, one of the 3D representation methods, is not applicable in this case because of the diffused reflection properties. Accordingly, we applied the anaglyph 3D image which can be implemented easily. In processing program, we installed two virtual cameras at a position ones two eyes apart in the horizontal direction [19]. Two cameras view the same image and extract each image as red and cyan colors. As an experimental approach, although we currently use an anaglyph 3D image system, active shutter 3D system is preferable for that it is much better at three-dimensional representation and high resolution implementation. Meanwhile, we implement the system applying stereoscopic front screen and 2D back layer screen. Whether to apply 3D stereoscopic images on both displays is an interesting issue and further investigation will be needed.

3.2.2 Spatial Exploration: Head tracking with depth camera

One depth camera (Microsoft Kinect) in front of the system faces the viewer and tracks the head to enable the motion parallax. It tracks the position of the viewers head and links it with the two cameras which render graphical elements in the virtual three-dimensional space (Figure 5). This allows the viewer to see the digitalized additional information as their attention is correctly registered on the physical information consistently. Therefore, it ensures the continuity of the spatial experience, increasing the interactivity between the information and the viewer (Figure 4(b)).

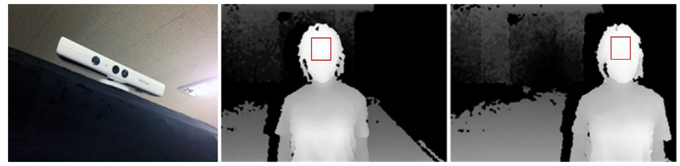

Fig. 5. Head tracking with depth camera in real-time

4 Feasibility Study

4.1 Comparison of 3D spatial perception

In this paper, we tested our system with experimental users, focusing the user study on how effective the system is in creating the 3D spatial perception. In order to verify the 3D spatial perception, it was unnecessary to operate back layer display at the same time. Twelve participants with past experiences with 3D user interfaces (age 20-32, 4 male and 8 female) were recruited to participate in the study. The total experiment time for each participant was between 30-40 min. Before the user test, users had the time to familiarize themselves with the system. We showed real object and virtual object images located in different z-value (depth) to users, and they experienced depth variations through the system by controlling the depth value of each virtual image (Figure 6).

Fig. 6. Virtual boxes and physical object located in differenct z-value(depth) to familiarize users with the system

Then we conducted a user evaluation with three physical variants of the SPAROGRAM: Type 1) the system applying 2D image (2D). Type 2) the system applying 3D stereoscopic image (3D). Type 3) the system applying 3D stereoscopic image and user interaction (view-dependent 3D) as shown in Figure 7 where the user viewed in front of the system. Tasks were designed to evaluate the 3D spatial perception, exclusively depending on the depth value regardless of other variants such as size. Users were asked to arrange a virtual ring image spatially aligned with the physical sphere model which is located in the middle of the system. We formally evaluated the error value (the difference of the position between the two objects in space), task completion time, and the total number of tries. Users were asked to complete the task as accurately and quickly as possible.

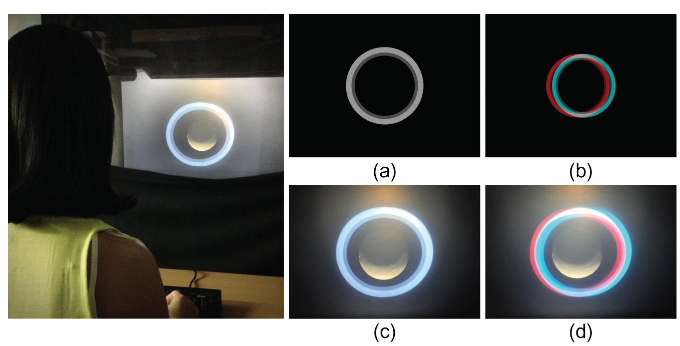

Fig. 7. User evaluation setup: (a)virtual 2D ring image, (b)virtual 3D ring image, (c)2D AR Hologram-virtual 2D ring image and physical sphere, (d)3D AR Hologram-virtual 3D ring image and physical sphere

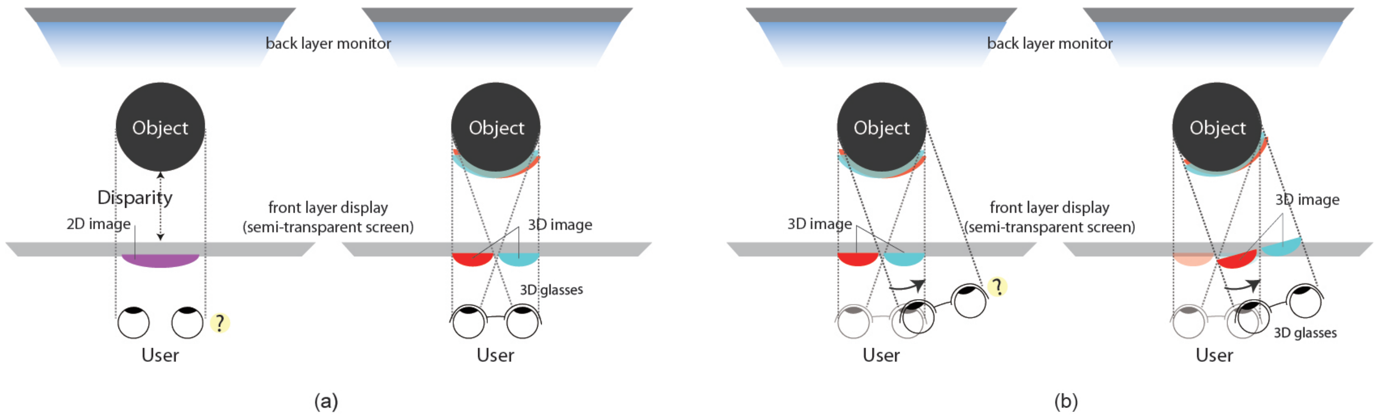

Fig. 4. (a)Spatial visualization: conventional system(left), system with multi-layer display and stereoscopic imaging(right), (b)Spatial Exploration: conventional system(left), system with head tracking interaction(right)

Figure 8(left) shows the difference of the position between the real object and virtual ring image. The 2D condition was 445.63 pixel (standard deviation: 62.74 pixel), followed by 3D 78.13 pixel (STD: 62.74 pixel), view-dependent 3D 56.87pixel (STD: 55.58 pixel). In 2D interface, users were confused because the virtual image looked as if it was always located in front of the real object. In contrast, in the case of 3D and view-dependent 3D, users placed the virtual ring image closer to the center of the physical object comparatively easier. Figure 8(right) shows the mean task completion time across all conditions (2D, 3D, view-dependent 3D). The 2D condition was the slowest 51.83s, followed by view-dependent 3D 32.17s, and 3D 31.08s being the fastest. In 2D condition, most participants looked confused. On the other hand, users performed the tasks more efficiently in view-dependent 3D interface since they were able to look in various angles by moving their heads. A repeated measures ANOVA yielded a significant difference between the three type conditions ($p < 0.05$). The results of the total number of tries are shown in Figure 8(right). Especially in the case of view-dependent 3D (35.67 number of times) participant performed tasks easier in creating 3D space perception without confusion. A repeated measures ANOVA yielded a significant difference between the three type conditions ($p < 0.001$). Users comments include "recognizing the space in 2D interface is difficult since the virtual image always seemed located in front of the physical object", "I feel as if I am adjusting the image size in the 2D flat screen rather than the depth of the virtual image". In contrast, in the case of 3D and view-dependent 3D condition, they easily positioned virtual image and the physical object like a one object effectively.

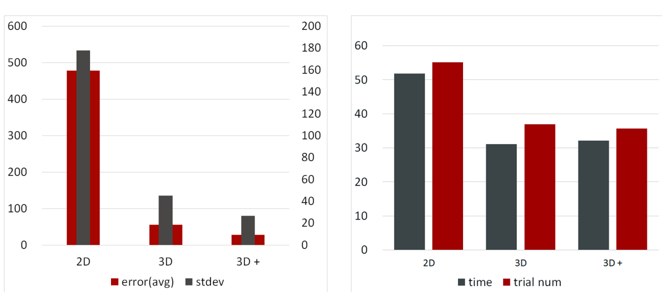

Fig. 8. Results of user evaluation: the difference of the position between the real object and virtual ring image (left), task completion time and total number of tries (right)

4.2 The effectiveness of SPAROGRAM for 3D visualization

We also conducted a user evaluation qualitatively to confirm the effectiveness of SPAROGRAM in visualizing three-dimensional AR information. Two prototype contents for user test were made and each of them had two types, one is for conventional AR hologram which is comprised of 3D graphics and a real object, and another is for newly conceived SPAROGRAM. We displayed same amount of information in each system and users observed contents for a period of time, then conducted the survey. First prototype contents are data visualization in medical environments (Figure 9(a),(b)). The system produces augmented medical information in the space surrounding the physical human model. For example, through the frontal semi-transparent display, virtual images such as human skeleton, structure of organs, and related information are augmented on each position of the human body model. At the same time, images describing contextual information is displayed in back layer display. The physical object and the back layer display are viewed by the participants through the semi-transparent front display simultaneously. The second prototype is exhibition information that visualize additional contents and information with the physical exhibits in museum environments. It helps the viewers understand content easier and better in exhibition field that deals with complex and various information such as text, image, video, 3D object and so on. Figure 9(c) and Figure 9(d) shows the exhibits related to the physical tower model and its explanation.

Questionnaire responses (5-point Likert scale) indicate that SPAROGRAM helped creating 3D depth perception by through spatial memory especially when using 2-layer display (2.1 vs. 3.9). Users comments include "not only applying stereoscopic image, but also using back display which is located at the back of the system enriches the display area continuously". Also, it revealed that SPAROGRAM was more effective in creating 3D spatial presence (2.3 vs. 4.3). Four participants commented that they received the impression that virtual images were merged into the physical object naturally. Also, visualizing much information divided into two layers and making them observe at the same time was helpful in perceiving information effectively. However, participants reported that the readability became poor when the information presented at the back layer display became too complex.

4.3 Discussion

User comments confirm that presenting three-dimensional AR information using the 2-layer display with the physical object is a promising method, and that they can benefit from the spatial memory. Also, we got some insights for future development. Some users commented that even though they can see the images on the two displays simultaneously, the back display presented images at the back side, offering a limited depth effect. Thus, we plan to explore technical issues for fully utilizing three-dimensional displays in such a way that the viewers experience a coherent and continuous 3D space. A few users also mentioned that visualizing dense information on both displays made them confused and overlapped information required extra efforts to interpret. In addition, the frontal semi-transparent display degraded the readability of the information, and strong light coming from the back

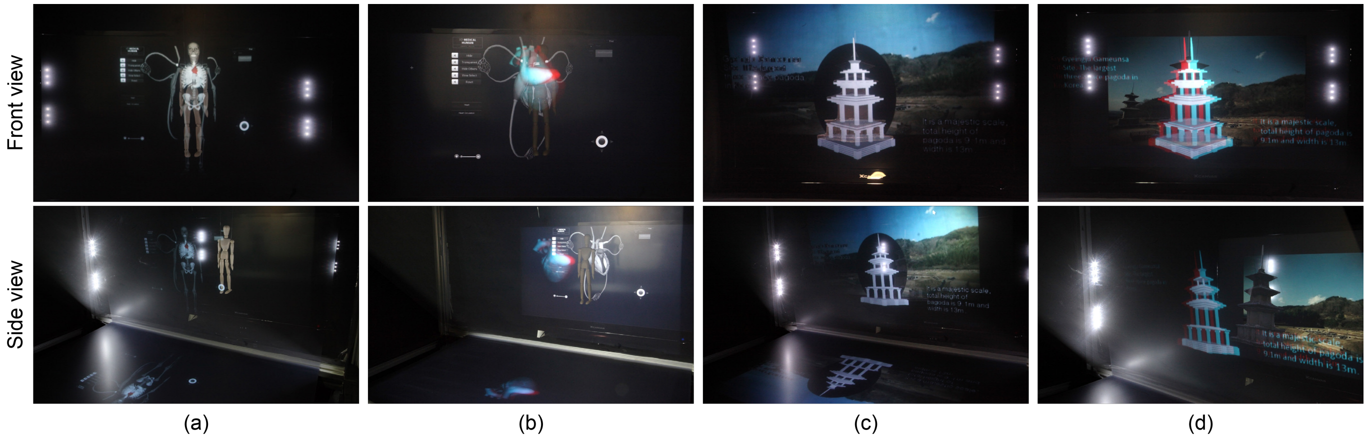

Fig. 9. Prototype of SPAROGRAM contents: (a)medical data visualization using conventional AR Hologram- front view(top), side view(down), (b)medical data visualization using SPAROGRAM, (c)exhibition visualization using conventional AR Hologram, (d)exhibition visualization using SPAROGRAM.

display disrupted the visual recognition. Accordingly, we plan to offer clear guidance and framework to visualize AR information effectively, such as the way to arrange and lay the data out, applying visual elements according to the characteristics of the display, and so on. We intend to improve the general usability with a careful design of the system.

5 Limitations and Futurework

Although the user study has revealed the effectiveness of the SPAROGRAM, our current prototype has the following limitations, which can be interesting subjects of future work for the completeness of the system. 1) User experience: Current system matches the physical object and the 3D information exactly, but the process is limited to one viewer. Although such limitation is not apparent in situations that do not require exact matching, it is necessary to consider multiple user interactions in order to provide an enhanced user experience. 2) Dynamic AR: Even though the current system is focused only on a static physical object, considering the possibility of a next generation system that may be used in dynamic environments such as incorporating moving object or actor in performances, an elaborate multi-tracking is needed. Through computer vision techniques, the system could expand the boundary of visualization subjects to dynamic objects. 3) Image Quality: Since the front display is semi-transparent, image is partially reflected, producing a less vivid image than that of the back layer display. Accordingly, further studies on the framework of information visualization for a better use of both displays to ensure vividness of images, and more experiments on various characteristics of display devices are required.

6 Conclusions

In this paper, we have presented a new 3D visualization system called SPAROGRAM that allows viewers to look at the physical objects as well as the displayed additional information on the front and back displays at the same time. We have focused on describing the concept of the system comparing with conventional 3D visualization techniques. We also have described our system implementation and evaluated the system through the user evaluation.

We summarize our contributions as follows: 1) a novel concept of the system for the three-dimensional visualization allowing the expansion of display area by using 2-layer display and applying the stereoscopic imaging and also user interaction. 2) a system design and implementation. 3) a user study quantitatively and qualitatively verifying the effectiveness of the proposed system. Results highlight that our system is significantly different from the general three-dimensional visualization method in the way that we used both the real space surrounding the physical object and the object itself as a display area at the same time. In particular, using a continuous three-dimensional space in AR visualization helps the user with not only more accurate 3D spatial perception (depth sense), but also with easier and better understandings of the information. We believe that the newly proposed Spatial AR Hologram is the beginning of an exploration of three-dimensional visualization. We expect our system to be useful in diverse fields such as exhibition, education, medical and biological applications, interactive presentations and performances where a real person acts as a physical object while manipulating the information on front and back displays and many others.

Acknowledgments

This research was partially supported by NRF and the BK21 Plus Framework.

References

[1] Arduino. http://www.arduino.cc/.

[2] O. Bimber and R. Raskar. *Spatial Augmented Reality: Merging Real and Virtual Worlds*. A. K. Peters, Ltd., Natick, MA, USA, 2005.

[3] A. Cockburn and B. McKenzie. 3d or not 3d?: Evaluating the effect of the third dimension in a document management system. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '01, pages 434–441, New York, NY, USA, 2001. ACM.

[4] A. Cockburn and B. McKenzie. Evaluating spatial memory in two and three dimensions. *Int. J. Hum.-Comput. Stud.*, 61(3):359–373, Sept. 2004.

[5] M. EyeLiner. http://musion.com/.

[6] G. E. Favalora. Volumetric 3d displays and application infrastructure. *Computer*, 38(8):37–44, Aug. 2005.

[7] G. S. Fischer, A. Deguet, D. Schlattman, R. Taylor, L. Fayad, S. J. Zinreich, and G. Fichtinger. Mri image overlay: applications to arthrography needle insertion. *Studies in health technology and informatics*, 119:150, 2005.

[8] J. D. Foley, A. van Dam, S. Feiner, and J. Hughes. *Computer Graphics: Principles and Practice*. Addison-Wesley, 3rd edition, 2013.

[9] J. Geng. Three-dimensional display technologies. *Adv. Opt. Photon.*, 5(4):456–535, Dec 2013.

[10] O. Gingrich, A. Renaud, and E. Emets. Kima-a holographic telepresence environment based on cymatic principles. *Leonardo*, 46(4):332–343, 2013.

[11] O. Hilliges, D. Kim, S. Izadi, M. Weiss, and A. Wilson. Holodesk: direct 3d interactions with a situated see-through display. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 2421–2430. ACM, 2012.

[12] A. Johnson, J. Leigh, P. Morin, and P. Van Keken. Geowall: Stereoscopic visualization for geoscience research and education. *Computer Graphics and Applications, IEEE*, 26(6):10–14, Nov 2006.

[13] B. Lee. Three-dimensional displays, past and present. *Print edition*, 66(4):36–41, 2013.

[14] H. Lee. 3d holographic technology and its educational potential. *TechTrends*, 57(4):34–39, 2013.

[15] J. Lee, A. Olwal, H. Ishii, and C. Boulanger. Spacetop: integrating 2d and spatial 3d interactions in a see-through desktop environment. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, pages 189–192. ACM, 2013.

[16] Y. Munz, K. Moorthy, A. Dosis, J. D. Hernandez, S. Bann, F. Bello, S. Martin, A. Darzi, and T. Rockall. The benfits of stereoscopic vision in robotic-assisted performance on bench models. *Surgical Endoscopy And Other Interventional Techniques*, 18(4):611–616, 2004.

[17] U. Obeysekare, C. Williams, J. Durbin, L. Rosenblum, R. Rosenberg, F. Grinstein, R. Ramamurthi, A. Landsberg, and W. Sandberg. Virtual workbench - a non-immersive virtual environment for visualizing and interacting with 3d objects for scientific visualization. In *Proceedings of the 7th Conference on Visualization '96*, VIS '96, pages 345–ff., Los Alamitos, CA, USA, 1996. IEEE Computer Society Press.

[18] T. Ogi, T. Yamada, K. Yamamoto, and M. Hirose. Invisible interface for the immersive virtual world. In *Proceedings of the 7th Eurographics Conference on Virtual Environments & 5th Immersive Projection Technology*, EGVE'01, pages 237–246, Aire-la-Ville, Switzerland, Switzerland, 2001. Eurographics Association.

[19] Processing. http://processing.org/.

[20] P. Ramachandran and G. Varoquaux. Mayavi: 3d visualization of scientific data. *Computing in Science Engineering*, 13(2):40–51, March 2011.

[21] J. Rekimoto and M. Green. The information cube: Using transparency in 3d information visualization. In *In Proceedings of the Third Annual Workshop on Information Technologies & Systems (WITS'93*, pages 125–132, 1993.

[22] G. G. Robertson, J. D. Mackinlay, and S. K. Card. Cone trees: Animated 3d visualizations of hierarchical information. In *Proceedings of the SIGCHI Conference on Human Factors in Computing Systems*, CHI '91, pages 189–194, New York, NY, USA, 1991. ACM.

[23] M. M. Sebrechts, J. V. Cugini, S. J. Laskowski, J. Vasilakis, and M. S. Miller. Visualization of search results: A comparative evaluation of text, 2d, and 3d interfaces. In *Proceedings of the 22Nd Annual International ACM SIGIR Conference on Research and Development in Information Retrieval*, SIGIR '99, pages 3–10, New York, NY, USA, 1999. ACM.

[24] H. S. Smallman, M. St. John, H. M. Oonk, and M. B. Cowen. Information availability in 2d and 3d displays. *IEEE Comput. Graph. Appl.*, 21(5):51–57, Sept. 2001.

[25] J. Steinmeyer. The science behind the ghost: A brief history of pepper's ghost, 1999.

[26] M. Tory and T. Möller. Human factors in visualization research. *IEEE Transactions on Visualization and Computer Graphics*, 10(1):72–84, Jan. 2004.

[27] M. H. P. H. van Beurden, G. van Hoey, H. Hatzakis, and W. A. Ijsselsteijn. Stereoscopic displays in medical domains: a review of perception and performance effects, 2009.