Virtual Reality Content-Based Training for Spray Painting Tasks in the Shipbuilding Industry

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Training is one of the representative application fields of virtual reality technology where users can have virtual experience in a training task and working environment. Widely used in the medical and military fields, virtual-reality-based training systems are also useful in industrial fields, such as the aerospace industry, since they show superiority over real training environments in terms of accessibility, safety, and cost. The shipbuilding industry is known as a labor-intensive industry that demands a lot of skilled workers. In particular, painting jobs in the shipbuilding industry require a continuous supplement of human resources since many workers leave due to the poor working environment. In this paper, the authors present a virtual-reality-based training system for spray painting tasks in the shipbuilding industry. The design issues and implementation details of the training system are described, and also its advantages and shortcomings are discussed based on use cases in actual work fields.

Keywords: Virtual reality, virtual training, paint spray simulation.

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I. Introduction

Virtual reality (VR) technology has been evolving for the purpose of providing virtual experience to users [1]. Not only do they reproduce a real-world experience in a virtual space, VR systems can also provide virtual experiences that are impossible to reproduce in real life. In some cases, experiences in virtual spaces appear to work even better than in real-world situations in terms of safety and cost. Consequently, VR systems have been widely used for training purposes in aerospace, military, and medical fields in order to overcome the limits in real training environments. Flight simulators are notable VR-based training systems, and pilots today (both military and commercial) are required to fly regular hours in a virtual space before they fly in the real world.

The shipbuilding industry is known to be one of the most labor-intensive industries and requires skilled workers. Hundreds of people in a shipyard work together with different specialties including welding, painting, heating, piping, and so on. While most of the jobs in the shipbuilding industry involve hard and difficult work, painting tasks, in particular, they create a continuous demand on human resources since many workers resign due to the poor working environment, for example, workers are exposed to noxious gasses included in paint.

Figure 1 shows a typical working environment for a spray painting task in a shipyard. While painting is known to be a difficult job, it is also one of the most important processes in ship construction. Not only affecting the construction schedule, the painting process is also directly related to the quality of the ship under construction. While it is usually known as a process for beautifying appearance, the more important purpose of painting is to prevent corrosion of the ship's body; therefore,

Fig. 1. Working environment of spray painting task in shipyard.

it is directly related to securing the durability and life span of a vessel. The paint must be coated evenly on the surface of the ship's body structure with a specific thickness, ensuring that the coating will not crack or wear out, exposing steel parts to corrosive seawater. Hence, it is particularly important to train paint workers so that they can paint evenly on large surfaces with a uniform thickness.

Most of the painting process in shipbuilding is done by spray painting on large structures and surfaces, followed by brushes and rollers for fine touch-ups and filling of holes. Therefore, the overall painting quality, that is, the thickness, is largely dependent on spray painting, and only those who are highly skilled experts are allowed to do such work in ship construction. To meet the continual demand for skilled experts, it is necessary to have efficient training courses for spray painting.

Currently, novice workers practice spray painting usually by spraying real paint onto steel structures. Some basic training courses also use water instead of paint in order to reduce the training costs, although it is difficult to check the results. There are certain problems with such training environments where real materials are used for practicing:

- Wasting paint and water is not only a financial problem but also involves environmental issues.
- Paints contain noxious gasses, making it difficult to continuously work or practice for an extended amount of time.
- Instructors and trainees need to wear masks while training, making it difficult to communicate with each other.
- After practicing, the painted structures need to be dried and cleaned, which is time consuming.
- There are space problems for storing huge steel structures.
- Only a limited number of trainees are allowed to practice at a single time.

In this research, the authors try to overcome these problems in the current training environment by applying VR content technology to a training course. In order to have training inside a virtual environment, the real working environment first needs to be reproduced as accurately as possible in a virtual space. For this purpose, in the VR-based spray painting training system, immersive stereo displays are used for visualizing the virtual training environment. A spray gun, the same tool as that used in the real field, is used as a training interface. A user operates this spray gun interface, practicing by painting on virtual models of steel structures visualized on an immersive display. As the user finishes painting, he/she receives feedback of the training results, such as paint thickness, instantly.

In the rest of this paper, the authors first review some of the related works and then illustrate the interface design of the proposed system based on the requirements collected from spray paint workers and instructors. Then, the simulation and visualization methods for presenting paint spray patterns in real-time within an interactive virtual environment is illustrated. Next, the implementation details of the prototype system are described, and also discussions are given on the usefulness of the training system with results from field tests at actual shipbuilding sites. Finally, the paper is concluded by suggesting future research directions.

II. Related Work

VR-based training systems are historically famous in aerospace, military, and medical fields. Stone [2] summarizes a number of cases where VR-based training has been successfully applied to such areas. Recently, there have been certain attempts to broaden its use into the industrial field as well. There are a couple of examples of VR simulators that have been developed for training welding tasks [3], [4]. Training safety guidelines within virtual environments are also one of the interesting issues in the mining industry [5]-[7]. In line with these attempts to apply VR content technology to the industrial training field, in this paper, the authors introduce a VR-based training system for spray painting.

Within the perspective of visualizing painting with computer simulation, there are a number of previous works in the computer graphics field [8]-[10]. However, these works are not suitable for a spray painting virtual training system in terms of their non-real-time processing performance and use of different painting tools, for example, a paint brush, for artistic expressions. In comparison, the proposed training system needs to reproduce realistic paint spray patterns in real-time, interactively, according to different angles and distances between the spray gun and the target structure.

There have been previous systems that simulate spray painting, such as Virtual Graffiti [11] and MY virtual graffiti [12]. Both use spray paint cans as their main interfaces and were targeted for artistic and entertainment applications. While these systems show a realistic and interactive visualization of spray painting, they lack in simulating the growing thickness of the paint coating. Consequently, they do not support measuring the paint film thickness which is also an important measure of skill for training purposes. Also, one of these systems was even limited to painting on two-dimensional planar structures, while for the training purpose in this work, painting on three-dimensional (3D) structures is necessary.

III. Interface Design

Since the main purpose of a training system is to help users (or trainees) acquire the skills needed for real situations, it is important to reproduce a realistic virtual environment that represents a real working environment. This includes both visualizing the actual working space convincingly [13] and providing working interfaces similar to those used in the real situation [14], harmonizing each, and fitting them into the teaching/training methods.

Providing a realistic visualization of a virtual training environment can be considered in terms of two aspects: display interface hardware and real-time rendering of the virtual scene. From the aspect of hardware, immersive displays, such as head-mounted displays (HMDs) or large-screen displays, are regarded as one of the mandatory components of VR systems in order to provide high-fidelity visualization. Immersive displays cover the whole sight of the user so that the user can feel as if he or she is within the virtual environment. In addition, in many cases, these displays also provide stereoscopic views, helping users understand the 3D structure of the virtual scene better.

Realistic rendering of a virtual scene is another aspect of visualization in which computer graphics technology plays an important role. Besides the visual realism of the rendered scene, it is important for a training system to visualize the virtual scene based on a correct physical simulation. In the case of spray paint training, the spray patterns painted on the structure must be correctly visualized according to the movement of the spray gun so that the users can learn physical skills through the virtual training process.

While visual feedback is the main sensual modality that users receive from a virtual training system, sound and haptic feedback are also important in order to reproduce a real working environment for training. When workers hold a spray gun in their hands and start to spray, they can feel a repulsive force when paint is ejected from the nozzle. They can also hear a spraying noise making them aware that the paint is being sprayed. Therefore, such aural and haptic feedback should also be reproduced in a training system in order to provide a realistic training environment to the users in a virtual space.

In the rest of this section, the authors focus on describing interface designs based on requirements and demands collected from paint spay workers and instructors. The simulation and visualization method of spray patterns are described in the next section.

1. Immersive Display

There are two main types of immersive displays widely used in VR systems for providing high-level spatial presence: CAVE-type display and HMD. CAVE [15] displays utilize a number of large projection screens forming a cubical room to cover the whole view of the user. Recently, tiled displays [16] are also becoming popular to overcome the limitations of projection-based display systems, such as low image resolution and large space requirements. On the other hand, an HMD is worn by the user, and the display screen is attached to the user's head, following the user's view. By tracking the user's head motion, an omni-directional view of a virtual scene can be provided to the user by updating the virtual scene image according to the user's view direction.

In order to provide the same experience as a real working environment, the authors considered the following guidelines when selecting the display platform. First, the display system must meet space and cost requirements. A number of display systems must be installed for multitudes of trainees, and therefore they should require minimal space and little cost. Second, for the trainee, stereo visualization and head tracking are necessary for a correct understanding of the 3D target structures.

Based on these requirements, the authors have selected two types of display configurations: a projection-based wall-type display and an HMD. The wall display was chosen to be used in a lecture room. The HMD configuration was set up for every individual trainee to practice on his/her own.

The size of the wall display was chosen according to the motion volume of the actual paint spraying activities. The size of the display screen is 150 cm in width and 200 cm in height. To cover the user's view and prevent users from hitting the physical screen with the spray gun interface, the users were asked to stand about one meter in front of the screen. Since the user stands relatively near the screen, it is necessary to provide a high enough image resolution on a large screen. Therefore, instead of using a single projector to cover the whole screen area, the projectors are installed in a 1 (horizontal) × 2 (vertical) tiled configuration, dividing the screen into upper and lower areas, and making each projector dedicated to the corresponding area. The images in the overlapping area were rendered with intensity gradient alpha masks for soft edge blending. A rear-projection configuration was chosen to prevent users from occluding the projected image.

To provide stereo images to the user, circular polarizing filters were used since they are relatively cheaper than other filtering methods, such as active shutters, and also allow users to turn their heads freely. Since the actual task of spray painting involves full body motions while looking at a 3D target structure, it is necessary to track the user's viewpoint for visualizing a correct 3D image. An off-axis projection was applied for visualizing stereoscopic images according to the tracked positions of the user's eyes relative to the screen, which is similar to the method used in the CAVE display.

An HMD provides fully-immersive views to the user with a relatively small device. While the wall display has a limitation regarding the user's viewing direction, an HMD provides an omni-directional view to the user by tracking their head movement and updating the scene shown on the display according to the user's viewing direction.

Motion training requires correct visual perception of a 3D work space, and spray painting tasks involve relatively close body motions. Therefore, visualization parameters for stereoscopic visualization on an HMD, for example, field of view (FOV), must be carefully calibrated so that users can see the virtual scene under the same configuration that they perceive a physical space.

To match the visualization parameters of a virtual scene to a physical space, a point-matching-based calibration method was developed for an optical see-through HMD configuration. By asking users to simply match up the tip of the physical spray gun to the visualized virtual calibration points, the view projection matrix for both eyes are solved automatically based on these corresponding points. While the method used in this work is similar to that described in [17], the authors used calibration points visualized in stereoscopic view instead of asking users to match the size of the calibration points. In this way, the calibration process is simpler and shorter since the proposed method calibrates both the left and right views at one time.

For the video see-through configuration, the FOV of the camera image was calibrated first by applying digital zooming and then performed the calibration method described above. For fully immersive configuration, the visual parameters calibrated in the optical see-through mode were simply applied.

2. User Interface

To provide the same experience as in a real working environment, the main user interface of the prototype paint spray training simulator was designed on top of the actual spray gun used out in the field. Electronic buttons are attached to the spray gun so that the gun triggering could be sensed by the computer. Since the real work process involves fully squeezing the spray gun trigger, the authors decided to use simple on/off buttons instead of pressure sensors.

In addition to the trigger, two more buttons were added for changing modes and navigating within the virtual environment. The mode button toggles between the spraying mode and measuring mode, and the navigation button allows the user to navigate within the virtual space according to the spray gun movement.

While the electronic button provides the triggering input, the motion tracking system provides 3D movement of the spray gun, and the virtual paint is sprayed according to this movement. The same tracking system is used for sensing the user's head motion, in order to provide correct stereo visualization corresponding to the user's viewpoint, as was mentioned already.

An air compressor was also connected to the spray gun in order to provide force feedback and the sound of spraying. The air pressure was adjusted to provide an amount of force similar to that of real paint spray. Although general haptic devices could also be applied, the authors have decided to use an air compressor due to its simplicity and practical use in the industrial field.

IV. Paint Spray Pattern Simulation and Visualization

Realistic visualization of paint spray in real-time is one of the important features of the proposed virtual training system. However, visualizing a paint spray pattern correctly is not sufficient on its own. In addition, it is also important to simulate the thickness of the paint accumulated on the surface of the target structure. Thickness is the main measurement for testing the trainee's skill level.

The most precise approach uses the computational fluid dynamics/finite element method for physical simulation of paint spray particles. However, this is not suitable for real-time processing due to limitations in performance on a PC platform.

As an alternative, the authors used a heuristic approach. Figure 2 illustrates the method used for simulating and visualizing spray patterns in real-time. The process includes an offline stage in which an approximate mathematical model of the spray pattern thickness is constructed, and in the real-time process, the spray pattern is simulated interactively according to this model and the user's motion.

What follows is a description of the whole simulation process in detail. We first created a database of spray patterns by measuring a set of real paint spray patterns for various cases (with different angles and distances between the spray gun and the surface). According to these measurements, an approximate mathematical model is developed for calculating the thickness of a paint spray pattern in real-time. In this work, a database

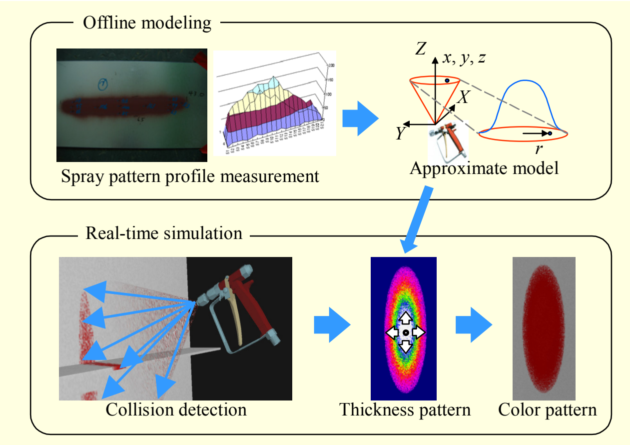

Fig. 2. Paint spray pattern simulation and visualization.

was constructed for two types of spray gun tips, which mainly affect the shape of the pattern, and two types of paint, which differ in thickness after drying. According to the pattern profiles from the database, a mathematical model of the spray pattern was developed based on Gaussian distributions proportional to the distance, forming a conical spray volume. The spray pattern model is described by the following equations:

$$f(x,y,z)=\frac{c}{z^2}\exp(-r^s(x,y,z)),$$

$$r(x,y,z)=\sqrt{\left(\frac{x}{az}\right)^2+\left(\frac{y}{bz}\right)^2},$$

where the output value of f represents the thickness value at a specific point (x, y, z) relative to the tip of the spray gun as seen in the upper right section of Fig. 2. Parameters a and b determine the elliptical shape of the spray pattern, and c and s change the amount and distribution of the paint thickness. These four parameters are determined by minimizing the differences between the mathematical model and the database of actual spray patterns.

At runtime, a simple ray casting method is used for detecting the collision area between the spray volume and the target structure surface in real-time. The number of rays is adaptively varied according to the complexity of the target structure. After obtaining the collision points on the target surface, the approximated spray pattern area is determined by searching the texture space. Finally, the thickness of the paint pattern is calculated per pixel on the texture according to the mathematical model developed previously.

After calculating thickness, the actual color of the paint pattern must be chosen for realistic visualization. The color of the paint pattern is calculated by merging the color of the paint being sprayed and the color of the virtual structure upon which the paint is sprayed. The colors of the points on the pattern texture with a paint thickness under a minimum threshold remain the same as the virtual structure, while the points having a thickness value over a maximum threshold are colored with the paint color. The colors of the points with a thickness value between the minimum and maximum thresholds are decided by interpolating the colors of the paint and the virtual structure. In this way, the texture image of the virtual structure is modified in order to visualize spray patterns formed on the surface of the virtual structure.

To balance between system performance and the quality of visualization, a texture resolution of 192 × 192 pixels is used for calculating the spray pattern on a one square meter target surface. In this case, the system runs in real-time at around 25 frames per second.

The virtual models of the target structure are acquired by converting computer-aided design (CAD) models of ship blocks. While converting the CAD data into a Virtual Reality Modeling Language (VRML) file, the surfaces of the model are divided into pieces having one square meter area, and additional information for spray painting simulation, such as texture coordinates, are added.

With real paint, when too much paint is sprayed on a surface, it starts to dribble down. This is called sagging and is one of the defects that trainees must avoid. While it would be good for enhancing visual realism, after consulting with a professional spray paint instructor, the authors concluded that realistic visualization of sagging is not that necessary for training purposes. Instead, a simple warning sign is given to the user when he tries to paint too much, and the paint thickness goes over the maximum value. According to a field test, this has turned out to be sufficient for training purposes.

V. Implementation

1. System Overview

Figure 3 shows some pictures of a prototype implementation of VR-based paint spray training system in use. In the prototype system, a user stands in front of a wall-type display (a projection-based large screen stereo display), watching a virtual scene of the training environment, shown in Fig. 3(a). The user holds a spray gun interface and practices painting on a virtual ship block in the same manner done with real paint spray. The spray gun interface is custom-built based on a real paint spray gun, adding electronic switches to sense when the user pulls the trigger. As the user moves and pulls the trigger on the spray gun, the computer tracks the 3D motion of the gun and simulates and visualizes the paint sprayed onto the surface of the virtual structure.

After finishing painting on a virtual structure, the user can

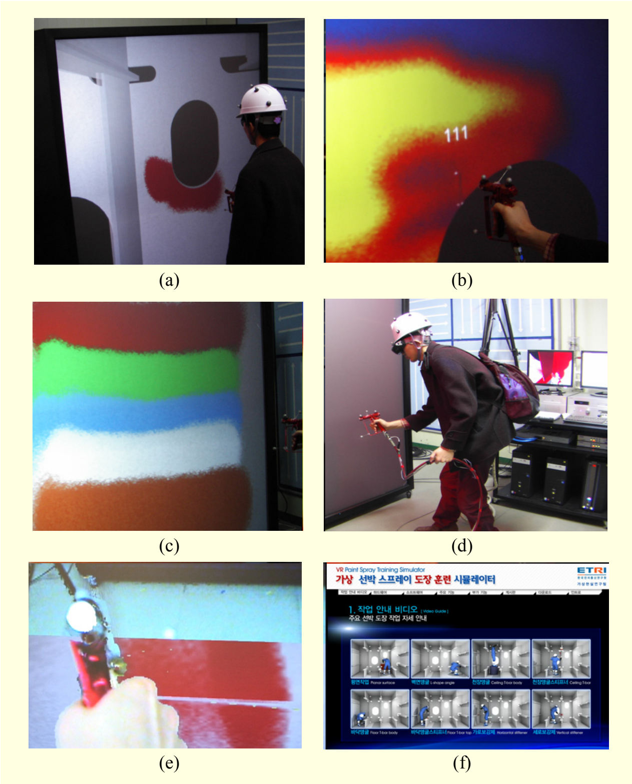

Fig. 3. VR content-based spray paint training system.

switch the system to measurement mode and check if the paint was coated uniformly over the surface by measuring the paint film thickness as shown in Fig. 3(b). In measurement mode, the painted structure is rendered in a color-coded fashion, which means the surface is colored according to the thickness of the paint. Those parts that are painted a lot are shown in a brighter color, while unpainted parts remain in dark blue. In this way, users can easily check whether they have painted the structure evenly. In addition, users can also obtain the paint thickness value in micrometers by pointing to the specific region they are interested in with the spray gun interface.

Users can also practice repeatedly under different configurations. They can choose different paints, shown in Fig. 3(c), with different physical attributes, such as color and viscosity. They can also change the nozzle of the virtual spray gun, which decides the size of the spray pattern and the amount of paint sprayed in the same amount of time. The training simulator also provides various training scenarios with different 3D models of virtual ship blocks.

Besides the wall display, which only covers the user's view in the front, the training simulator also supports another display configuration with an HMD, shown in Fig. 3(d). With an HMD, the scene displayed on the display changes according to head movement so that users can turn and look around the virtual training environment. This display configuration is especially useful for practicing painting on a ceiling or a floor of the target ship block structure.

While the HMD normally provides an immersive view mode in which the user's view of the real world is obscured, it can also provide see-through views where users can see virtual scenes merged into the real world view forming augmented reality (AR) [18] style visualization. Both optical-based and video-based see-through modes are available. Figure 3(e) shows a user's hand holding the spray gun interface and painting on a virtual structure. The painted structure and paints are rendered by computer, while the rest of the scene is captured from a live video camera attached in front of the HMD.

The training system also provides digital lecture material, shown in Fig. 3(f), which depicts a 3D animated character with a motion-captured standard work process. The user can choose different scenarios and different view angles to review and understand the detailed motion before practicing it on the simulator.

2. System Configuration

Figure 4 presents the system architecture of the Virtual Paint Spray Training Simulator. The software processes are depicted in the middle part, the input data and interfaces shown at the bottom, and the visual displays are shown at the top part of the figure. The system is designed to support various VR interfaces and displays to actively respond to the needs in different training scenarios. The detailed specifications and design of the training system were chosen according to the demands and requirements collected from paint spray instructors working at an actual ship construction field.

The system is based on a PC clustering technology in order to simulate and visualize the virtual environment in real-time. Four personal computers were used in total: one as a tracking server, two for visualizing four display channels (two channels, each), and one for the master control. Each personal computer runs under Microsoft Windows XP, and they are connected through a local Gigabit Ethernet switch.

The OpenSG [19] visualization library was used for real-time clustered rendering on multiple display devices in the wall display. For processing the camera image to provide AR visualization under video see-through HMD configuration, the system uses the OpenCV [20] computer vision library. The user's hand region is masked by detecting skin color from the live camera image to present correct depth occlusion between the user's hand and virtual structures. In combination, a masking virtual object corresponding to the spray gun interface is also used in order to correctly visualize occlusions between the real spray gun interface and virtual objects.

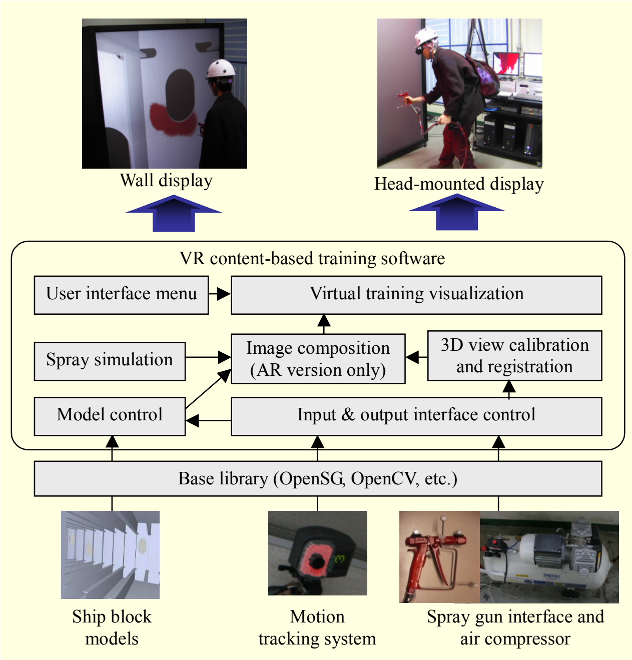

Fig. 4. System architecture of training system.

There are two main types of display hardware configurations: a wall display and an HMD. The wall display is a projection-based stereoscopic display with four projectors, each providing a resolution of 1024×768 and 3,500 lumens, presenting four channels of real-time rendered images from two personal computers with a hardware-accelerated 3D graphics interface. The HMD utilized in the prototype system supports both optical and video see-through features for AR visualization and provides SXGA (1280×1024) resolutions. To support video see-through visualization with stereoscopic view, two cameras are attached in front of the HMD with careful calibration of the base line distance and the convergence angle according to the optical viewing parameters of the HMD. The camera used in this work captures live video at 1024×768 pixels and 30 frames per second.

For tracking the user's movement, the training system uses a Motion Analysis HAWK digital motion capture system, including 6 infrared cameras. The tracking system tracks the 6 degrees of freedom motion of the user's head and the custom-built spray gun interface.

VI. Field Test

1. Use Cases

The training system has been installed and is being used in shipyards of two major Korean shipbuilding companies for training new workers.

The first company had been running spray painting courses for novice workers, training about 20 workers a month. They had previously used water for training basic poses and skills before starting to practice with real paint. While water costs less than real paint, it was difficult to show how spray patterns build up on a surface. Also, being able to measure thickness, which is necessary to check the quality of the result, is not even available with water spraying.

After testing the simulator, spray painting experts and instructors responded that it is surely good enough to replace the basic water-based training course. Furthermore, the simulator was considered more efficient than using real paints for training purposes since they can practice repeatedly within a short amount of time. In comparison, they had previously been spending a lot of time preparing real paint and steel structures as well as waiting until the paint dried (usually a whole day) before being able to practice again. Using the simulator, trainees were able to practice repeatedly, and had more chances to try and practice within the same amount of time.

At the second company, there were actually no official training courses running before introducing the simulator due to problems with the space and costs required for running a training center. Training spray painting requires a dedicated space equipped with facilities for ventilation and drainage. Furthermore, using expensive paint for training is prohibitive (the first company spent about 1,000 USD in paint for each worker to practice for a month). In comparison, a normal office was large enough for installation of the simulator, and there was no need to consume real paint or water. With the simulator, a basic training course was provided for novice workers, with four workers participating one hour a day for one week. While it was common for new workers to spend about a year in the field before being able to work with spray paints, after taking the simulator-based training course during the field test, they were able to do simple spray painting tasks in the actual work field.

2. Discussion

In this subsection, we summarize responses from users who have tried the prototype simulator system during the field test and other public exhibitions.

The most remarkable advantage of training spray painting tasks using VR content mentioned by the test users is in allowing trainees to practice repeatedly for a longer time as compared to practicing with real materials. The preparation time before practicing has also been reduced significantly, and there is no need to wait until the paint dries after each practice session. Instead, they are able to simply continue practicing over and over.

Another meaningful merit of VR-based training that was mentioned frequently was better communication between instructor and trainees. With the simulator, participants were not required to wear masks in the training environment since they were free from noxious gases. This helped trainees not only to practice in a more comfortable situation, but also enabled more effective communication between trainees and instructors, resulting in a better understanding of the given instructions. Without masks, communication between them was much more fluent and free, making it easier to teach and learn the skills in detail.

Coinciding with the recent growth of interest in green technologies, many test users also gave positive responses to the environmental friendliness of the simulator. Besides the cost effectiveness, reducing waste of paint and water by replacing them with VR content was considered as contributing toward the prevention of pollution and maintaining the environment.

Besides its merits, some of the shortcomings of the prototype system have also been reported. Tracking failures that occurred from time to time due to insufficient tracking volume and occlusion were one of the major problems which needed to be solved. This problem was partially resolved by adding more motion capture cameras to the tracking system which initially included only four cameras at the first field test and by attaching more markers on the tracking objects. However, the occlusion problem is yet considered unavoidable unless by using other tracking methods, such as electro-magnetic sensors.

While an air compressor was utilized to provide repulsive force feedback in the prototype system, the amount of force was not controllable in runtime according to different painting conditions and situations. This caused users to feel a gap between the real and virtual environments. Some of the trainees reported that they needed some time to get used to the amount of repulsive force when they started to practice with real paints after training on the simulation system. Designing a haptic device to overcome this limitation would be an interesting topic for a future work.

VII. Conclusion

In this paper, the authors proposed a VR-based training system for practicing spray painting. The training system provides realistic visualization of the working environment on immersive displays and allows users to interact with the virtual work space using the same interface (a spray gun) used in a real working situation.

Providing olfactory feedback is a possible improvement to raise the sense of presence and make users feel greater realism within a training system. However, this could also make users feel uncomfortable and prevent them from practicing for long periods. This goes against the original design purpose of the training simulator and might need further inspection.

Besides simulating the virtual environment in as real a manner as possible, providing additional information for training, such as virtual motion guides [21] could improve the proposed training system. With such features, it would be much easier for trainees to correct their faults and practice in a more standardized way. For visualizing such guide information with correct depth perception, a layered multiple display technique [22] could be applied, which would help users to correctly see the virtual guides visualized on top of their physical hands.

The authors are also planning to extend the work by applying VR content technology to other industrial training applications such as welding and part assembly where more personalized displays and interfaces [23] would be beneficial.

References

[1] G.J. Kim, *Designing Virtual Reality Systems – The Structured Approach*, London: Springer, 2005.

[2] R. Stone, "Virtual Reality for Interactive Training: an Industrial Practitioner's Viewpoint," *Int. J. Human- Computer Studies*, vol. 55, no. 4, Oct. 2001, pp. 699-711.

[3] K. Fast, T. Gifford, and R. Yancey, "Virtual Training for Welding," *Proc. 3rd IEEE ACM Int. Symp. Mixed and Augmented Reality*, 2004, pp. 298-299.

[4] http://www.123arc.com

[5] M.T. Filigenzi, T.J. Orr, and T.M. Ruff, "Virtual Reality for Mine Safety Training," *Applied Occupational and Environmental Hygiene*, vol. 15, no. 6, 2000, pp. 465-469.

[6] L.G. Mallett and R.L. Unger, "Virtual Reality in Mine Training," *SME Annual Meeting Exhibit*, 2007, pp. 1-4.

[7] P.M. Stothard, J.M. Galvin, and J.C.W. Fowler, "Development, Demonstration and Implementation of a Virtual Reality Simulation Capability for Coal Mining Operations," *Proc. ICCR Conf.*, 2004. http://www.mining.unsw.edu.au/Publications/publications_staff/Paper_Fowler_ICCR_2004.pdf, retrieved June 18, 2010.

[8] M. Agrawala, A.C. Beers, and M. Levoy, "3D Painting on Scanned Surfaces," *Proc. Symp. Interactive 3D Graphics*, 1995, pp. 145-150.

[9] P. Hanrahan and P. Haeberli, "Direct WYSIWYG Painting and Texturing on 3D Shapes," *Proc. 17th Annual Conf. Computer Graphics Interactive Techniques*, 1990, pp. 215-223.

[10] T. Van Laerhoven and F. Van Reeth, "Real-Time Simulations of Watery Paint," *J. Computer Animations Virtual Worlds Special Issue*, vol. 16, no. 3-4, 2005, pp. 429-439.

[11] P. Eschler and D. Stricker, "Virtual Grafitti: From Stone-Age to

Digital Art," *CG Topics*, vol. 1, no. 1, 2003, pp. 32- 33.

[12] M.Y. Lim and R. Aylett, "MY Virtual Graffiti System," *Int. Conf. Multimedia Expo*, 2004, pp. 847-850.

[13] S. Bryson, "Virtual Reality in Scientific Visualization," *Commun. ACM*, vol. 39, no. 5, 1996, pp. 62-71.

[14] http://www.osc.edu/research/video_library/ford.shtml

[15] C. Cruz-Neira, D.J. Sadin, and T.A. Defanti, "Surround Screen Projection-Based Virtual Reality: the Design and Implementation of the CAVE," *Proc. SIGGRAPH*, 1993, pp. 135-142.

[16] M. Hereld, I. Judson, and R. Stevens, "Introduction to Building Projection-Based Tiled Display Systems," *IEEE Comput. Graphics Appl.*, vol. 20, no. 4, 2000, pp. 22-28.

[17] A. Fuhrmann, D. Schmalstieg, and W. Purgathofer, "Fast Calibration for Augmented Reality," *Proc. ACM Symp. Virtual Reality Software Technol.*, 1999, pp. 166-167.

[18] R.T. Azuma, "A Survey of Augmented Reality," *Presence: Teleoperators and Virtual Environments*, vol. 6, no. 4, 1997, pp. 355-385.

[19] http://www.opensg.org

[20] http://www.opencv.org

[21] U. Yang and G.J. Kim, "Implementation and Evaluation of 'Just Follow Me': An Immersive VR-based, Motion-Training System," *Presence: Teleoperators and Virtual Environments*, vol. 11, no. 3, 2002, pp. 304-323.

[22] G.A. Lee, U. Yang, and W. Son, "Layered Multiple Displays for Immersive and Interactive Digital Contents," *Proc. 5th Int. Conf. Entertainment Computing*, LNCS 4161, 2006, pp. 123-134.

[23] D. Jo, U. Yang, and W. Son, "Design Evaluation System with Visualization and Interaction of Mobile Devices Based on Virtual Reality Prototypes," *ETRI J.*, vol. 30, no. 6, 2008, pp. 757-764.

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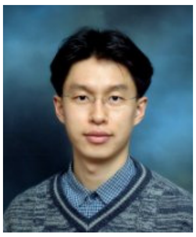

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