Virtual Reality: Fundamentals and nuclear related applications

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Abstract: Since the first virtual reality (VR) system was developed by Dr. Ivan Sutherland in the 1960s, various research and development have been conducted to apply VR to many fields. One promising application is a nuclear-related one. VR is useful for control room design support, operation training, maintenance training, decommissioning planning support, nuclear education, work image sharing, telecollaboration, and even providing an experimental test-bed. In this lecture note, fundamental knowledge of VR is presented first, and various VR applications to nuclear fields are stated along with their advantages. Then appropriate cases for introducing VR are summarized and future prospects are given

Keyword: virtual reality; training support; design support; planning support

1 Introduction

Virtual Reality (VR) [1,2] is defined as "a medium composed of highly interactive computer simulations that sense the user's position and replace or augment the feedback of one or more senses – giving the feeling of being immersed, or being present in the simulations" [3]. Objects in a VR environment are not completely identical to real ones, but the effect is fundamentally same. The users of VR can feel the same sensations and behave as though they were in a real environment.

These features of VR enable users to experience various situations without the need for developing real environments, which presents many advantages when applied to the work in nuclear-related fields. In fact, VR is useful for control room design support, operation training, maintenance training, decommissioning planning support, nuclear education, telecollaboration, and even provides experimental test-beds.

In this lecture note, fundamental knowledge of VR is presented first. Then various VR applications to nuclear fields are stated with their advantages; finally, appropriate cases for introducing VR are summarized and future prospects are given.

2 Fundamentals of virtual reality

2.1 Three subsystems that compose VR systems

Interaction with the external world usually involves the following steps.

1. Recognition of the external world through personal receptors.
2. Making appropriate behavioral decisions.
3. Changing the state of the external world through personal effectors.

A VR system measures the behaviors at step 3, simulates a virtual world in real time that imitates the external world, and then displays the generated stimulus to the person for step 1. Accordingly, Fig. 1 shows that a typical VR system consists of three subsystems for measuring, simulation, and display. The Measuring Subsystem measures users' movements; the results are sent to the Simulation Subsystem. The Simulation Subsystem controls the virtual environment and updates the status based on users' movements. The Display Subsystem displays a
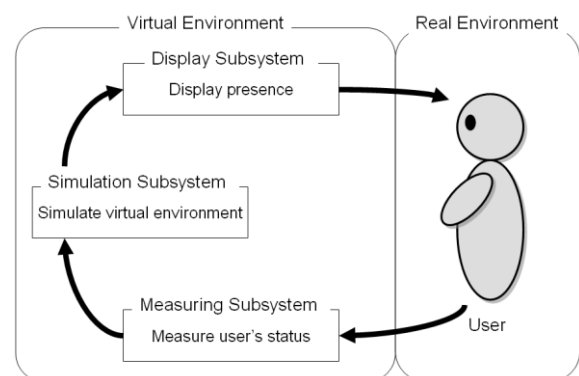

Fig. 1 Three basic subsystems for VR.

virtual stimulus according to the simulation results such that it appears and feels like a real environment.

In the following sections, basic knowledge for implementing each subsystem is described.

2.2 Measuring subsystem

The Measuring Subsystem measures a user's current status. The measurement target can include not only the physical status of the user, such as the position, orientation, and pose, but also the physiological and psychological status of the user such as heartbeat and brain waves. In a usual case, the measurement target in nuclear applications is the physical status of the user, such as the position and orientation of the hands and body.

A magnetic sensor is widely used for measuring the position and orientation of a user's hand. The system consists of a source transmitter that generates a magnetic field and a magnetic field sensor that is sensitive to the generated magnetic field [4]. Actually, six degrees of freedom (6 DOF; three-dimensional, 3D, position and angles around three axes) of the sensor can be measured relative to the source transmitter. This method is stable and accurate in an ideal environment. However, this method is sensitive to metal objects located in the magnetic field; the accuracy decreases when a large metal object is in the field.

Sensors of two types are used to measure the hand shape: a fiber optic bend sensor and a resistor type bend sensor [5]. Both sensors are attached to a finger sheath. For a fiber optic bend sensor, small slits are made on the optical fiber. A light source is attached to one terminal and a light sensor is attached to the other. The amount of light that passes through the optical fiber varies according to the angle of the optical fiber because the light leaks from the small slits. The greater the finger angle, the more light leaks from the slits. However, for a register-type bend sensor, the electrical resistance of a strap is measured whose electrical resistance value changes according to its bending angle.

When the user is presumed to move in a large virtual environment with intuitive gestures, a motion-capturing system that measures the user's whole body is used as the measuring subsystem [6, 7]. The motion-capturing system measures the 3D positions of specific parts of the human body such as the head, hands, hip, and feet, or angles of human joints such as those of the neck, knee, wrist, and shoulder. Inertial, optical, sonic, or magnetic sensors are used for measuring 3D positions. In contrast, for measuring angles of joints, mechanical links, and a rotary encoder are used that can detect the rotational angle accurately. Among these various motion capturing systems, the optical motion capturing system is widely used. The optical motion capturing system uses LED markers or reflective markers pasted on the specific part of human body and multiple cameras placed around the user. Images captured with the cameras are processed in real time and the 3D position of the LED markers or reflective marker is determined through geometric triangulation.

Employment of these special devices for VR is effective to give the impression to users that "This system is not an ordinary one, but a special one". However, these devices are too expensive in some cases when their cost-effectiveness is examined. For example, game-machine controllers are useful and better than motion-capturing systems when the system is presumed to be used to learn novice knowledge such as working procedures instead of high-level skills of maintenance.

2.3 Display subsystem

The Display Subsystem stimulates users' receptors with the virtual stimulus generated according to the state of the virtual environment. The target receptors include not only sense of sight but also senses of force, touch, hearing, smell, taste, and others.

For the sense of sight, a head-mounted display (HMD) presented in Fig. 2 or a Cave Automatic Virtual Environment (CAVE) depicted in Fig. 3 is usually used to enable the user to view the virtual environment all the time, even if the user looks in different directions [8-10].

A typical HMD has two small displays and an optical system that channels images from the displays to the

eyes. Stereo view can be presented by drawing different images on the two displays. The CAVE is a room-type display surrounded by semitransparent large screens with back-side projections with multiple projectors. Stereo view can be presented using two projectors with polarizing filters or presenting time-division images. The HMD is less expensive than the CAVE, but the HMD can not be shared among multiple users. Multiple users can use the CAVE simultaneously.

Both HMD and CAVE are effective in some cases, but sometimes it is not necessary to use these expensive devices. In many cases, a normal 2D display is sufficient. We should also note carefully that some people have so-called stereo anomaly: they can not perceive a proper 3D view when viewing stereo images [11]. The VR system must be designed so that these people can use the system with no difficulty.

For the senses of force and touch, various haptic (tactile) feedback displays have been proposed; some are available commercially [12-17]. Receptors for the sense of force and touch exist in almost all parts of the human body. Therefore, it is difficult to stimulate all the receptors with the current technology. Current major target receptors are on the hand, arm, and foot.

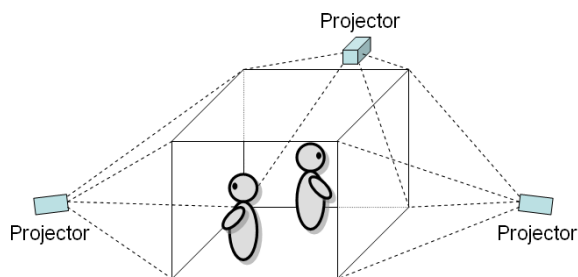Fig. 2 Example of Head Mounted Display.

Fig. 3 Cave Automatic Virtual Environment.

Haptic displays are divided into two categories—ground-based and body-based devices—according to where the base of the device is placed. The ground-based devices are placed on a fixed base such as a floor or desk. Such devices include force-feedback joysticks, pen-based skeleton link devices, ground-based robot arms, and ground-based wire link devices. The body-based devices are attached to a part of the user's body. Such devices include force and tactile feedback gloves, suits, and exoskeleton arm devices. Usually, body-based devices are smaller than ground-based devices. The user of the body-based devices can move freely in a virtual environment, but it is difficult to prevent users from digging into virtual objects when the user collides with the virtual objects. Unrealistic interaction of this kind between virtual objects and a user not only decreases the reality of the VR application but also causes a discrepancy between the real and virtual environment.

For the sense of hearing, stereo speakers or headphones are usually used to realize stereo sound. For more accurate sound localization, 3D sound systems are used that can generate more exact sound fields at the two ears [18]. Humans recognize three-dimensional sound according to the inter-aural time difference and inter-aural level difference. A 3D sound system is used to generate a sound field as accurately as possible using a Room Transfer Function (RTF) and Head Related Transfer Function (HRTF). Both RTFs and HRTFs differ among environments and users. Therefore, measurements must be done in advance to build these functions. A 3D sound system is effective to increase the realism of the virtual environment, especially when VR is applied to maintenance training in which a trainee must diagnose instruments by their abnormal sound.

For the sense of smell, few means are available to stimulate the sense [19,20]. A typical means is to use air pumps: one terminal of the tube is placed in front of the user's nose; the other side of the terminal is connected to an air pump [20]. Several flavor materials are prepared; they are emitted selectively by the air pump. It is difficult to change the flavor rapidly because the user might notice the air flow if

the air flow is too fast. The result is decreased realism. It might be effective to employ a device of this kind if the purpose of introducing VR is to train maintenance workers to learn maintenance skills using the sense of smell. However, the technology is not sufficiently matured to apply it for increasing the reality of the virtual environment.

2.4 Simulation subsystem

2.4.1 Simulating virtual environment

The Simulation Subsystem simulates a virtual environment so that the user can feel that the virtual environment behaves similarly to a real environment. For example, if a pen is grasped using a hand, then the pen must be attached to the hand. If the hand is opened, then the pen must fall onto a desk or floor. The pen should not dig into the desk or floor.

Interaction and physical laws of all these kinds need not be realized if the purpose of using VR is merely viewing VR environment with no interaction, but in many cases, whether the VR application becomes useful or not depends on how much interaction and physical laws of these kinds are properly realized.

One solution to realize a Simulation Subsystem that can simulate virtual environment with high reality is to use a physical simulation engine such as an Open Dynamics Engine [21] or Bullet Physics Library [22]. These engines include a collision-detection engine and a rigid body dynamics engine. Using these engines, it is rather easy to build a virtual environment in which virtual objects behave as real objects do. For instance, virtual objects do not mutually overlap. One object can move another object through collision. However, it remains difficult to realize physical constraints that are usually necessary to simulate a nuclear power plant environment; behavior of one object is strictly restricted by the other object. For example, a lid can not be removed before nuts and bolts that fix the lid are removed. Too much computational power is required to simulate such interactions using only rigid body dynamics. It is necessary to build a model to represent physical constraints in the other way. Some existing physical engines also support constraints of this kind, but an important problem is that the constraints must be set as constraint rules

from scratch by hand; the work is too complicated and burdensome when the number of virtual objects becomes large. The number of objects in virtual objects always becomes large when the simulation target is a nuclear power plant.

2.4.2 Constraint representation using a Petri net

One solution to this issue is employing a Petri net as a modeling and visualization tool for physical constraints [23,24]. A Petri net is a general tool for describing the behavior of simultaneous discrete events [25]. In the field of factory automation, a Petri net is often used for representing the states of automated assembly lines in a factory [26].

Table 1 and Fig. 4 show notations of the Petri net and examples of representations of constraints in a virtual environment in which a pen, desk, lid, and hand mutually interact. In this figure, 'transition' represents an event that occurs. The occurrence of an event is called 'firing' of a transition. 'Places' are on both sides of a transition and are connected with the transition by arcs. The place from which an arc starts is called an 'input place' and represents a condition for the firing of the transition, whereas the 'output place' is the place at which an arc ends and means the resultant states of the firing. The satisfaction of conditions is represented by a 'token' in the input place. The condition for a transition to fire is that each of its input places has one or more tokens. When a transition fires, a token in each input place disappears and appears in each output place.

As shown in Fig. 4, it is readily noticeable that the user must touch and grasp a pen before drawing a mark on a lid with the pen. It is also readily noticeable that no way exists to remove the mark in the current interaction representation. In fact, it is possible to find how to draw a mark on a lid with a pen automatically by executing a reachable test on the Petri net. Therefore, it is possible to demonstrate how to conduct a certain task automatically when the constraints of the virtual environment are represented with the Petri net.

3 Applications of VR

By realizing VR, it is possible for users to experience various situations without developing a real environment. This advantage is important for VR employment in various applications related to nuclear fields. In this section, the various kinds of VR application are stated along with their attendant advantages.

3.1 Design support of main control room

A power plant is usually controlled using a control system located in a central control room, which enables operators to monitor and control the plant operations. All signal parameters obtained from sensors attached to instruments are sent to the control system. Operators must monitor those parameters and understand the conditions within the power plant. Especially in the case of a power plant malfunction,

Table 1 Notations of Petri net for representing physical constraints in virtual environment

|	Terminology	Symbol	Meaning
(1)	Transition		This transition fires when at least one token is in all the input places and a corresponding action is performed by the user, or a corresponding event occurs in the virtual environment.
(2)	Token		Represent one status of virtual objects. Existence of one token means that the virtual object related to the token is in the corresponding state.
(3)	Arc		Represent relations between places and transitions. Tokens move through the arcs.
(4)	Object Place		Only one token is permitted to exist in this place at once. Existence of one token in the place means that the corresponding condition is fulfilled.
(5)	Automatic Transition		This transition fires automatically without a user's action when at least one token is in all the input places.
(6)	Pool Place		Plural tokens are permitted to exist in this place at once.
(7)	Control Place		Used to control complicated conditions without objects related to tokens.
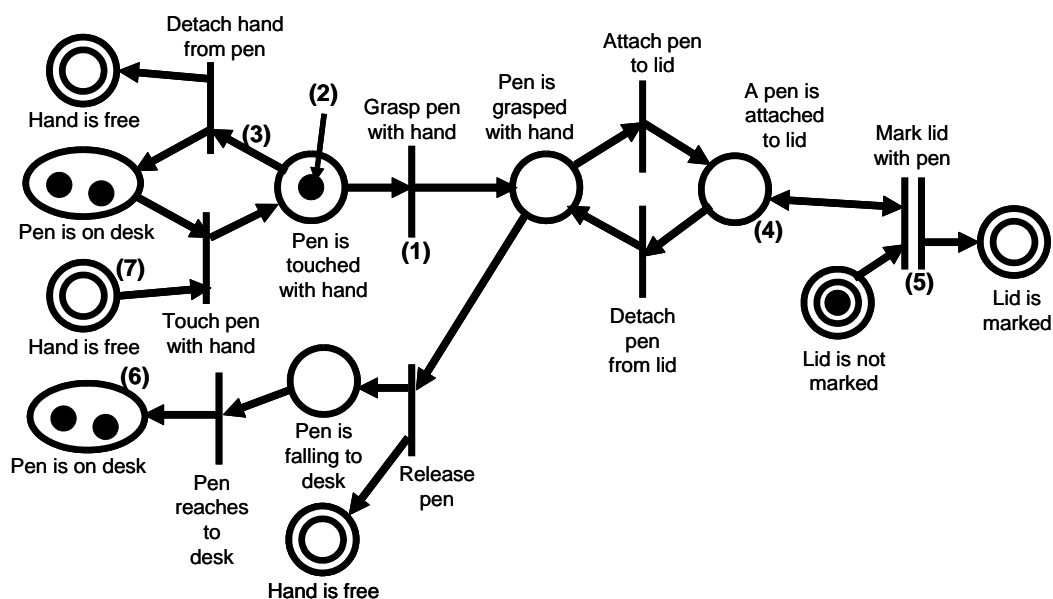
Fig. 4 Petri net representation of constraints in a virtual environment.

Table 2 Problems of plant training and improvement by applying VR

		Problem of plant training	Improvement by VR application
Both operation and maintenance	(1)	It is necessary to build real size mockups and its cost is very high.	Training can be conducted without real size mockups.
	(2)	It is not easy to change the training contents.	It is easy to change the training contents.
	(3)	It is necessary for all participants to come together to conduct training.	It is possible for multiple trainees in different locations to join the training via the internet.
	(4)	A large space is necessary for the training.	Training can be conducted using only computers and some hardware.
Operation	(5)	An instructor who has special knowledge about the training is necessary.	It is possible to add a function which makes it possible for trainees to learn by themselves using Computer Assisted (Aided) Instruction (CAI).
Maintenance	(6)	Training with real size mockups is as dangerous as training with real machines.	Training with virtual mockups is very safe.
	(7)	There are some training environments which are difficult to realize with real size mockups.	Almost all training environments can be realized in a virtual environment even if they are difficult to be realized with real size mockups.
	(8)	Mockups can be broken.	Virtual mockups cannot be broken (Easy to be backed-up).

the operators must review numerous signal parameters and operate control panels to avoid severe accidents. Therefore, control room design is important for safe power plant operation.

For constructing new control rooms, real-size mockups are built; operators must control simulated power plants using them to validate the control room design, meaning that validation is both time-consuming, and expensive. Therefore, in recent years, some control rooms have been designed and validated in a virtual environment. Actually, HVR CREATE [27] is one design and validation tool using VR technology. Using this software, the control room designer can drag-and-drop virtual objects interactively from the model library into a virtual control room and can then virtually walk through the designed control room. The control rooms can be validated by measuring the distance between arbitrary points in the control room and simulating a virtual view of virtual operators. This software also enables multiple participants to join the design and validation process even if they are in different locations.

3.2 Operation and maintenance training

For reliable operation and maintenance of power plants, it is important that operators and field workers be well trained to meet the required skill level. To train many operators and field workers, some training centers have been established and many training courses have served operators and field workers. They have provided the guidance of experienced instructors using various mockups of machines and equipment that are actually used in power plants. Such off-the-job training is effective in building up workers' maintenance skills, but many problems hinder training using real-size mockups and instructors, as shown in Table 2 (left). Various problems can be mitigated by application of VR to

Fig. 5 Training system for control panel operation.

training, as Table 2 shows (right).

Figure 5 presents a typical snapshot of a training system with which a trainee can watch a virtual operator diagnosing a root cause of power plant malfunction by watching plant parameters displayed on virtual control panels connected to a real time plant simulator [28]. Using this training system, a trainee can view how to diagnose a malfunction of the power plant from the perspective of a virtual operator.

Figure 6 shows typical snapshots of a training system for maintenance of check valve [23,24]. This training system consists of 60-inch display, crystal eyes for stereo view, data gloves for hand gesture measurement, and Polhemus sensors for hand position measurement, to realize mutual interaction between the system and trainee. Through these devices the trainee can watch virtual objects by 3D graphics and manipulate the object by emulated hands such as grasp, rotate, release, and so on. Physical restrictions among virtual objects are described using a Petri-net so that unacceptable operation of virtual objects in real world can not be conducted in a virtual world such as removing the lid of the check valve before removing nuts and bolts that fix the lid on the base of the check valve. In this system, the instruction function that demonstrates the right procedure for assembling and disassembling the check valve is also realized using Petri-net representation of the maintenance procedure and the right procedure search algorithm using Petri-net.

3.3 Decommissioning planning
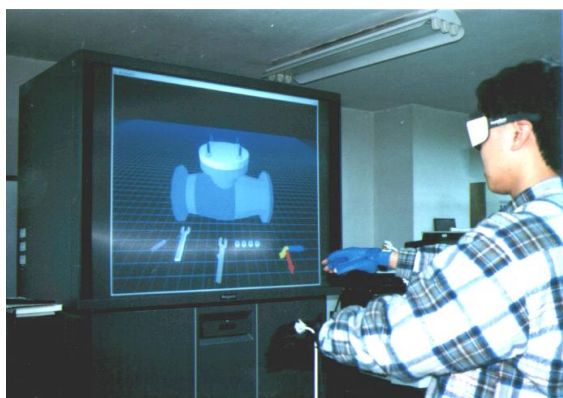After the service period of a nuclear power plant

Fig. 6 Training system for check valve maintenance.

terminates, the nuclear power plant must be decommissioned. Some parts of nuclear power plants remain radioactive. To reduce field workers' scattering of radioactive waste and their exposure to it, a detailed dismantling plan must be made.

By building a 3D model of the target nuclear power plant and making it possible to calculate radiation levels, it becomes possible to estimate the total dose for each worker when they work according to a scenario. It also becomes possible to visualize the working procedure as 3D computer graphics to share the working image and to cultivate understanding by the public.

For that purpose, HVRC VRdose is a software tool that can display a dose-rate distribution and give estimates of occupational doses for work scenarios in nuclear facilities using VR technology [29].

3.4 Nuclear education
One important feature of VR is that users can see a certain target model from any desired perspective, even if the target is invisible or the viewpoint is impossible in the real world. For example, the detailed processes of nuclear fission, whereby heavy atoms such as uranium or plutonium are split into lighter atoms, or of nuclear fusion, whereby multiple hydrogen atoms are fused into a helium atom, can not be viewed directly in a real environment, but VR technology enables learners to see fission or fusion processes as 3D computer graphics and to interact with the atoms to control the reactions. Education using VR technology is not only effective and safe but also very motivating for learners.

3.5 Tele-collaboration
Furthermore, VR is useful to support workers who are in different places to communicate with each other. One example of an application of this kind is as communication support for a satellite maintenance and operation center [30]. In this concept, skilled workers are in the center, which is far away from nuclear power plants. When workers in the nuclear power plants need assistance of skilled workers, they can communicate via the internet. Usual communication media will be voice, chat, and video communications, but using only these

communication channels, it is difficult for skilled workers to understand the situation at the remote plants. The VR technology can solve this problem.

The skilled workers at the center will be immersed into the virtual environment in which all the instruments at the remote nuclear power plant are built as 3D models and the status of the virtual instruments are updated in real time by the measurement results obtained at the remote plants. The current plant view with the remote workers is captured using a remote camera or measured using motion sensors. Then the results are used to update the virtual avatar in the virtual environment. The skilled worker can understand the situation at the remote plant and can give appropriate instructions to the remote workers. Applications of this kind are categorizable as telexistence [31] or augmented virtuality [32].

3.6 Experimental test-bed

The VR environment is useful as an experimental test-bed. To introduce a newly designed interface, evaluation experiments must be conducted repeatedly to examine what will happen with the new interface. Building an actual-size mockup is painstaking, time-consuming, and costly; moreover, it is not easy to modify the mockup if a new problem arises. It is difficult to replace the real size mockup completely with a virtual one but it is very effective to use the VR in an early stage of the evaluation because once the virtual mockup has been developed, it is easier to modify the virtual mockup than to change the real mockup.

4 Appropriate cases for introducing VR

As described above, VR technology is applicable to various purposes related to nuclear fields. However, cost-effectiveness must be considered when we newly try to introduce VR technology.

Employing special VR devices such as haptic devices or CAVE is actually effective to give the users the impression that the system is not an ordinary one. However, these devices are sometimes too expensive for their effect because the reality of these devices is insufficient for some purposes. Building 3D models

that accurately portray the real ones is also a time-consuming and costly task. A particular problem is that building a virtual environment with real physical constraints is too difficult for many people. Therefore, the building tasks are usually delegated to engineers who have special knowledge to build the virtual environment. Therefore, people who need the virtual environment must communicate with the engineers every time when they need to modify the virtual environment. One solution to this problem is to build an authoring tool that enables everyone to produce virtual environments [33].

The appropriate cases in which VR technology can be introduced can be summarized as the following.
1. Building a target environment in real world is very difficult, impossible, dangerous or expensive.
2. VR gives basic knowledge to novice users.
3. Numerous users can use it.
4. The VR system is useful for a very long time.
5. 3D models are available in advance of actual apparatus.

The following can particularly benefit from VR technology:
6. Cases in which it is necessary to record and analyze the activities of users.
7. Cases in which plural users can not be in a single place or can not do activities simultaneously.

5 Future prospects

More than 40 years have passed since development of the first VR system [8]. Various technological problems have been solved and VR technology has been introduced into various fields such as entertainment and advertisement. However, many problems remain to be solved before VR technology is useful actively for nuclear fields.

The crucial problem will be that no appropriate device will be able to provide various stimuli with sufficient reality. A current approach for realizing display devices is to stimulate human receptors with external hardware devices that are attached externally to users. However, limitations exist with this approach. It is almost impossible to stimulate all the receptors properly, as described in this lecture

note. A promising approach will be an ambitious attempt to plug the stimulus directly into the human nervous system or brain, as in the science fiction movie "The Matrix" [34].

References

[1] VINCE, J. A.: Introduction to Virtual Reality, Berlin: Springer, 2004.

[2] BURDEA, G. C., COIFFET, P.: Virtual Reality Technology, New York: Wiley -IEEE Press, 2003.

[3] SHERMAN, W. R., ALAN C.: Understanding Virtual Reality: Interface, Application, and Design, San Francisco: Morgan Kaufmann Publishers, 2002.

[4] RAAB, F., BLOOD, E., STEINER, T., JONES, H.: Magnetic Position And Orientation Tracking System, IEEE Transactions on Aerospace and Electronic Systems, 1979, 15(5):709-718.

[5] STURMAN, D. J., ZELTZER, D.: A Survey of Glove-based Input, IEEE Computer Graphics and Applications, 1994, 14(1): 30-39.

[6] MOESLUND, T. B., HILTON, A., KRUGER, V.: A Survey of Advances in Vision-Based Human Motion Capture and Analysis, Computer Vision and Image Understanding, 2006, 104(2):90-126.

[7] DEJNABADI, H., JOLLES, B. M., AMINIAN K.: A New Approach to Accurate Measurement of Uniaxial Joint Angles Based on a Combination of Accelerometers and Gyroscopes, IEEE Transactions on Biomedical Engineering, 2005, 52(8): 1478-1484.

[8] SUTHERLAND, I.: The Ultimate Display. In Proceedings of the International Federation of Information Processing Congress, 1965, 2:506-508.

[9] CAKMAKCI, O., ROLLAND, J.: Head-Worn Displays: A Review, Journal OF Display Technology, 2006, 2(3): 199-216.

[10] CRUZ-NEIRA C., SANDIN D.J., DEFANTI T.A., KENYON R.V., HART J.C.: The CAVE: Audio Visual Experience Automatic Virtual Environment, Communications of the ACM, 1992, 35(6): 65-72.

[11] RICHARDS W.: Anomalous Stereoscopic Depth Perception, Journal of the Optical Society of America, 1971, 61(3):410-414.

[12] BURDEA G. C.: Force and Touch Feedback for Virtual Reality, John Wiley & Sons, New York, 1996.

[13] KIKUUWE, R., YOSHIKAWA, T.: Haptic Display Device with Fingertip Presser for Motion/Force Teaching to Human, In Proceedings of the 2001 IEEE International Conference on Robotics & Automation, 2001: 868-873.

[14] MASSIE, T. H., Salisbury J. K.: The PHANTOM Haptic Interface: A Device for Probing Virtual Objects, In Proceedings of the ASME Winter Annual Meeting, Symposium on Haptic Interfaces for Virtual Environment and Teleoperator Systems, 1994, 55(1): 295-301.

[15] SATO, M.: Development of String-based Force Display: SPIDAR, In Proceedings of The Eighth International Conference on Virtual Systems and Multi Media, 2002: 1034-1039.

[16] PHANTOM, SenseAble Technologies, Inc., http://www.sensable.com/.

[17] SPIDAR, I-NET CORP., http://www.ddd.co.jp/product/spidar/ (In Japanese).

[18] BEGAULT, R.: 3D sound for virtual reality and multimedia, Durand National Aeronautics and Space Administration, 2000.

[19] NAKAIZUMI, F., YANAGIDA, Y., NOMA, H., HOSAKA, K.: SpotScents: A Novel Method of Natural Scent DeliveryUsing Multiple Scent Projectors, In Proceedings of IEEE Virtual Reality 2006: 207-212.

[20] YOKOYAMA, S., TANIKAWA, T., HIROTA, K., HIROSE, M.: Wearable Olfactory Display: Using Odor in Outdoor Environment, In Proceedings of the IEEE conference on Virtual Reality, 2006: 199-206.

[21] Open Dynamics Engine, http://www.ode.org/.

[22] Bullet Physics Library, http://bulletphysics.org/.

[23] ISHII, H., KASHIWA, K., TEZUKA, T., YOSHIKAWA, H.: Development of Machine-Maintenance Training System using Petri Net and Virtual Environment, In Proceedings of Cognitive Systems Engineering in Process Control, 1996, :138-143.

[24] ISHII, H., KASHIWA, K., TEZUKA, T., YOSHIKAWA, H.: A Study on Constructing a Machine-Maintenance Training System Based on Virtual Reality Technology, In Proceedings of the 5th International Topical Meeting on Nuclear Thermal Hydraulics, Operations and Safety, 1997: DD2-1 - DD2-6.

[25] PETERSON, J. L.: Petri Net Theory and the Modeling of Systems, Prentice Hall, 1981.

[26] D'SOUZA, K. A., KHATOR, S. K.: A survey of Petri net applications in modeling controls for automated manufacturing systems, Computers in Industry, 1994, 24(1):5-16.

[27] SEBOK, A., NYSTAD, E.: Design and Evaluation of Virtual Reality Systems: A Process to Ensure Usability, In Proceedings of the Virtual Reality Design and Evaluation Workshop, 2004.

[28] ISHII, H., WU, W., LI, D., SHIMODA, H., YOSHIKAWA, H.: Development of a VR-based Experienceable Education System -A Cyber World of Virtual Operator in Virtual Control Room -, In Proceedings of the 3rd World Multiconference on Systemics, Cybernetics and Informatices and the 5th International Conference on Information Systems Analysis and Synthesis, 1999, 1: 473-478.

[29] IGUCHI, Y, KANEHIRA, Y., TACHIBANA, M., JOHNSEN, T.: Development of Decommissioning Engineering Support System (DEXUS) of the Fugen Nuclear Power Station, Journal of Nuclear Science and Technology, 2004, 41(3): 367-375.

[30] OHI, T., WU, W., OZAKI, Y., YOSHIKAWA, H., SAWARAGI, T., KITAMURA, M., FURUTA, K.,

GOFUKU, A., ITO, K.: Development of an Advanced Human-Machine Interface System to Enhance Operating Availability of Nuclear Power Plants, In Proceedings of the 10th International Conference on Human-Computer Interaction, 2003:1273-1277.

[31] TACHI, S.: Telexistence, World Scientific Publishing Co. Inc., 2009.

[32] MILGRAM, P., KISHINO, F.: A Taxonomy of Mixed Reality Visual Displays, IEICE Transactions on Information Systems, 1994, E77-D(12):1321-1329.

[33] ISHII, H., TEZUKA, T., YOSHIKAWA, H.: A Study on Design Support for Constructing Machine-Maintenance Training System by Using Virtual Reality Technology, In Proceedings of the 7th IFAC/IFIP/IFORS/IEA Symposium on Analysis, Design and Evaluation of Man-Machine Systems, 1998: 389-394.

[34] SAKAGUCHI, H., KAMEI, M., FUJIKADO, T., YONEZAWA, E., OZAWA, M., CECILIA-GONZALEZ, C., USTARIZ-GONZALEZ, O., QUIROZ-MERCADO, H., TANO, Y.: Artificial vision by direct optic nerve electrode (AV-DONE) implantation in a blind patient with retinitis pigmentosa, International Journal of Artificial Organs, 2009,12:206-209.