Journal of Zhejiang University SCIENCE A
ISSN 1673-565X (Print); ISSN 1862-1775 (Online)
www.zju.edu.cn/jzus; www.springerlink.com
E-mail: jzus@zju.edu.cn

SimWall: a practical user-friendly stereo tiled display wall system*

XIE Li-jun†, ZHENG Yao†‡, YANG Ting-jun, GAO Wen-xuan, PAN Ning-he

(*School of Computer Science and Center for Engineering and Scientific Computation, Zhejiang University, Hangzhou 310027, China*)

†E-mail: zdxlj@zju.edu.cn; yao.zheng@zju.edu.cn

Received Sept. 11, 2006; revision accepted Dec. 4, 2006

Abstract: SimWall is a user-friendly, stereo tiled display wall system composed of 18 commodity projectors operated by a Linux graphics cluster. Collaborating together, these projectors work as a single logical display capable of giving a high-resolution show, large-scale, and passive stereo scene. In order to avoid tedious system setup and maintenance, software-based automatic geometry and photometric calibration are used. The software calibration is integrated to the system seamlessly by an on-card transform method and is transparent to users. To end-users, SimWall works just as a common PC, but provides super computing, rendering and displaying ability. In addition, SimWall has stereoscopic function that gives users a semi-immersive experience in polarized passive way. This paper presents system architecture, implementation, and other technical issues such as hardware constraints, projectors alignment, geometry and photometric calibration, implementation of passive stereo, and development of overall software environment.

Key words: Tiled display wall, Stereoscopic display, Multi-projectors display, Parallel rendering, Camera-based geometry and photometric calibration

doi:10.1631/jzus.2007.A0596 **Document code:** A **CLC number:** TP391

INTRODUCTION

Large scale displays play an important role in various applications, such as scientific visualization, monitoring of city traffic, analyzing satellite cloud images, collaborating in meetings, and so on. It provides user experience totally different from common monitors or single projector. The benefits include showing whole view of large scene, offering enough area to place lots of windows at the same time for group collaborating, providing much more details of the objects, and giving users immersive feeling (Robertson *et al*., 2005).

However, large-scale displays have not been widely used due to their high costs. Most display wall systems today are still very expensive because they are built with high-end projectors, complicated supporting hardware, and high-end graphics machines. From the late 1990s, scientists and engineers began to seek ways to construct tiled display walls by off-the-shelf components driven by cluster and commodity projectors. Such kind of tiled display wall can be configured flexibly to meet various user requirements and its cost is much lower. For example, using LCD projectors and software calibration, a 2×2 tiled display wall driven by a single workstation only takes no more than 10 000 dollars.

While such systems are effective at providing large-scale imagery to users, its installation and operation is often a tedious undertaking. In recent research, some parts of the setup work have been automated, but due to the design constraints, many problems still require to be solved, among which there are three main problems. One is the alignment of projectors. In a project array with more than eight projectors, manual alignment becomes extremely time-consuming and even technically impossible. The second problem is how to eliminate the photometric variation between projectors. Unlike high-end pro-

‡ Corresponding author

* Project supported by the National Natural Science Foundation of China for Distinguished Young Scholars (No. 60225009), and the Major Research Plan of China (No. 90405003)

jectors, there exists significant color and intensity variation between low-cost projectors. Although commodity projectors provide some functions for color adjustment, the color space they can display are intrinsically different. So it is impossible to make all the projectors match photometrically by adjusting their properties. The third problem is how to provide a practical, user-friendly software environment. In order to support high resolution and complex scenes rendering, tiled display walls need a graphics cluster to drive them. The cluster introduces a totally different architecture, which needs programmers to divide and synchronize tasks between nodes.

In this paper, we introduce the SimWall system, which integrates some existing technologies in a novel way to automate the setup and maintenance process and to provide an easy-to-use environment. The projectors can be casually placed with small area of overlap between neighbors. Using a single camera and computer vision techniques, the geometry and photometric calibration can be achieved automatically. The calibration is performed as a background daemon with an innovative on-card transform method. The different architecture and additional calibration work are transparent to the end users.

SimWall can show stereoscopic display to give users a semi-immersive experience in polarized passive way. This character introduces many new design and implementation problems, such as screen material selection, polarized color offset, stereo image generation, strict geometry alignment, etc. Carefully treating these issues, SimWall provides a very good effect stereoscopic environment. Notice that this system can be extended to a fully immersive CAVE easily in terms of technology (Cruz-Neira *et al.*, 1993).

The remainder of this paper is organized as follows. Section 2 provides an overview of related work. Section 3 introduces the hardware framework of SimWall and guide rules to choose the commodity components. Section 4 details the automatic alignment of multi-projectors. The entire software environment and some results are addressed in Section 5. The final section provides conclusions and outlines future work.

RELATED WORK

Projected large display systems play a dominant role in virtual reality field. There exist several different configuration modes, such as curved surface projection, CAVE, etc. In this paper, we focus on the planar tiled display wall system.

Argonne National Laboratory developed a display wall named Active Mural (Hereld *et al.*, 2000). They designed a projector positioner with six freedoms to achieve accurate alignment. However, as they indicated, such manual approaches to alignment began to become difficult at 15 projectors. They also developed techniques for adjusting the projector characteristics to obtain color and luminosity matching.

Li *et al.*(2000) explored many applications running on the display wall of Princeton University. Their research group contributed much to the developing of display walls. The topics they covered included seamless imaging, parallel rendering, data visualization, intelligent networking, spatialized sound, camera-based tracking, and design methodologies.

The Office of the Future Group in the University of North Carolina at Chapel Hill introduced Pixel Flex, which is a scalable wall-sized multi-projector display system. It achieved single-pixel accuracy for geometric blending with casual placement of projectors, and performed photometric calibration with a single conventional camera using high dynamic range imaging techniques rather than an expensive photometer (Yang *et al.*, 2001; Raij *et al.*, 2003).

Brown and Seales (2002) introduced a very flexible and practical tiled display wall system. Their system allows placing the projectors totally casually. The self-calibrating method they introduced can finish the geometry registration in no more than 1 min automatically.

PowerWall in the University of Minnesota, is a tiled display wall based on large disk storage systems for raw or image data and many powerful Silicon Graphics MIPS R8000 processors. It is designed to visualize and display very high resolution data from large scientific simulations or from high resolution imaging applications. Although it is driven by a high-end computer, its display system is comprised of low-end tiled projectors (http://www.lcse.umn.edu/research/powerwall).

SAGE of Illinois University at Chicago envisions situation-rooms and research laboratories in which all the walls are made from seamless ultra-high-resolution displays fed by data streamed over ultra-high-speed networks from distantly located visualization, storage servers, and high-definition video cameras (Jeong *et al*., 2005). It allows local and distributed groups of researchers to work together on many distributed heterogeneous datasets and uses lambda table to interactive with the wall.

HARDWARE ISSUES

Fig.1 shows the schematic representation of SimWall. The framework is similar to the display wall of Princeton University (Li *et al*., 2000). The significant character that distinguishes ours from theirs is that each rendering machine in our system drives a pair of projectors projecting to the same area of screens. Mounting polarized filter before them, the users who wear 3D glasses which match the polarization of the projected image will see stereo scene. The projector pair is mounted in ceiling and table mode as shown in Fig.1a.

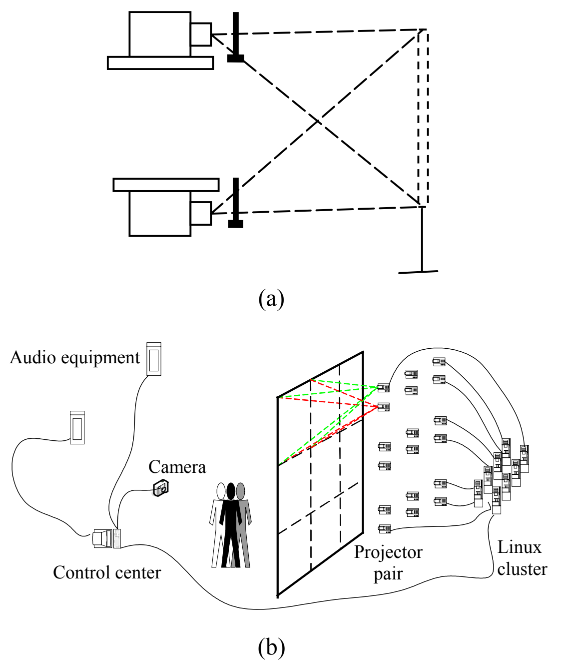

Fig.1 Projector pair mounted in ceiling and table mode (a) and schematic representation of SimWall (b)

The display wall is comprised of a 2.5 m×2.2 m rear projection screen with nine pairs, 3×3 arrays of Epson EMP-74 LCD projectors, each pair driven by a dual 2.4 GHz Xeon CPU PC with a NVIDIA Geforce 5200 graphics accelerator. The resulting image is about 3000×2300 high in resolution.

We do not choose active stereo method because it needs much expensive CRT projectors and LCD shutter glasses. Polarized passive stereo display is widely used in low-end situation. It only needs very low costs polarizing filters and corresponding polarizing 3D glasses. However, it requires rear projected screen materials to keep the polarizing property. Pape *et al*.(2003) evaluated numerous screen materials and tested their properties related to stereo performance. Based on their research and our test results, we select Stewen Filmscreen 200 which has low crosstalk and wide half gain view angle.

Dual-head graphics accelerators are necessary in our configuration to drive projectors pairs. Nowadays, there is an abundant choice in the market for dual-head graphics cards. We select NVIDIA Geforce 5200 for its high performance/price ratio. Better graphic card will give better performance surely.

Considerations involved when choosing projectors included brightness, contrast, resolution, controls, cost, and polarization effects. We use Epson EMP-74 LCD projector, which provides 2000 lumens, XGA resolution, and 500:1 contrast ratio. Benefits of LCD are that it has historically delivered better color saturation than DLP projector and is cheaper. LCD projectors have two main weaknesses. The first is visible pixelation, or what is commonly referred to as the "screen door effect" because it looks like you are viewing the image through a screen door. This phenomenon is diminished in tiled display as each of them only projects to a small area of screen. The second weakness is not-so-impressive black levels and contrast, which are vitally important elements in a good video image. However, in scientific visualization, this is not a significant problem.

GEOMETRY AND PHOTOMETRIC CALIBRATION

To achieve a large seamless uniform display, adjacent projectors must be aligned precisely to remove gap or overlap, and color variation between projectors must be eliminated or reduced perceptually. These two processes are called geometry calibration and photometric calibration correspondingly.

Geometry calibration

In the past, the construction of the projected display wall was quite tedious, requiring precise projector alignment and overlap by hand. Some research groups designed six freedoms projector positioners to mechanically align the projectors (Hereld *et al*., 2000). But in practice, for a project array with more than eight projectors, manual alignment to achieve sub pixel alignment in each dimension becomes almost impossible.

Software calibration can eliminate the trivial handwork and does not need expensive positioners. The main idea is shown in Fig.2. Misalignment of projectors can be captured and measured by cameras with computer vision. The task to get the mapping relation between each projector's image coordinates and the display's global coordinate is called geometric registration. After geometric registration, the origin projector's images can be pre-warped and projected just onto the desired areas. Several research labs implemented these ideas in different ways.

Surati (1999) introduced a software approach using calibrated cameras for planar screen. Raskar *et al*.(1999) developed a general solution for all kinds of surface using physical calibration pattern and stereo cameras. Chen *et al*.(2000) provided a mechanism which used an un-calibrated camera and simulated annealing method. Chen *et al*.(2002) built and refined a camera homography tree to automatically register any number of un-calibrated camera images. Most of these methods have global error of less than 2 pixels and local error of less than 1 pixel.

Our method uses a digital camera which can see the entire screen to process geometry register. Because the image distortion from projector to screen, and from screen to camera are both projective transformation, their coordinates can be transformed by a projective matrix. This relation is shown in Fig.2a. Then the transform matrix between the projector's image coordinate and the display's global coordinate, $\boldsymbol{P}$, can be calculated as follows:

$$\boldsymbol{P}=\boldsymbol{C}'\boldsymbol{T},$$

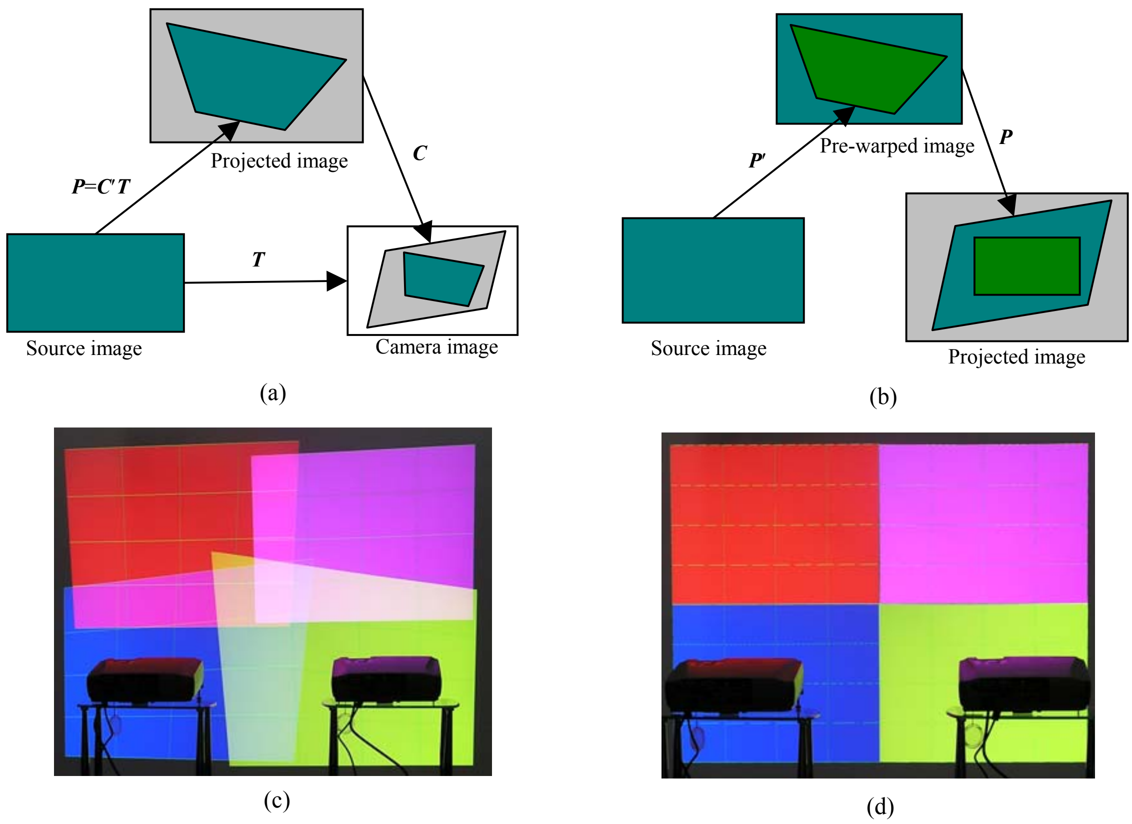

Fig.2 Process of geometry registration and calibration. (a) Relationship between computer, projector (global) and camera coordinate; (b) Pre-warping the computer image according to geometry registration; (c) 4×4 projected image before calibration; (d) 4×4 projected image after calibration

where ***C*** is the projective matrix from the projector's image space to the camera's image space, ***T*** is the projective matrix from camera's coordinate to global display's coordinate. In practice, the lens of camera and projectors will distort images in nonlinear ways. The nonlinear distortion of camera is removed by a preprocess with OpenCV. The nonlinear radial distortions of projectors is approximated by dividing its image space into small rectangle areas.

The matrixes ***C*** and ***T*** are obtained by finding corresponding points in the three different coordinate space. A computer vision method is used to automatically find the relation points. By projecting some features and recognizing them, the relationship between image space and camera space can be obtained. We select structured light circles as features and seeking their center in the camera's image. By many experiments, we found that this is one of the most precise features a camera can recognize. Four green circular features are placed on the four corners of the screen for camera recognition and calculation of projective matrix between screen and camera.

After matrix ***P*** is obtained, a pre-warp process can be added to the source image, which is shown in Fig.2b. Methods to integrate this pre-warp process seamlessly to common softwares are presented in Section 5.

Fig.2c and Fig.2d show images of a 2×2 projector array system before and after geometry calibration using our method. The global error is less than one pixel.

Photometric calibration

To eliminate photometric invariance is much more complicated than geometry calibration. Stone (2001a; 2001b) analyzed the color variance sources and established a theory for color spaces transform in multi-projectors. However, there are no methods to precisely measure the color character of LCD or DLP projectors till now.

Majumder *et al*.(2000) developed a series of methods to form a perceptual photometric seamless display. In summary, the main idea is to find the intensity transfer function (ITF) of each projector and then create attenuation blending mask, black offset mask, and color mapping table to unify the color response of all projectors. ITF can be measured by spectroradiometers, colorimeters or cameras. The attenuation blending mask is used to blend the overlap projection areas which will be twice brighter otherwise. The black offset mask is used to deal with the different black offsets in LCD and DLP projectors. The color mapping table can unify the color gamut of all projectors (Majumder *et al*., 2003; Majumder and Stevens, 2005; Wallace *et al*., 2003).

Our photometric calibration method is similar to that of (Majumder *et al*., 2003). We use cheap camera to measure the ITF with high dynamic range (HDR) imaging method. This method uses differently exposed photographs to recover the response function of the imaging process. Although spectroradiometers and colorimeters are precise color measure devices, they can only test color character of one point each time. This makes it very difficult to measure the spatial large display of projectors by them. What is more, they are quite expensive for common users.

After the ITF is obtained, the luminance mapping table for each projector can be calculated. We ignore the chrominance variance because it is less perceptually notable but much difficult to measure. The color mapping table is inserted before the frame buffer output in each render machine to get a uniform luminance response.

Projector overlapped regions need to be incorporated otherwise they will cause noticeable bright areas. This process is called edge blending. Edge blending can also blur the small position error on edge area. We calculate the blending mask with the technique presented in (Raskar *et al*., 1999). The frame buffer-sized alpha masks attenuate the pixel values of the corrected image accordingly.

SOFTWARE ENVIRONMENT

SimWall can run all kinds of GUI programs based on X or OpenGL API. The programs with the ability of running on tiled display, such as Paraview, EnSight DR, can run on SimWall directly. Other common programs need some additional tools to do distributed rendering. Currently in SimWall, this distributing work is done by Chromium (Humphreys *et al*., 2002) and distributed multi-head X (DMX) (http://dmx.sourceforge.net/).

Chromium is a system for interactive rendering on clusters of workstations. It provides sort-first, sort-last and hybrid distributed rendering ways. Most OpenGL programs can run on Chromium without modification.

DMX is a proxy X server that provides multi-head support for multiple displays attached to different machines (each of which is running a typical X server). The multiple displays on multiple machines are presented to the user as a single unified X desktop. Most other systems choose VNC as the desktop platform because it transfers the image of the desktop screen and so it is easy to apply image modification (Richardson *et al*., 1998). DMX runs in a different mode, it distributes 2D primitives to clients instead of rendered image. This can decrease the load of both the server host and networks. By integration with Chromium, DMX can render all kinds of common GUI and OpenGL programs.

We develop two methods to integrate the geometry and photometric calibration to the applications. The two methods correspond to two running modes in SimWall. One is common mode for 2D GUI programs and common OpenGL programs. All non-stereo applications, such as Paraview, Ensight DR, common programs running on DMX and Chromium, run in this mode. In this mode, the calibration process runs as a background daemon. Programs applying it will not notice its existence at all. The other mode is stereo mode especially for OpenGL stereo programs. These two modes utilize the two channels of a graphic card in different ways as shown in Fig.3. The common mode utilizes one channel to do normal rendering job, and the other for seamless geometry and photometric calibration. Only the output of the second channel will be projected and tiled as a large display. The stereo mode renders left and right eyes separately in the two channels and projects both their output images.

Common mode

The direct way to integrate software calibration is modifying the source codes of the applications. However, this is impossible for most applications because their codes are not open. Another method is to modify the distributed render architecture on which other applications run. For example, Brown and Seales (2002) performed the calibration on WireGL. Raij *et al*.(2003) performed the calibration on Chromium and VNC. But WireGL and Chromium are designed only for distributed OpenGL rendering, and VNC is only for desktop applications. When running programs do not depend on these tools, such as ParaView and Ensight DR we mentioned above, this method cannot work.

We developed an on-card transforming, two pass rendering method to integrate the geometry and photometric calibration. It is implemented as a daemon program transparent to other applications. All non-stereo applications can run on the system directly as before.

Fig.3a shows the flow chart of this method. Applications run in a normal way on the first channel of graphic cards. But the output image of this channel is

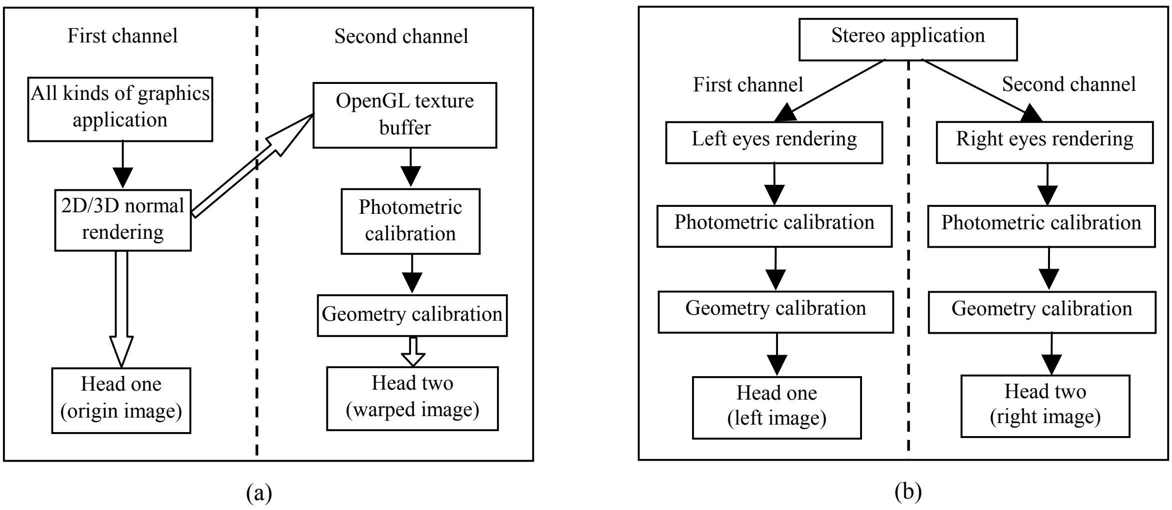

Fig.3 Rendering pipelines of common mode (a) and stereo mode (b)

not used directly. The background calibration daemon captures this output frame buffer periodically and transfers it to the texture buffer. Then the daemon multiplies the texture with pre-computed alpha masks and warps it according to the geometry registration in the second channel. At last, only the output of the second channel is projected to the display and tiled to a large display.

The whole calibration process runs in graphic card, which is why it is called an on-card transforming method. Because we take full advantage of the hardware accelerating ability, the method can run at high speed with low CPU usage. The frequency of frame buffer capturing and transferring can be controlled. Commonly, 30 fps is fluent enough for human. At such speed, our method takes an average CPU load of less than 1% and peak load of no more than 5%. Note that the calibration process is independent of scene complexity.

Stereo mode

As described in Section 3, our hardware system supports passive stereo mode. As to software, the quad-buffer passive stereo and side-by-side stereo modes in OpenGL are supported. Using Chromium or other distributed software, the image pairs for left and right eyes are displayed to the two heads of graphic cards respectively. For non-stereo OpenGL programs, it is possible to run them in stereo mode by capturing all the OpenGL primitives, modifying the projection matrix, and creating left and right rendering pair. However, the suitable stereo parameters are difficult to be automatically calculated. This needs good knowledge about the stereo pair generating technology.

In this mode, both channels are utilized for rendering, so the on-card calibration method used in common mode cannot work. We developed a stream processing unit (SPU) for Chromium (http://chromium.sourceforge.net/doc/). This SPU intercepts the *glSwapBuffer* function and adds calibration process before it. The flow chart is shown in Fig.3.

Results

Fig.4 shows some results on SimWall. Fig.4b is the initialized scene when the SimWall starts. It consists of nine KDE desktops with overlap between neighbors. Fig.4c is a 3D OpenGL program simulating water dropping. The geometry and photometric calibration is done in common mode. Scientists can get much more details in this mode than in a low-resolution display. Fig.4d shows two researchers wearing polarized 3D glasses are collaborating in a stereo mode. The users are satisfied with the immersive effect.

CONCLUSION

In this paper we have presented techniques to build SimWall, a user-friendly stereo multi-projector display system. The main goal is to make large-scale stereo display systems affordable and available to end-users. We address our experience on the commodity hardware selection and installation. We automate the calibration process using computer vision techniques and develop an on-card transform method to integrate this process seamlessly. We show that all applications based on X protocol or OpenGL standard can run on our system without any modification. The large-scale stereo display provides users a semi-immersive experience.

The current configuration of SimWall is operated by keyboard and mouse. However, in a large-scale stereo display, this is not intuitionistic or convenient. New interactive ways between human and machine is a large research area. We plan to add camera-based gesture recognition and speech recognition to the system. This would greatly simplify the operation on SimWall.

Another open problem is the photometric calibration. We only deal with the intensity variance and the overlap between the projectors. The chrominance differences are left and noticeable. This is a barrier for fully uniform experience of users.

References

Brown, M.S., Seales, W., 2002. A Practical and Flexible Tiled Display System. 10th Pacific Conference on Computer Graphics and Applications (PG'02), p.194. [doi:10.1109/PCCGA.2002.1167859]

Chen, Y., Clark, D.W., Finkelstein, A., Housel, T.C., Li, K., 2000. Automatic Alignment of High-Resolution Multi-Projector Display Using an Un-calibrated Camera. Proc. Conference on Visualization, p.125-130.

Chen, H., Sukthankar, R., Wallace, G., Li, K., 2002. Scalable Alignment of Large-Format Multi-Projector Displays Using Camera Homography Trees. Proc. IEEE Visualization, p.339-346.

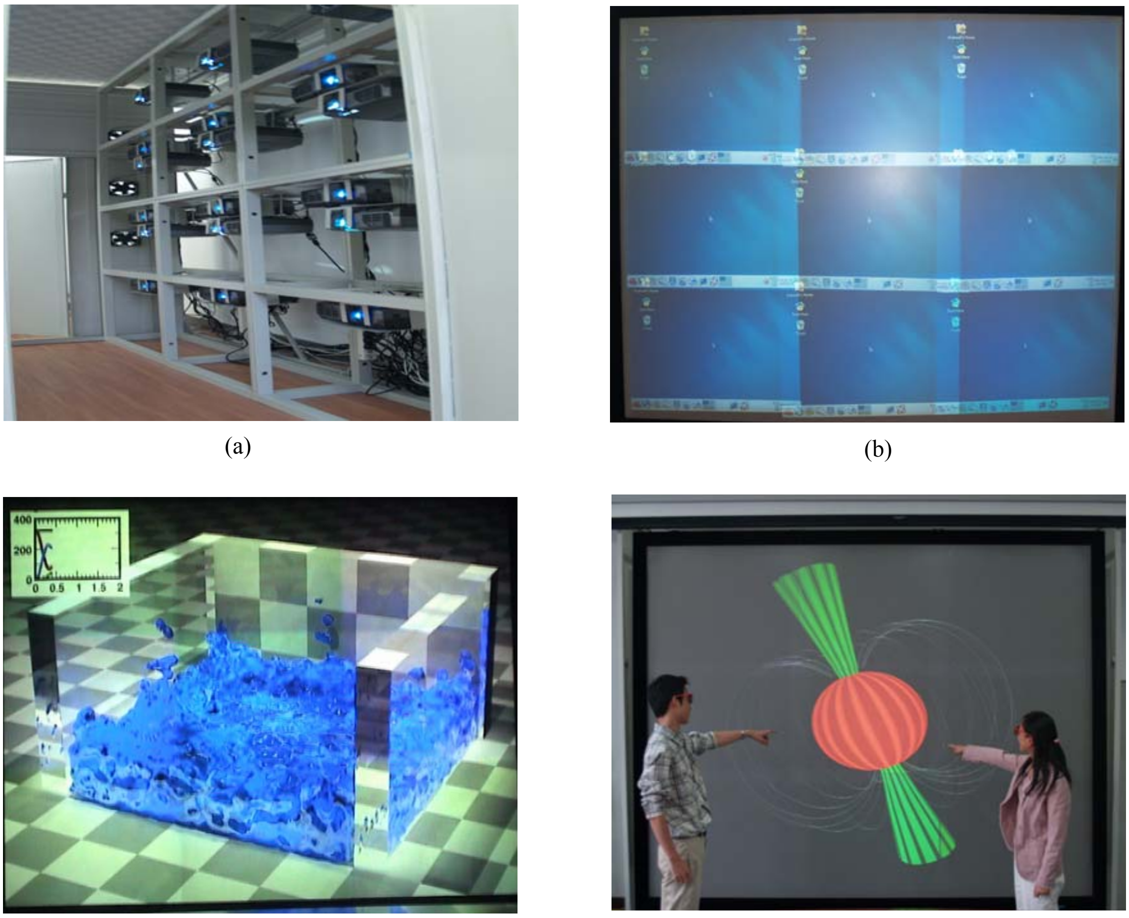
(a) (b) (c) (d)

Fig.4 Some results of SimWall. (a) The projector array; (b) Nine origin KDE desktops without calibration; (c) Simulation of water dropping in common mode; (d) Collaboration in stereo mode

Cruz-Neira, C., Sandin, D.J., DeFanti, T.A., 1993. Surround-Screen Projection-Based Virtual Reality: The Design and Implementation of the CAVE. Proc. 20th Annual Conference on Computer Graphics and Interactive Techniques, p.135-142. [doi:10.1145/166117.166134]

Hereld, M., Judson, I.R., Stevens, R.L., 2000. Introduction to building projection-based tiled display systems. *IEEE Computer Graphics and Applications*, **20**(4):22-28. [doi:10.1109/38.851746]

Humphreys, G., Houston, M., Ng, R., Frank, R., Ahern, S., Kirchner, P.D., Klosowski, J.T., 2002. Chromium: a stream-processing framework for interactive rendering on clusters. *ACM Transactions on Graphics*, **21**(3):693-702. [doi:10.1145/566654.566639]

Jeong, B., Jagodic, R., Renambot, L., Singh, R., Johnson, A., Leigh, J., 2005. Scalable Graphics Architecture for High-Resolution Displays. IEEE Information Visualization Workshop.

Li, K., Chen, H., Chen, Y., Clark, D.W., Cook, P., Damianakis, S., Essl, G., Finkelstein, A., Funkhouser, T., Housel, T., 2000. Building and using a scalable display wall system. *IEEE Computer Graphics and Applications*, **20**(4):29-37. [doi:10.1109/38.851747]

Majumder, A., He, Z., Towles, H., Welch, G., 2000. Achieving Color Uniformity Across Multi-Projector Displays. Proc. IEEE Visualization, p.117-124.

Majumder, A., Jones, D., McCrory, M., Papka, M.E., Stevens, R., 2003. Using a Camera to Capture and Correct Spatial Photometric Variation in Multi-Projector Displays. IEEE International Workshop on Projector-Camera Systems.

Majumder, A., Stevens, R., 2005. Perceptual photometric seamlessness in projection-based tiled displays. *ACM Transactions on Graphics*, **24**(1):118-139. [doi:10.1145/1037957.1037964]

Pape, D., Anstey, J., Dawe, G., 2003. Low-Cost Projection-Based Virtual Reality Display. SPIE, **4660**:483.

Raij, A., Gill, G., Majumder, A., Towles, H., Fuchs, H., 2003. PixelFlex2: A Comprehensive, Automatic, Casually-Aligned Multi-Projector Display. IEEE International Workshop on Projector-Camera Systems.

Raskar, R., Brown, M.S., Yang, R., Chen, W.C., Welch, G., Towles, H., Seales, B., Fuchs, H., 1999. Multi-Projector Displays Using Camera-Based Registration. Proc. Conference on Visualization, p.161-168.

Richardson, T., Stafford-Fraser, Q., Wood, K.R., Hopper, A., 1998. Virtual network computing. *IEEE Internet Computing*, **2**(1):33-38. [doi:10.1109/4236.656066]

Robertson, G., Czerwinski, M., Baudisch, P., Meyers, B., Robbins, D., Smith, G., Tan, D., 2005. The large-display user experience. *IEEE Computer Graphics and Applications*, **25**(4):44-51. [doi:10.1109/MCG.2005.88]

Stone, M.C., 2001a. Color and brightness appearance issues in tiled displays. *IEEE Computer Graphics and Applications*, **21**(4):58-66. [doi:10.1109/38.946632]

Stone, M.C., 2001b. Color Balancing Experimental Projection Displays. Proc. 9th IS&T/SID Color Imaging Conference, p.342-347.

Surati, R.J., 1999. Scalable Self-Calibrating Display Technology for Seamless Large-Scale Displays. Ph.D Thesis, Massachusetts Institute of Technology.

Wallace, G., Chen, H., Li, K., 2003. Color Gamut Matching for Tiled Display Walls. Proc. Workshop on Virtual Environments, p.293-302. [doi:10.1145/769953.769988]

Yang, R., Gotz, D., Hensley, J., Towles, H., Brown, M.S., 2001. PixelFlex: A Reconfigurable Multi-Projector Display System. Proc. Conference on Visualization, p.167-174.