핸드헬드 가상현실 시스템의 설계와 평가

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황재인

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Design and Evaluation of Hand-held Virtual Reality System

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by

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Abstract

While hand-held computing devices are capable of rendering advanced 3D graphics and processing of multimedia data, they are not designed to provide and induce sufficient sense of immersion and presence for virtual reality. In this thesis, we propose minimal requirements for realizing VR on a hand-held device. Furthermore, based on the proposed requirements, we have designed and implemented a low cost hand-held VR platform by adding multimodal sensors and display components to a hand-held PC. The platform enables a motion based interface, an essential part of realizing VR on a small hand-held device, and provides outputs in three modalities, visual, aural and tactile/haptic for a reasonable sensory experience. We showcase our platform and demonstrate the possibilities of hand-hand VR through three VR applications: a typical virtual walkthrough, a 3D multimedia contents browser, and a motion based racing game.

In the hand-held VR system, the question is raised whether such a “small” and “reduced” device could serve as an effective virtual reality (VR) platform and provide sufficient immersion and presence, e.g. through multimodal interaction. In this thesis, we address this question by comparing the perceived field of view (FOV) and level of immersion and presence among the users’ of VR platforms, varied in the sizes of physical/software FOV and in styles of interaction. In particular, we consider a motion based interaction, a style of interaction uniquely suitable for the “handheld” devices. Our experimental study has re-

vealed that when a motion based interaction was used, the FOV perceived by the user for the small hand held device was significantly greater than (around 50%) the actual. Other displays using the button or mouse/keyboard interface did not exhibit such a phenomenon. In addition, the level of user felt presence was higher than even that from a large projection based VR platform. The other method to overcome the limitation of the small screen is dynamic rendering in which the FOV is adjusted depending on the viewing position and distance. Although not formally tested, this method is expected to bring about higher focused attention (and thus immersion) and association of the visual feedback with one's proprioception.

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CHAPTER 1

Introduction

1.1 Motivation

One easy way to realize “virtual reality (VR)” that provides an immersive and multimodal sensory experience is to simply employ expensive sensors and large scale displays such as fully immersive displays, 6-DOF trackers, motion simulators, 5.1 surround sound systems, and haptic devices. To make VR more viable, practical, available and appealing to the general public, researchers have struggled to engineer for a more economic alternative, such as the desktop VR, and proposed to overcome the platform shortcomings (in terms of sensing and display capabilities) with innovative interaction and content design.

Recently, hand-held devices have emerged as one possible candidate for such an alternative platform for VR. Like the desktop computing environment, hand-held devices clearly lack in sensing and display capabilities, however, it is an attractive platform, because it is portable and everyone seems to own one these days (like cell phones, phone cams, and PDA). The performance and functionalities of hand-held computing and media devices have advanced dramatically in recent times. Hand-held devices are those computer embedded systems that are small and light enough to be held in one hand such as personal digital assistants (PDA), cell phones, ultra mobile computers, and portable game consoles. Several researchers have used cell phones and PDA's for VR and AR applications [3, 4], and hand-held console grade games have become a reality (e.g. SONY PSP®). However, it is difficult to declare that hand-held devices, as they are in their nominal configuration, are fit for implementing VR contents. Most related works to date either are limited to playing 3D graphic contents (with a button-based interface), or targeted for limited application domain, untested in terms of the degree of immersion. Moreover, one can be still skeptical whether such devices can be used for "virtual reality," e.g. to the extent of eliciting immersive feelings (not just for 3D contents viewing).

Although there are limitations of hand-held devices as the platform of virtual reality as described, there are many researches developing various hand-held VR applications [5]. However, the framework for future hand-held VR is not yet fully presented in spite of the value of this research area. Due to the absent of the framework of hand-held VR, the hardware and software system factors of hand-held VR changes depending on the application requirements. For more compound exploration of the hand-held VR, the overall framework should be established and the development should be also followed.

Therefore, we attempt to design the hand-held VR framework which can be used generally. Also we concentrate on the some important features of the suggested framework such as hand-held device tracking, motion-based interaction and visually adjusted display. Also we tries to evaluate the effect of our approaches by performing some user studies.

1.2 Framework of Hand-held Virtual Reality

In this section, we propose the overall framework of hand-held virtual reality which we are pursuing in long term plan. The framework in this section is the foundation that the hand-held VR system can be implemented. In the long term, we believe the proposed framework will be realized and used in public. In this overall framework, we designed and implemented selected factors such as hand-held motion tracking, user distance tracking, view dependent rendering.

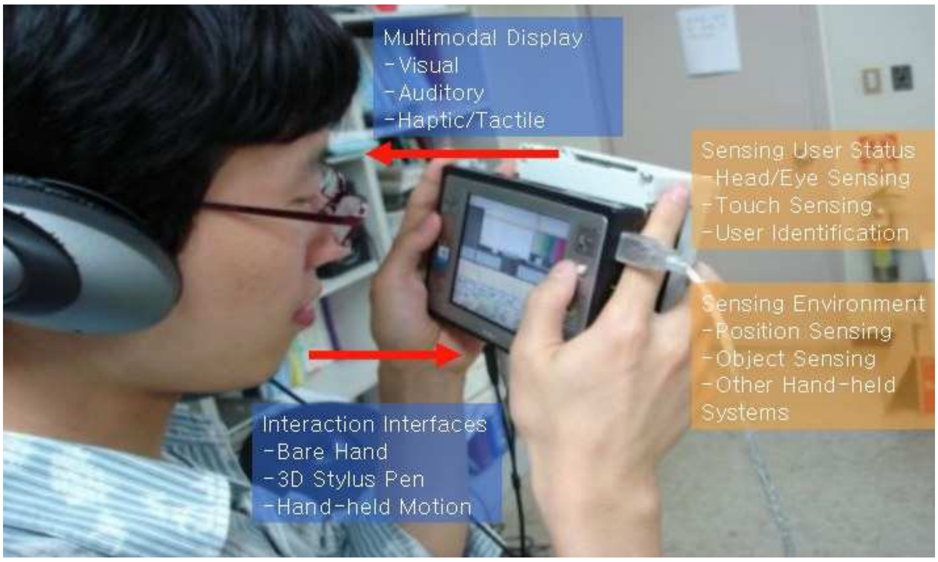


Fig. 1.1 Foreground (blue boxes) and background (scarlet boxes) interactions among hand-held device, user and environment

In Figure 1.1, the interactions between hand-held device and user and environment are illustrated. According to Hinckley's work [6], there are two interaction with sensor-enhanced mobile devices. *Foreground* concerns deliberate user activity where the user is attending to the device, while the *background* is the realm of inattention or split attention. We described interactions in the hand-held VR system in Figure 1.1. There are two groups of foreground interactions between user and hand-held device. Multimodal display, such as visual, auditory and haptic/tactile, is an interaction which is given to the user. And user can interact with hand-held device using bare hand, 3D stylus pen and hand-held motion itself. Also there are two groups of background interactions, user status sensing and environment sensing. User status include the head/eye movement of the user, the touch/grab of hand-held device, and the identification of the user. Using user status, we can control and provide user adaptive contents. In the Hinckley's work [7], touch sensor was attached on the side of the hand-held device to detect the user's grabbing of the device. User identification can be used to provide user specific VR contents. With head/eye tracking, we can provide more immersive visual effects such as dynamic field of view and perceptually rendered image. Also, by manipulating display resolution and complexity of the image we can reduce CPU or GPU usage of hand-held device. Environment sensing includes sensing the device position, environmental object sensing and sensing of other hand-held systems.

1.2.1 User Status Sensing

Tracking User's Distance(Head/Eye)

By tracking user's head or eyes, we can control the visual display of hand-held VR. For instance, dynamic FOV, perceptually rendered mesh, dynamic resolution is possible with user's head/eye position. To track user's eyes or head, there are several candidates. Camera-based eye tracking is one of the candidates [8]. Camera-based eye tracking is not easy to track eye distance but good to track relative direction from the device(left/right of hand-held device).

In case of the head tracking, infrared distance sensor and ultrasonic sensor can be good solutions. Infrared distance sensor calculates distance of the collision point in the normal direction by triangular surveying. Ultrasonic sensor can get the closest point in the sensing area [9].

Touch Sensing

Touch sensor detects capacitance of the user's hand. Using touch sensor, we can know whether the user is holding the device or not [7]. By using multiple touch sensors various interaction in hand-held VR is possible.

User Identification

By identifying user, hand-held VR can provide user specific contents. Vision based user identification is one candidate for making personalized contents. And fingerprint identification is another candidate more accurate but little more cumbersome.

1.2.2 Environment Sensing

Device Position Sensing

The device position sensing means both the absolute position sensing and relative position from landmarks. From the view of the working area, position sensing also can divided into indoor tracking and outdoor tracking [10]. GPS is one useful tool for absolute position tracking in the outdoor environment. There are some indoor tracking system such as Cricket Indoor Location System [11, 12]. Cricket is indoor location system which uses ultrasonic sensors to identify the sensor position. Normally, indoor tracking system provides space identifiers, position coordinates, and orientation. Recently, some position sensing system such as GPS is equipped with the hand-held device.

Environmental Objects Sensing

Sensing environment objects can be another functionality of hand-held VR system. By sensing environment objects such as electronic devices, furniture, buildings, we can provide proper information and interactions to the user. There are several ways to identify and locate environment objects. By using camera, we can detect and identify the markers or features on the objects. Also some researchers are using RFID to identify real objects.

Sensing and Communicating with Other Hand-held Systems

Interaction with other hand-held VR system is also important feature for collaboration and sharing environment. To do this, hand-held VR system should detect other hand-held VR system and should provide communication and interaction methods. Similarly with environmental objects sensing, camera and RFID are good method for this. The major difference between environmental objects and external hand-held VR system is that external hand-held VR system also has interaction, sensing, and data sharing functionalities.

1.2.3 Interaction Interfaces for Hand-held VR

Hand-held Device Motion

The motion of the hand-held device itself can be used for interaction with virtual environment. The tilt of the hand-held device is useful interaction interface for motion based interaction [7, 13]. However, the limited degree of freedom in the motion tracking of the hand-held device makes complex interaction difficult in virtual environments. Using more sensors, such as camera, acceleration sensor, ultrasonic and IR distance sensor, more interaction becomes possible. Combining motion sensors with camera is also good method for interaction design [14, 15, 16].

Barehand Interaction

Barehanded means that no device and no wires are attached to the user, who controls the computer directly with the movements of his/her hand. Therefore barehand interaction is one of the easy and comfortable interaction method for user. Generally, hand motion is tracked with vision technique such as finger tracking and hand posture recognition [17]. In the hand-held VR, barehand can be a good interaction methodology because of the limitations in the mobility.

1.2.4 Multimodal Display of Hand-held VR

Visual Display

- Autostereoscopic Display

  Due to nonnecessity of the peripherals such as shutter glass, the autostereoscopic display is preferred method for stereoscopic generation of hand-held devices [18]. To make autostereoscopic display on the hand-held device, parallax barrier should be on the display panel [19, 20]. If we can know exact eye position, more accurate stereoscopic image can be generated [8].

- View Dependent Rendering

  Dynamic rendering adjusted by the view position could be another system factor for hand-held VR. Graphics rendering which considering user's perception and gaze has been a common issue in the graphics rendering [21]. In the hand-held VR, the fact that the display itself moves make additional improvement in the rendering. The optimization of the rendering quality such as mesh complexity, display resolution could be possible using user's view distance. Also dynamic FOV control is possible with view distance.

Auditory Display

- 3D Sound Generation

  3D sound was known as the fact that can give influence on the spatial perception of the user. Therefore, the 3D sound generation is the very basic feature of current VR systems. Thus, the effects of 3D sound in hand-held

VR is also another undiscovered research area. Unlikely previous VR systems, combining real environment and 3D sound can be challenging issue in hand-held VR.

Haptic Display

- Vibro-tactile for Hand-held VR

  Vibro-tactile sensation by vibrator has been known as the medium which enhances collision detection, presence, and realism of virtual environments [22, 23]. By using vibro-tactile, interaction in the VE also becomes more usable in the close range [24]. The fact that users are grabbing the hand-held device makes the practical use of the vibro-tactile on the hand-held VR.

1.3 Contributions

The contribution of this thesis is as follows.

- **Hand-held VR Platform**

  We designed and implemented the hand-held VR platform which satisfies some basic requirements such as hand-held device tracking, user distance estimation, multiple vibro-tactile, autostereoscopic display and view dependent display. The developed platform could be used on various applications.

- **Motion based Interaction and Its Evaluation**

  We built motion-based interaction of the hand-held VR based on designed platform. Four degree of freedom relative tracking was suggested and implemented to detect the motion of the hand-held device. By this motion tracking, we can use hand-held device motion for interaction of the hand-held virtual environments. Also we evaluated the effects of the motion-based interaction in the hand-held VR. And showed the benefits from motion based interaction on the hand-held VR.

- **Visual Adjustment in Hand-held VR**

  We suggested visual adjustment technique using user distance that can be used in hand-held VR. The suggested visual adjustment techniques are dynamic FOV adjustment, model simplification, and dynamic resolution control.

- **Hand-held VR Applications**

  We developed several hand-held VR applications such as virtual environment walk-through, multimedia contents browsing and manipulating and hand-held games. Also we discovered some features that should be considered depending on the applications such as adjusting horizon with user's view.

1.4 Organization of the Dissertation

This thesis is organized as follows. In Chapter2, we will list some related work of hand-held device as a tool of virtual reality or augmented reality. In Chapter 3, we propose several requirements for a hand-held device to support minimal level of immersion and sensory experience as a viable platform for VR. Also the Chapter 3 covers the actual hand-held VR platform built according to our proposal. In Chapter 4, the motion interaction in the hand-held VR is presented and the evaluation results are shown. In Chapter 5, we propose visual adjustment technique which can be used in the visualization of hand-held virtual reality. Applications which use our platform are introduced in Chapter 6. Finally, we report our experiences and come to a conclusion and avenues for future work in Chapter 7.

CHAPTER 2

Related Work

Possibilities for virtual reality with hand-held devices (palmtop computers) were first investigated in 1993 by Fitzmaurice et al. [4]. In the paper, the authors suggested several principles for display and interface for palmtop computer VR. Due to the limited technology at the time, the prototype was demonstrated and tested with a wired 6-DOF sensor and the display generated by a workstation. After Fitzmaurice's work, the progress of the hand-held VR research was slow because of the limitations of hand-held device itself. However, as we mentioned at Section **??**, the improvement of functionalities and performance of hand-held device made 3D visualization and multiple sensor handling possible. With these improvement, some researchers used hand-held platform for platform of mixed environment. The researches can be divided into three categories. At first, hand-held device can be used as interaction tool in mixed environment. This kind of research was done when the performance of hand-held devices was not enough to give multi-modal sensation. The second one is using hand-held VR system as stand-alone system. The last one is hand-held augmented reality. Hand-held augmented reality is mixing virtual object in the image from the camera attached in the hand-held device.

2.1 Hand-held Device as Interaction Tool for Mixed Environment

Hand-held devices (with visual display) were perhaps first used in the context of virtual reality as interaction devices. Watsen et al. have used a PDA to interact in the virtual environment, but the interaction was mostly button or touch screen based and no tracking was used [25].

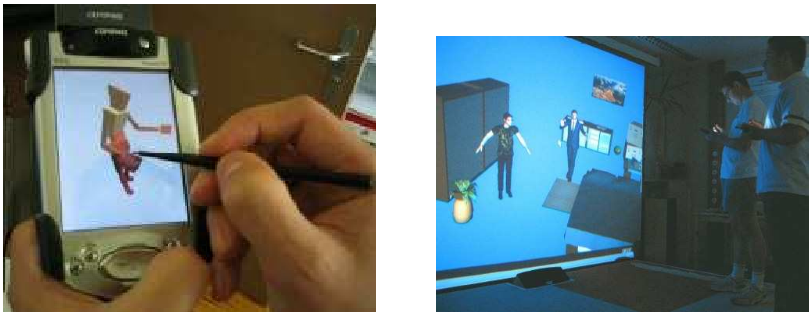
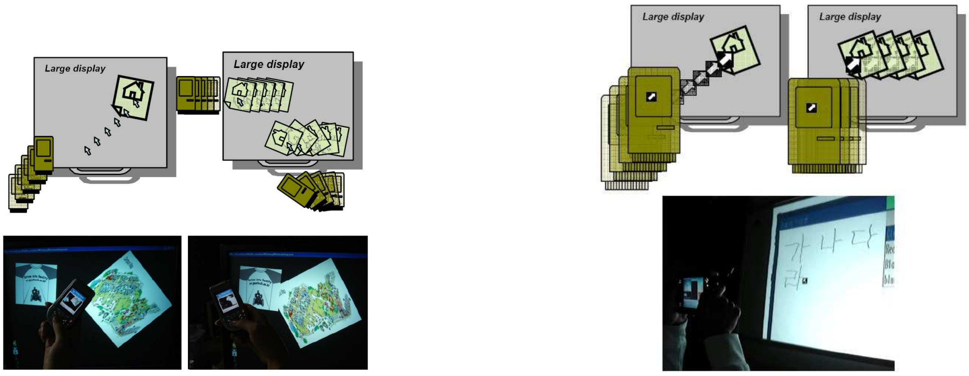

(a) Character control on the PDA (b) Users interacting in VE

Fig. 2.1 Manipulating virtual character using PDA [1]

In the Gutierrez's work [1], the PDA was used to interact with character in the collaborative virtual environment displayed on the large screen. In this system, the simplified model of the virtual character is displayed on the PDA display. By manipulating the simplified model in the PDA, the user can interact with other collaborators.

Chen [5] used hand-held device for search task in virtual environments. Kukimoto et al. also developed a similar PDA based interaction device for VR, but with a 6-DOF tracker attached to it. This way, they were able to demonstrate 3D interaction such as 3D drawing through the PDA (moving it and pressing the button) [26]. Various special sensors and displays like accelerometer, gyros, vibro-tactile motors and even haptics have been used to enhance hand-held oriented interactive experience [27, 28].

In particular, researchers have long been interested in using the camera (or computer vision) as interfaces for computers, particularly for 3D interactions in large display [29, 30]. Generally robust tracking with as little environment constraints as possible is a hard problem, and much more so with hand-held devices which lack the needed computational power [31]. However, the computational power of the hand-held devices is ever-more increasing with respect to their physical size and cost. Ballagas et al. has demonstrated direct manipulation for large displays using camera phones [32]. We can manipulate cursor in large screen using camera interface in the hand-held device [2]. In Figure 2.2, user can manipulate cursor by recognizing marker or detecting hand-held motion with motion flow.



(a) Manipulating cursor using motion flow (b) Manipulating cursor using cursor-marker

Fig. 2.2 Manipulating cursor using hand-held motion [2]

2.2 Hand-held Device as Stand-alone Platform for VR

Using a hand-held device stand-alone platform for virtual reality is the research area just got interests by researchers. Because of the limitations of hand-held device, implementing virtual reality applications on the platform was very difficult only a few years ago. Therefore, simulating virtual reality on the small screen was only the way to evaluate the feasibility of the hand-held virtual reality. As previously mentioned, Fitzmaurice [4] suggested several principles for display and interface for palmtop computer VR in the simulated environment. The limitations of the sensing capability of the hand-held device has been solved by researchers such as Hinckley [7]. Hinckley developed sensing techniques for mobile interaction by attaching proximity range sensor, touch sensor and tilt sensor. Also he provided the principles of interaction when using sensor-enhanced mobile devices [6].

Some 3D applications such as 3D GIS [33] and medical information visualization were implemented on the hand-held platform Especially, the medical system on the hand-held platform is becoming popular because of its portability in the hospital [34]. Also, it is useful to visualizing medical data on the hand-held device (See Figure 2.3).

(a) 3D GIS system [33] (b) Medical visualization system [35]

Fig. 2.3 3D applications with hand-held devices

Using hand-held display as a window to the large virtual workspace is another approach of this category. The Peephole display [9], developed by Yee, is a spatially aware display which can change displayed image by tracked position.

2.3 Hand-held Augmented Reality

Pursuit of mobile augmented reality system is one of main stream in the AR research. The fact that normal AR system uses one camera for its implementation makes it possible to use in the mobile situation such as outdoor. Hollerer developed MARS (Mobile Augmented Reality System) which works in indoor and outdoor environment [36]. In the mobile AR, user interface in the indoor and outdoor environment is also provided [16, 10]. The mobile AR can be used in various applications such as assembly and construction [37, 38], maintenance and inspection [39, 40, 41], navigation and path finding [42, 43],tourism [44, 45, 46], geographical field work [47], journalism [36], architecture and archaeology [36, 48], urban modeling [49, 50, 51], entertainment [52, 53], medicine [54, 55], military training and combat [56], personal information management and marketing [46, 57].


(a) Before virtual object augmentation (b) After virtual object augmentation

Fig. 2.4 Hand-held augment reality applied in the geology education

With advances of the hand-held device functionalities, the mobile AR became feasible in the hand-held platform. Wagner developed hand-held augmented reality system and applied it to the Signpost project (e.g. smart space with augmentation for navigation and information browsing) [58, 3]. Because we can put the hand-held device on the hand, we can use hand-held display as see through window to the augmented environment as Figure 2.4. Paelke et al. has presented a foot-based interaction for a soccer game on a mobile device using a camera [59].

CHAPTER 3

Design of Hand-held Virtual Reality Platform

In this chapter, based on research by others and our own, we attempt to derive minimal and general requirements for a hand-held platform for virtual reality. We hope and believe that hand-held virtual reality contents can indeed exhibit sufficient immersive and sensory experience, if the platform was built with our proposed requirements and employed the style of interaction enabled through the proposed platform. We demonstrate our ideas by presenting our own implementation of a hand-held VR platform.

3.1 Requirements for Hand-held Virtual Reality

In order to provide sufficient immersive and sensory experience through the hand-held devices, their sensing and display capabilities must be first considered. The nominal hand-held device generally lack in terms of the number of styles and modalities of interaction it can support. In particular, in terms of interaction, we must keep in mind that in hand-held devices, the place of display and interaction are co-located, and thus the user's hand-eye coordination should be an important factor. In addition, the advantages and uniqueness of the hand-hand device such as portability, low cost, and high usability must be preserved.

3.1.1 Sensing and Tracking Requirements

Hinckley et al. proposed a mobile interactive platform in which they distinguished between two types of sensing, i.e. foreground and background [6]. The foreground sensing corresponded to the sensing of the user's intended movement and background to that of the environment context including the user's physical state. In hand-held devices, with the limited display channels (e.g. small visual display size and FOV, limited areal contact, low sound quality), a more flexible and dynamic interaction incorporating various form of the user state, than buttons and touch screen input, is required to overcome such limitation. Furthermore, as the hand-held display is physically coupled with interaction, it is particularly important that ***some form of tracking of the device (or equivalently the hand) and the user's view (or equivalently the head) exist***.

The tracking of the device (e.g. relative or absolute to the environment) enables a motion or body based interaction at least through the holding hand of the user. Involving one's body stimulates one's sense of proprioception and this is known to be one of the best ways to improve the virtual experience, task performance and presence [60]. In our own experimental study, we considered the use of a motion based interaction as the factor for the style of interaction [61, 62]. The results have shown that the motion based interaction on hand-held platforms could help improve the perceived FOV and presence/immersion up to a level comparable to the nominal VR platforms with the desktop or even projection based display. The motion based interface also has shown promising results in terms of task performance as well. This is an interesting case of interaction compensating for the limitation in the modality display.

One of the distinguishing characters of VR systems to the 3D graphics or multimedia viewing is the dynamic display according to the naturally controlled view points of the user, for instance, through head tracking. Note that device tracking can be coupled with user tracking, for instance, using a camera that recognizes and follows user's eyes (in our case, we used a separate sensors for device and user tracking). Through this sensing ability, it becomes possible to generate rendering based on the viewing direction, distance and even the perceptual ability of the user very naturally, contributing to the minimal level of immersion and viewing interactivity.

3.1.2 Multi-sensory Display Requirements

Nominal hand-held devices are obviously quite limited in terms of providing various styles of and multimodal interaction in a faithful way. Still improvements can be made with relatively low cost. First of all, in combination with the requirement and capability to track the user (at least approximately), view dependent dynamic rendering can much improve the static nature of the nominal hand-held visual display. Although not formally tested, it is expected dynamic rendering coupled with hand-held interaction can bring about higher level of focused attention (and thus immersion) and association of the visual feedback with one's proprioception. Current hand-held devices have much support for sound generation already. Adding software support for simple 3D sound simulation (e.g. volume/phase modulation between the right and left ear) can be added with not too much computational cost. Even with simple and approximate sound spatialization, when combined with other modalities, it can prove to be very effective [63].

Finally, tactile/haptic displays, if they can be made possible, would be most appropriate for hand-held interaction. This is because, it is expected that the hand-held device itself can represent certain virtual objects that the user will interact with, and the device itself already provides natural passive tactile and haptic feedback. Furthermore, hand-held devices are usually equipped with vibrator motors just for that matter. Similarly to the auditory display, a more careful implementation and utilization of this resource easily make hand-held device a viable platform for reasonable virtual reality. Few researchers have proposed hand-held haptic devices using mechanisms other than vibration motors [28, 22]. However, currently, the vibro-tactile device seems to be the most preferred because of its size, low price, usability and relative effectiveness. The vibro-tactile device can increase egocentric field of view, perception of the collision, and presence [23, 24, 64]. Thus, for a reasonable tactile/haptic stimulation for VR, we propose to ***use multiple vibrators and moderately complex tactile/haptic rendering***, in conjunction with other modality display.

3.1.3 Considerations for usability

The final requirement refers to the “must-preserve” quality of the hand-held devices: ***portability and ease of use***. We believe that due to the limited display channels, the hand-held device user can easily get distracted. One source of distraction is the use of, or connection to external entities such as markers, servers, and wired modules (for various purposes like more robust sensing or tapping into more computational resource). As goes with our definition of hand-held devices, we put forth a requirement that the hand-held VR platform be ***self-contained*** in terms of sensing, display and computation. Furthermore, any sensors or display support in addition to what is already contained in the nominal platform must be in reasonable size and weight, and ***modularized*** for ease of attachment and detachment.

3.2 A Hand-held Virtual Reality Platform

Based on the requirements listed in previous section, we designed and built a “general” hand-held virtual reality platform which can be applied to various virtual reality applications. In this section, we cover the implementation detail. We claim that the nominal hand-held devices are not equipped sufficiently to realize virtual reality. Our platform implementation uses sensors and displays that are not usually available with standard hand-held media or computing devices, but the platform uses relatively inexpensive off-the-shelf components and can easily be interfaced into the hand-held device. Moreover, hand-held devices are still evolving and advancing in terms of their sensing and display capabilities.

3.2.1 The Proposed Hand-held VR Platform

Figure 3.1 shows the overall system architecture of the proposed hand-held VR platform. The figure illustrates the added sensing and display capabilities to a nominal hand-held computer. As for sensing, as claimed in the previous section, sensing at least some part of the user and the operating environment, and the motion of the device was deemed necessary to support reasonable level of realistic interactivity. Using the camera, which is already integrated into many of the hand-held devices today, is thus an inexpensive way for many types of sensing. It can be used not only for simple object recognition and relative tracking of the device motion, but also for augmented reality applications as well. The acceleration sensor too is becoming a standard part in many hand-held devices, and in our design, is devoted for sensing device motion characteristics (and to relieve and share the responsibility of the vision processing at the same time). To reflect the status of the user, we adopted an ultrasonic/IR proximity sensor module that can approximately measure the relative viewing position of the user.

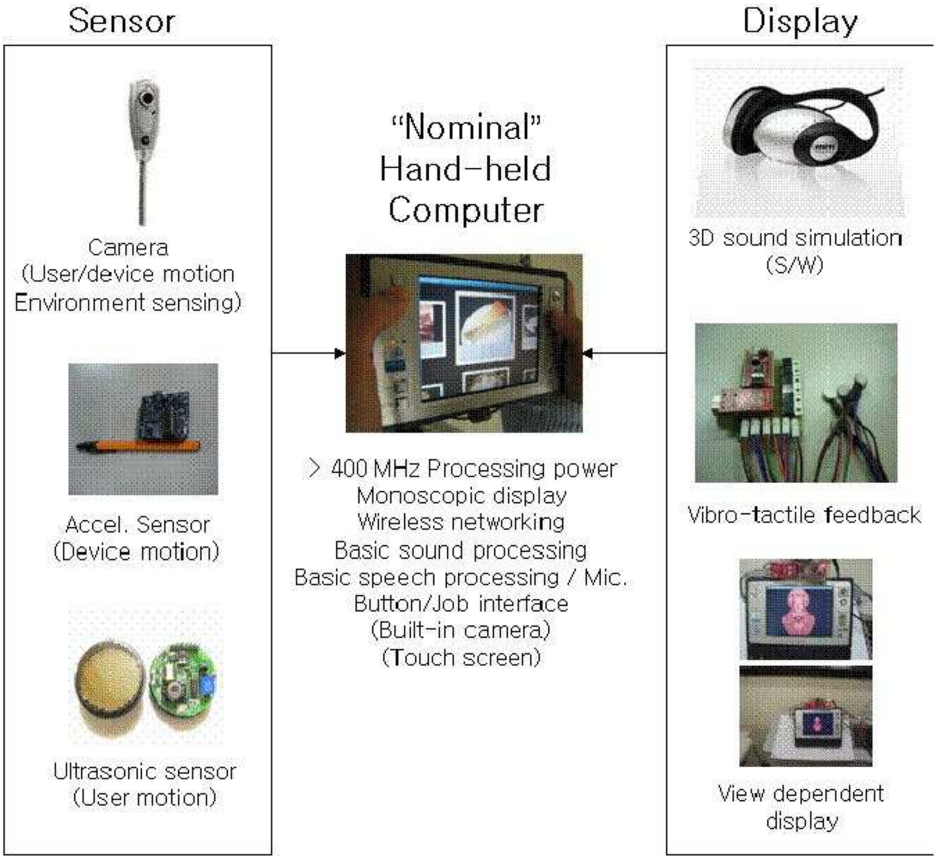


Fig. 3.1 The overall architecture of the general purpose hand-held VR platform

As for the added display capability, we have claimed that at least three major modalities be supplied in one way or another. The nominal hand-held device provides monoscopic display, basic sound production and a single on-off vibration feedback. Our design adds hardware and/or software support for simple 3D sound simulation, multiple vibration motors for an improved tactile/haptic effects and view dependent display. The following sections give more details.

3.2.2 Sensing and Tracking

Hybrid Relative Device Motion Tracking

We use a hybrid method to track the movement of the hand-held device. That is, we use the camera (and vision processing) and the acceleration sensor. Relative motion tracking refers to an approximate tracking of the hand-held VR system (thus, the user's hand or body) in relation to the environment. Combining sensor and vision technique for tracking is a popular approach in mobile and AR applications. Foxlin developed "Vis-tracker" which uses vision and intertial sensor for wearable self-tracker [65]. In the AR applications, hybrid approach is used for better registration of virtual object and real image [66, 67].

Even though the tracking is only approximate (mostly due to hardware constraints such as the limited computing power, use of single camera, its resolution, etc.), we believe that the user would still able to interact quite naturally and without much difficulty relying on one's hand-eye coordination, quickly adapting to the small inconsistency between the scale of the movement between the real and the virtual worlds. We make a note of the work done by Hinckley [7] which employed a proximity, two axis tilt, and touch sensor to improve interactivity of a mobile device. While we agree that this is an improvement, sensing in more degrees of freedom is required to provide the minimum "virtual reality" of our claim. Our relative tracking provides 4 DOF motion, including 3D rotation and forward/backward movement.

To make our hand-held VR system as self-contained as possible, we inte-

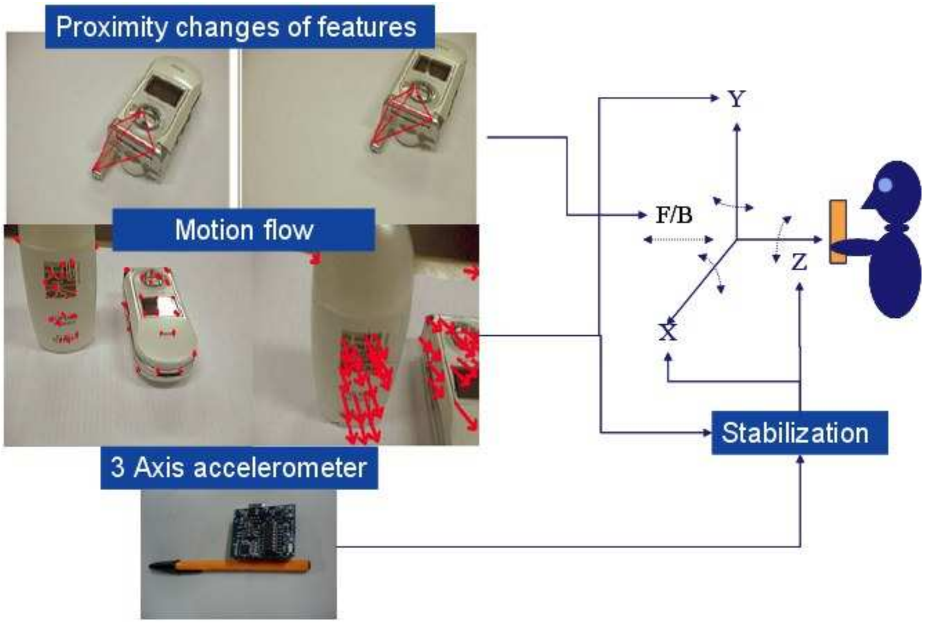


Fig. 3.2 4-DOF hand-held motion tracking with the camera and 3-axis accelerometer

grated a vision based motion tracking and 3-axis accelerometer (MMA 7260Q 3 axis accelerometer from Freescale™). Cameras (e.g. phone-cams) and accelerometers are becoming viable sensors for today's hand-held devices (e.g. Samsung SPH-S4000, SPH-S310). Our motion tracker tracks motion in 4 degrees of freedom, i.e. forward/backward movement, rotation about Y axis (yaw) and tilts about the X and Z axis (pitch, roll) (See Figure 3.2) [68, 62]. The forward/backward motion and rotation around Y axis are estimated with the optical flow. We used the pyramidal implementation of the Lucas-Kanade feature tracker for matching the features between two sequential images [69]. The tilts about the X and Z axis are measure using 3-axis accelerometer. The tilt data from the 3-axis accelerometer are digitized in relatively low resolution (8 bit, 0.92° 6.51°), and relying only on them results in an unstable virtual camera control. We stabilize (filter) the data from accelerometer when the motion flow as recognized from the camera is not significant (within a given threshold). Figure 3.3 shows a case of applying the motion tracked data to view control.

The particular choice of the degrees of freedom derives from our observation of the users. For instance, directing pure lateral translation in a hand-held posture is rather unnatural (e.g. left/right). It is more natural to rotate around the Y axis (perpendicular to the ground, around the body) to gain the similar effect. Similar argument goes for moving up and down. It is hard to imagine the user walking side ways (holding the hand-held device in the middle) or moving the hand-held device sideways away from the middle of the body to achieve pure "translation." Even though the forward/backward and Y-axis rotation tracking is only approximate (mostly due to use of single camera without marker in the environment, its resolution, etc.), the user is still able to interact quite naturally relying on one's hand-eye coordination and quickly adapting to the small inconsistency between the scale of the movement between the real and the virtual worlds. Also note that the motion tracking data can be used for recognizing more abstract gestures (for interaction).

(a) Initial viewpoint

(b) Rotating the view

(c) Translation to z axis (forward/backward)

Fig. 3.3 Hybrid tracking of the hand-held VR device

Detecting Hand-held Motion with Camera

Features such as corner in the image from camera are good clues for motion of the camera. We attempt to select a good distinct feature from the incoming images and use them for motion analysis. Generally, a corner is regarded a “good” feature. If can be found, we take the 15 “best” corner features for the subsequent motion calculation. Once the “corner” features are identified and selected, the next problem is to track them, in other words, find the corresponding feature in the next image frame.

Feature Finding

The matrix below computes the spatial image gradient for a pixel located at (x, y). The two eigenvalues of the matrix reflect the amounts of differences in intensities in the respective directions. Thus we can use the smaller eigenvalue to represent the “corner-ness” of the given pixel. The image gradient matrix is as follows:

$$\begin{bmatrix} \sum\limits_{neighborhood} \left(\frac{\partial I}{\partial x}\right)^2 & \sum\limits_{neighborhood} \frac{\partial^2 I}{\partial x \partial y} \\ \sum\limits_{neighborhood} \frac{\partial^2 I}{\partial x \partial y} & \sum\limits_{neighborhood} \left(\frac{\partial I}{\partial y}\right)^2 \end{bmatrix}$$

I : imageintensity

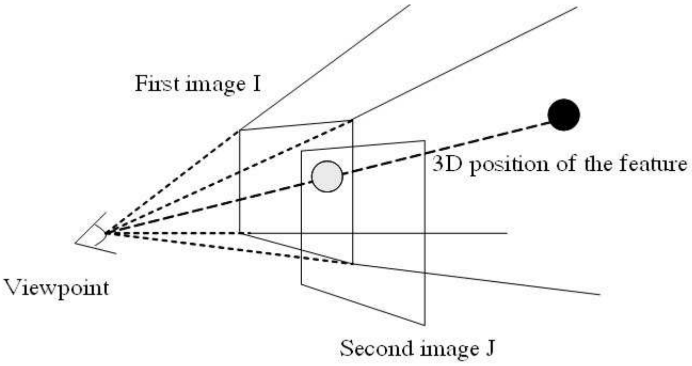
We have used OpenCV, a public domain image processing library that provides a function to find the corner-ness of the image pixels based on this principle in real time. The accuracy of motion estimation is improved with more corresponding feature points. If can be found, we take the 15 “best” corner features for subsequent motion calculation. If there are only few features with good enough (this threshold is set empirically too) corner-ness, an approximated method is used.

Feature Tracking

Once “corner” features are identified and selected, the next problem is to track them, in other words, find the corresponding feature in the next image frame. We define the problem as finding the displacement vector, d, that minimizes the residual function ε defines as follows:

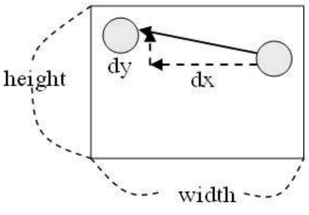
$$\varepsilon(d) = \varepsilon(d_x, d_y) = \sum_{x=u_x-w_x}^{u_x+w_x} \sum_{y=u_y-w_y}^{u_y+w_y} (I(x,y) - J(x+d_x, y+d_y))^2$$

I : firstimageJ : secondimage



$$\Delta\omega \approx FOVy \times \frac{1}{n} \sum_{i=1}^{n} \frac{dy}{heigth}$$

$$\Delta\phi \approx FOVx \times \frac{1}{n} \sum_{i=1}^{n} \frac{dx}{width}$$



Movement of the feature in the viewing plane

Fig. 3.4 Estimation of the rotation around X axis ($\Delta\omega$) and Y axis ($\Delta\phi$).

To solve this problem, we used a pyramidal implementation of the Lucas-Kanade feature tracker for matching the features between two sequential images [69, 70]. This algorithm searches for the corresponding pixel in the target image by down sampling the image and hierarchically searching for corresponding feature. Given the set of corresponding feature points between two consecutive image frames, we can derive rotational motion parameters (See Figure 3.4). Among X, Y axis rotation values, only the Y axis rotation value is used.

We have used the proximities between features as a measure of the forward/backward factor because the proximities are affected little by the rotational movement (See upper part of Figure 3.2). While the connections between features (in-between-ness) do not change between in the projected consecutive images, the inter-distance could change as the view moves. We define the proximity between features in an image as follows:

$$P = \frac{1}{n(n-1)} \sum_{j=1}^{n} \sum_{i=1}^{n} \sqrt{(u_i - u_j)^2 + (v_i - v_j)^2}$$

when

$$n > 1$$

The proximities are proportional to the distances from 3D feature point to the camera position. Therefore we can estimate the ratio of the distance between z positions of the two cameras. as the proximity in time t and P_{t+1} is the proximity in time *t+1*. $P_{t+1}/P_t = 2$ represent the ratio of the feature distances. For example, if $P_{t+1}/P_t = 2$, it means the distance of the feature from the camera became twice as closer. With this metric, we can estimate relative distance in z direction between the frames.

X/Z Axis Tilt Measuring with Accelerometer

We are using the Freescale MMA7260Q series 3-axis accelerometers for X, Z axis tilt sensing. The MMA7260Q provides a sensitivity of 800mV/g (gravity) in 3.3V. The typical output of capacitive, micro-machined accelerometers is more like a sine function. The output voltage from accelerometer increases or decreases as the device is tilted. Because of the nonlinearity, the degree resolution decreases as the device tilts around the 90° or -90°. From voltage output of accelerometer we can calculate angle of tilt as follows [71].

$$\begin{gathered}
V_{out} = V_{offset} + \left(\frac{\Delta V}{\Delta g} \times 1.0 \times \sin\theta\right) \\
\theta = \arcsin\left(\frac{V_{out} - V_{offset}}{\frac{\Delta V}{\Delta g}}\right) \\
V_{out} = \mathrm{AccelerometerOutputinVolts} \\
V_{offset} = \mathrm{Accelerometer0gOffset} \\
\Delta V / \Delta g = \mathrm{Sensitivity} \\
1g = \mathrm{Earth's Gravity} \\
\theta = \mathrm{AngleofTilt}
\end{gathered}$$

The Accumulated Error of the Hand-held Tracking

Due to the limitations of the vision based tracking, the accumulated error was occurred in the yaw movement and forward/backward movement. Because the forward/backward movement detection algorithm is relative motion sensing, the motion was interpreted as the relative amount of forward/backward movement. Therefore, it was hard to tell about the accumulated error. In case of

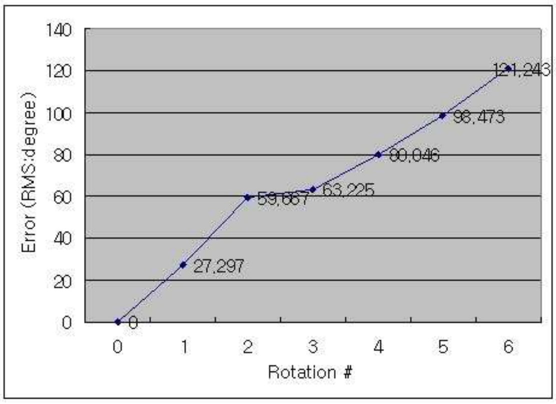


Fig. 3.5 The accumulated error in the yaw movement (vision based tracking)

the yaw motion, we measured accumulated error by recording the error when hand-held was rotated 6 times (See Figure 3.5). The error measured 20 times repeatedly. In the figure, the error was about 20° with a 360° rotation. Fortunately, this amount of accumulated error in the yaw does not make confusion of the user's orientation sensation in the virtual world. In case of other two rotation, the sensor itself does not makes accumulated error.

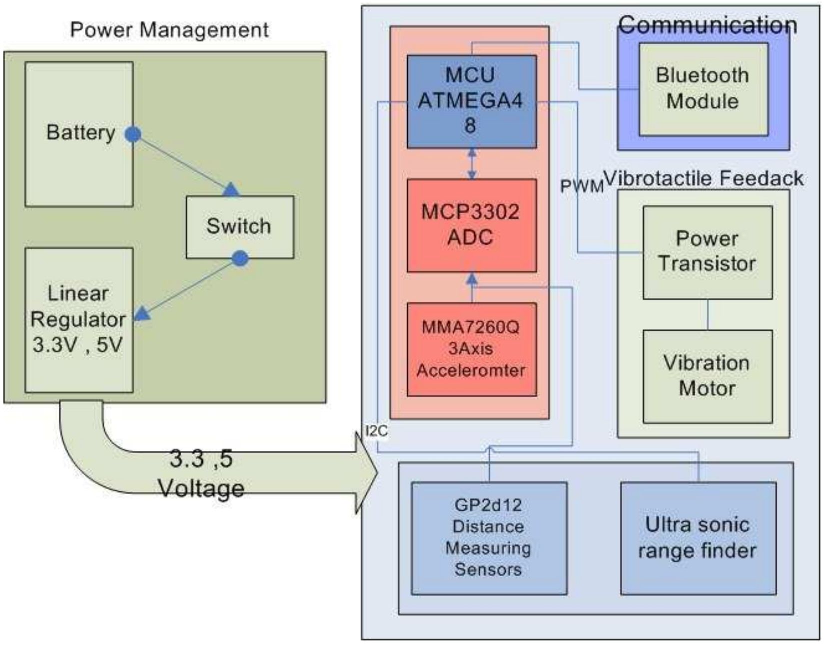
User Distance Sensing

Aside from device motion tracking, tracking the user is also important with regards to our requirements for hand-held VR. To detect the distance of the user from the device, two range sensors were implemented (See Figure 3.6). However, only one of them is sufficient for the approximate measurement of the relative user position or distance. Currently, this module is able to detect obstacles (or user's head) in the range of 3 cm to 6 m from the hand-held device screen. We assume that in a normal use, the user is facing directly toward the hand-held device and there exists an unobstructed line of sight between the hand-held device and the user's head. The viewing distance is used for a natural dynamic view dependent display as described in the next section.

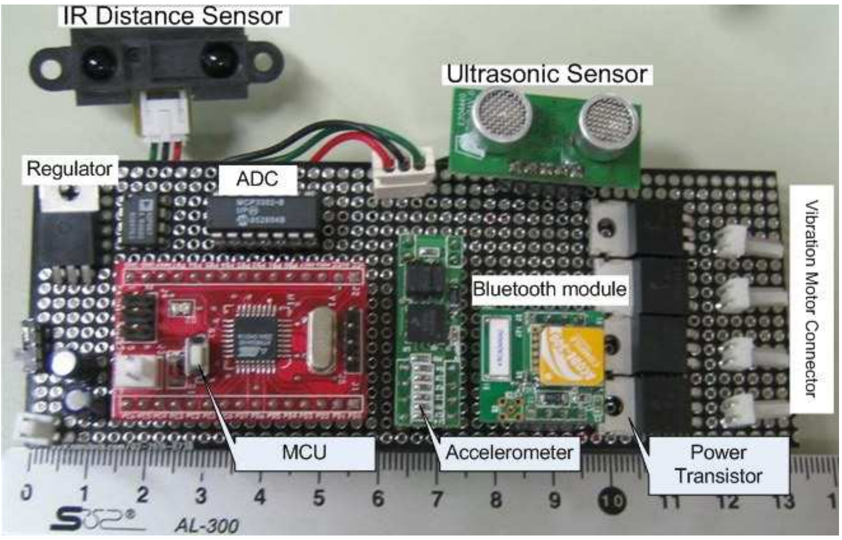
3.2.3 Multimodal Display

3D Sound Simulation

To provide 3D sound, we used the 3D sound capabilities of the DirectSound(TM) from Microsoft. DirectSound(TM) uses a HRTF based technique to create sounds with apparent directionality. The 3D sound is specified according to the virtual locations of the sound sources and the location of the user with respect to the device (obtained from the ultrasonic/IR sensor). For less computationally powerful hand-held devices such as cell phones or PDA's, simpler 3D sound simulation might more appropriate using volume and phase modulation



(a) Diagram of tracking and sensing module



(b) The hardware module

Fig. 3.6 The hardware module for the ultrasonic/IR sensing and tactile display. These modules are integrated for ease of implementation, although they should ideally be separated for modularity (See Appendix C)

Multiple Tactile Display

To provide any sense of tactility or haptics (the third major modality in our view) on a hand-held device, one of the most practical approaches is to use vibration motors [72, 24]. Vibration motors in fact have been used very effectively on gloves (CyberGlove® from Immersion) and even on mobile devices (VibeTonz® from Immersion). While there has been proposals for hand-held haptics (e.g. non-exoskeleton type), their sizes are still not small enough to go with hand-held devices. As nominal hand-held devices only usually employ a single on-off vibration motors, we propose to use several more and provide the controllability at discrete levels of amplitude and frequency. Currently, our hardware (shown in Figure 3.6) can support four vibration motors for various tactile effects, and when combined with the visual and aural feedback, it can even induce illusory haptic sensation as well. We hope, in the future, by manipulating the timing, intensity and placements of the multiple vibrators, a more realistic illusory haptic sensation with finer level of directionality and magnitude can be achieved.

Autostereoscopic Display

There are several methods for stereo display of virtual objects. The most common method is using shutterglass or passively polarized eyewear, in which the observer wears eyewear that blocks one of two displayed images from each eye [73]. The autostereoscopic display can give stereoscopic view of simulated objects, without artifacts. Therefore autostereoscopic is appropriate for hand-held VR system. The parallax barrier is common method for autostereoscopic display [19, 20]. With eye tracking, more accurate stereo image can be generated [8].

We attached specially made parallax barrier made by Pavonine®on the PDA(Hewlett Packard iPaq rx6100). To generate autostereo image, we used stencil buffer algorithm which is similar to the Perlin's method [20]. Using stencil buffer algorithm, we generated two images for each eyes and stitched them line by line. In Figure 3.7, we can see the generated autostereo image of simulated torus. Unfortunately, due to the difficulty of the eye-tracking with hand-held device, the autostereoscopic display was not applied on our final platform but developed separately.

Fig. 3.7 The autostereoscopic display using parallax barrier and stencil buffer algorithm

View Dependent Display

The narrow FOV and small size of the hand-held display (without any other provision) can cause lowered immersion in the hand-held VR. In addition, we claim that the fixed FOV despite changing viewing distance is also unnatural and can bring about similar effects. We suggest two different software FOV manipulation techniques using an approximate measurement of the eye (or head) position relative to the hand-held device using the user tracking hardware described in the previous section.

The first proposed FOV technique is to adjust the visual FOV to mimic the behavior of a magnifying glass. The FOV becomes narrower as the view distance is reduced. This method is useful for the applications in which the detailed views of the object are important but size perception is not.

The second proposed FOV technique is to use the hand-held device in an opposite way, as a see-through window into the virtual environment. As the head gets closer to the screen (or window), there are more parts of the virtual environment visible, thus the FOV widens (and objects are drawn smaller). The size of the virtual object “perceived to the user” is kept the same regardless to the eye-display distance. This approach is better suited for applications in which size or spatial perception is important such as medical training VR systems.

CHAPTER 4

Motion-based Interaction and Its Effects in Hand-held VR

From the point of view of traditional virtual reality (that has pursued the replication of rich sensory experience in the large-scale), it is somewhat odd that people can feel immersed in such “small” environments. However, such could be explained easily from the on-going debate about “form vs. content” about user felt presence [74, 75]. The “content” proponent would say that this is one evidence that “mind-catching” contents (no matter how simplistic the interaction or the sensory stimulation is) is sufficient to induce presence or the feeling of immersion.

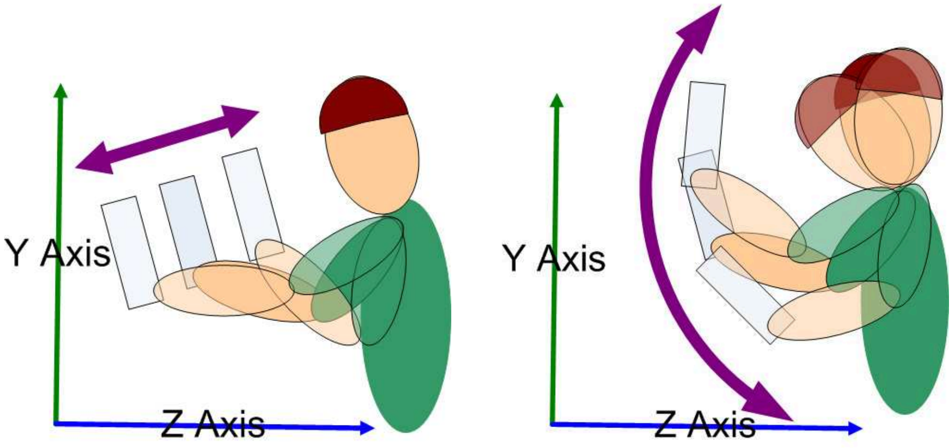
On the other hand, we are interested in knowing if it is possible or how, to make these ever-advancing hand-held devices more “multi-modal” so that the user experience and task performance can be further enriched and improved. In this chapter, we address this issue by comparing the perceived field of view (FOV), the level of immersion and presence, task performance and usability among the users’ of various VR platforms including the hand-held device. That is, the VR platforms were varied in their sizes of physical/software FOV and in styles of interaction.

In this comparative study, we considered the use of a motion based interaction as the factor for the style of interaction. Motion based interaction (e.g. gesture, direct interaction) is already considered a desirable style of interaction for virtual reality systems [76]. This is because it involves many parts of our body (if not the whole) and leverages on one's sense of proprioception, improving the overall user felt presence and immersion (and even task performance) [60]. In the case of hand-held devices, the motion based interaction also becomes coupled with the visual display/head (a situation unique to the hand-held device) because the sensors and the displays are all physically integrated (and moving) together. Currently, interaction in the hand-held devices is still mostly button and finger-based and naturally, and one way is to enrich the user experience is to provide the body-based and motion based. To realize motion based interaction (and to carry out the experiment), we have implemented relative tracking using a camera/accelerometer mounted on the hand-held device. Note that our notion of hand-held VR also hinges on self containment, without any external computational assistance.

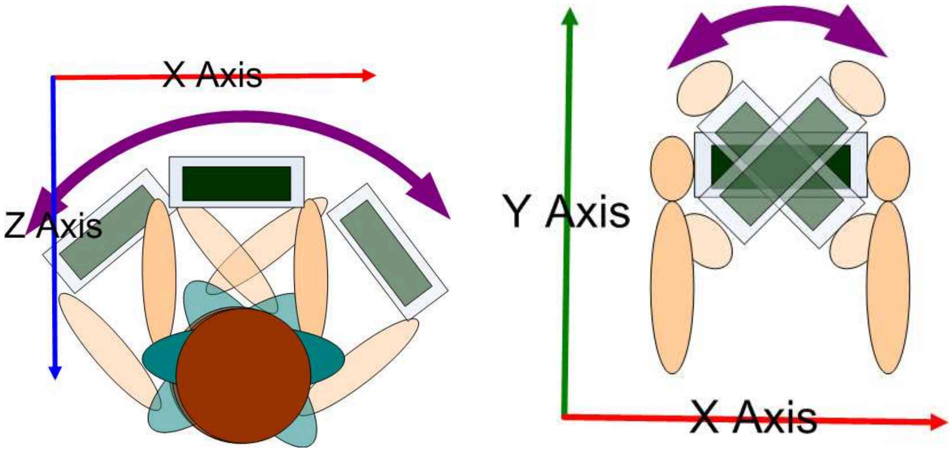
4.1 Motion based Interaction in Hand-held VR

4.1.1 Measured User Motion in Hand-held VR

In the Chapter3, we designed and implemented four degree of freedom tracking of the hand-held device. In the Figure 4.1, the measured motions are listed. We selected these four motions among full six degree of freedom because they are relatively easy and accurate to detect with provided sensors. And rotate and zoom using selected motion is a popular and natural interface in VR applications such as QuickTime®VR [77] and panoramic image navigation.



(a) Forward and backward movement (b) Pitch movement



(c)Yaw movement (d) Roll movement

Fig. 4.1 User motion with hand-held device

4.1.2 Mapping Hand-held Motion with the Motion in the VR

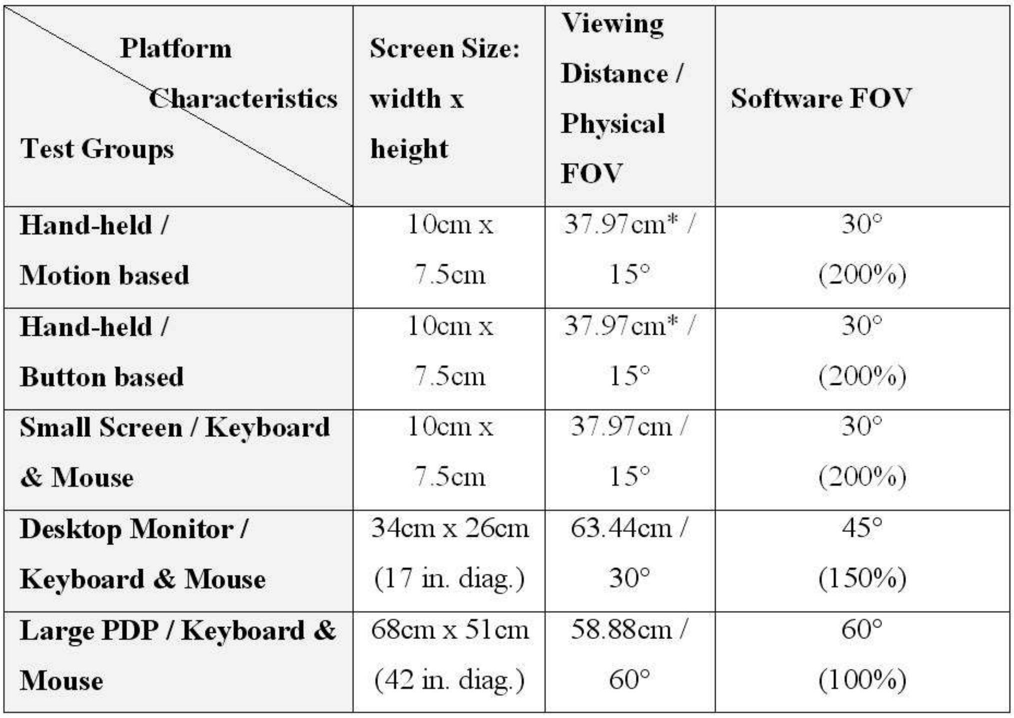
Using measured motions, we can map the hand-held motion with the motion of the virtual camera of hand-held VR. This can be changed depending on what is the metaphor of the hand-held device. If the hand-held device represents virtual camera or the window to the virtual world, the motion of the hand-held device itself is mapped as the same movement of the virtual camera or the window. In the case of the indirect metaphor, such as handle of a car, the hand-held motion represented as control motion. When the hand-held motion is used as continuous input interface such as wheel device, the motion is interpreted as a continuous command.

Among the various usages, we chose the direct mapping method for navigating virtual world and we performed evaluation for that interaction method because it is most general and intuitive interaction in the VR applications. In the next section, we will describe about how we performed evaluation and the results.

4.2 Evaluation of the Motion based Interaction of Hand-held VR

Because of the rapid changes in the hand-held device area, the evaluation of mobile devices are becoming another important research issue. Amant's model based evaluation of cell phone menu interaction [78, 79] is one of the noticeable approach for menu interaction. Other researches are also handling usability issues in the hand-held interaction [5, 80]. However, the evaluation of the motion based interaction of hand-held device is in the beginning research area [61].

The main purpose of this study was to assess the feasibility of virtual reality with relatively small screens (as in the hand-held devices) by taking advantage of motion based interaction. The basic approach was to have the subjects navigate through a given virtual environment (Experiment I) and search and select objects (Experiment II) using VR platforms differing in their screen sizes and software (geometric) FOVs (SFOV). The software FOV (SFOV) differs from the actual physical FOV (PFOV) in that it refers to the angle encompassing a given scene in its original scale (See Figure 4.2). For instance, 100% SFOV coincides with that of the PFOV, and 200% SFOV would allow one to see twice as much angular-wise (or the scene is reduced by half angular-wise).



Platform Characteristics Test Groups	Screen Size: width x height	Viewing Distance / Physical FOV	Software FOV
Hand-held / Motion based	10cm x 7.5cm	37.97cm* / 15°	30° (200%)
Hand-held / Button based	10cm x 7.5cm	37.97cm* / 15°	30° (200%)
Small Screen / Keyboard & Mouse	10cm x 7.5cm	37.97cm / 15°	30° (200%)
Desktop Monitor / Keyboard & Mouse	34cm x 26cm (17 in. diag.)	63.44cm / 30°	45° (150%)
Large PDP / Keyboard & Mouse	68cm x 51cm (42 in. diag.)	58.88cm / 60°	60° (100%)

Table 4.1 Six test conditions in the experiment. Asterisks denote mean values (when experimenting with the hand-held devices as it was not feasible to tightly fix the viewing distances)

There were five conditions for the two experiments as shown in Table 4.1. The primary condition represents the motion based hand-held platform, and as comparison groups there were four others. The button-based hand-held platform represents the current form of the hand-held devices. To see the effects

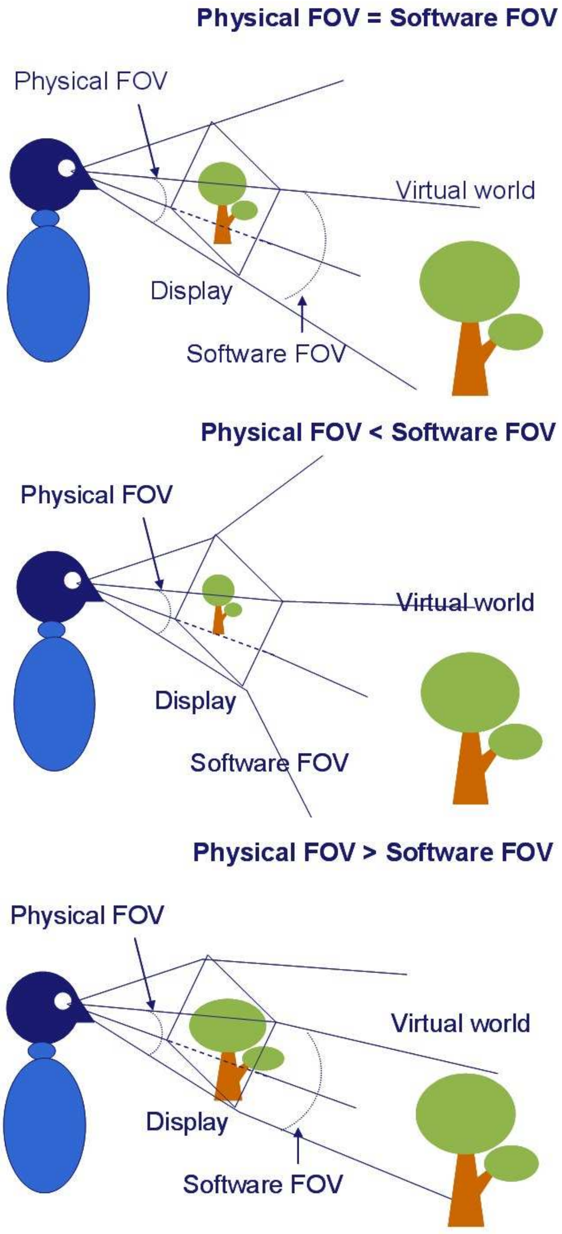


Fig. 4.2 Relations between physical FOV and software FOV.

of “hand grasping” (whether the mere hand grasping contributes to a possible immersion or sustained attention), a small (same as the hand-helds) screen platform condition was also added. The desktop monitor and large PDP display based platforms represent the nominal VR platforms with larger display sizes (larger PFOV and SFOV).

We performed two experiments. In Experiment I, the users were questioned for presence, system usability, enjoyment and perceived field of view after navigating through the virtual environment in the given platform (See Appendix B). In Experiment II, the task (navigating and selecting objects) completion time was measured.

4.2.1 Experimental Design and Procedure

A one factor within-subject experimental design was for both experiments. In both cases, the independent variable was the type of the VR platform. The major dependent variables for Experiment I were the level of presence/immersion, various usability, and perceived FOV, and for Experiment II, the task completion time. See Section 4.3 for their numerical derivation from the questionnaire answers. The subjects experienced each VR platform in an order specified by a balanced Latin-square design.

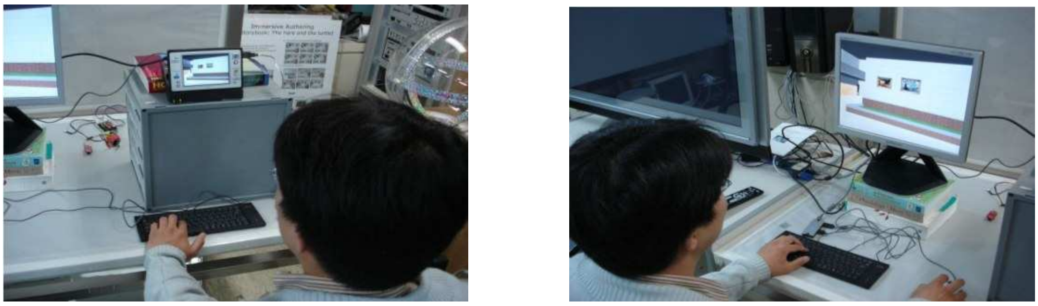
For each experiment, the subject was first briefed for the main purpose of the experiment and one’s vital information was collected such as age, gender, background, power of vision, color blindness, and experiences with 3D games or AR/VR systems. As the first experiment assessed presence and immersion, the respective subjects had to fill out an immersive tendency questionnaire which was adapted from the work by Witmer and Singer [81]. All subjects happened to fall in within the norm in terms of their immersive tendency (plus/minus twice the standard deviation) and thus, their data were all included in the final analysis. For a given VR platform, the subjects were given instructions as how to navigate or search and select the object. Few trials of training were given. For Experiment I, after completing the navigation task in the given VR platform, the subject was given a questionnaire to fill out about one's sense of immersion, presence, usability and perceived FOV. In Experiment II, the task completion time (search and select) was captured by the system automatically. While the experiments were designed as a one factor (i.e. VR platform) experiment, the results from the first two and last three test conditions (in Table 4.1) can be analyzed separately with respect to the factor of interface type and the sizes of the FOV respectively.

The overall experiment (for one subject) lasted about an hour. Figure 4.3 shows snapshots from the experiment. Twenty five subjects participated in each of the experiment. The subjects were engineering students (22 males and 3 females) with the average age of around 23, and paid for their services.

4.2.2 Experimental Tasks and Measurements

The experimental tasks carried out by the subjects in the two experiments were as follows. For Experiment I, at the start of the experiment, given a particular VR platform, the subject was situated in front of a virtual office building, and was asked to enter and navigate through the building for five minutes. The duration of five minutes was derived from a separate prior experiment to give a sufficient amount of time for the user to adapt oneself and establish one's spatial sense and orientation in the virtual environment [63]. Figure 4.4(a) shows the snapshot from the test environment for the navigation in Experiment I. Table 4.2 shows the presence/usability questionnaire used in Experiment I. The questionnaire was adapted from those of the standard usability surveys [82, 76], Witmer and Singer [81] (which indirectly assesses presence by asking questions about various contributing factors to presence) and Slater and Usoh [75] (which directly asks about one's feeling about immersion and presence). The questions were answered in the 7-Likert scale. The final "presence score" was computed as the averaged value of answers of questions that were

(a) Hand-held / Motion based (b) Hand-held / Button based



(c) Small Screen / Keyboard and Mouse (d) Desktop Monitor / Keyboard and Mouse

(e) Large PDP / Keyboard and Mouse

Fig. 4.3 The five VR platforms tested.

directly deemed related to presence. In Table 4.2, those questions are shown in bold face. This was more for the sake of simplicity, and an analysis with respect to answers to each individual question was surely possible.

As for assessing the perceived FOV, the questionnaire included a question of whether the display of the given VR platform provided sufficient FOV. In another assessment, the user was asked to mark on a pictorial snapshot of the virtual environment the extent to which one felt one could see through the display (See Figure 4.5). For Experiment II, the subjects were situated in another environment, filled with geometric objects (such as spheres, cubes, cones, and cylinders) in 3D space. The subjects were asked to navigate, search and select a particular type of geometric object as fast as they could (Figure 4.4(b)).

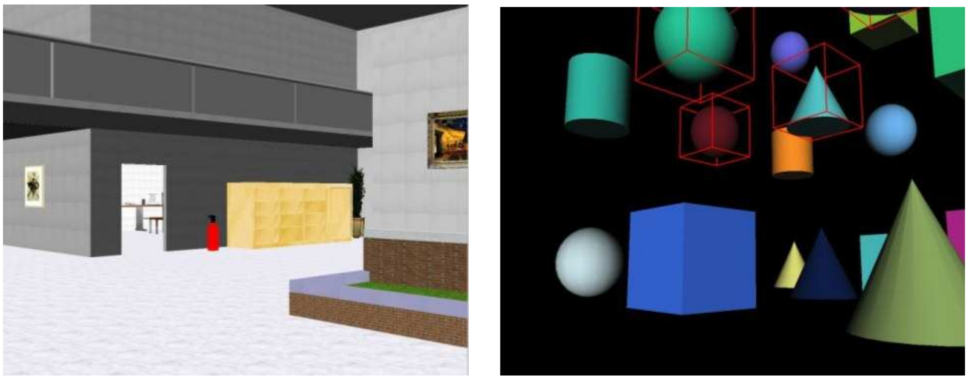

(a) (b)

Fig. 4.4 The two test virtual environments (a) Navigation environment used in Experiment I (b) Search and selection environment used in Experiment II

4.2.3 Experimental Setup (Interfaces)

As for the experimental set up, the different display sizes and SFOV used for each VR platforms are summarized in Table 4.1 and well illustrated in Figure 4.3. There were three types interfaces used for the various VR platforms for two tasks (navigation in Experiment I/II and selection in Experiment II). The three types of interfaces were (1) motion based (for the hand-held device), (2) button based (for the hand-held device) and (3) keyboard and mouse (for the rest). Table 4.3 summarizes the details of how they worked.

Fig. 4.5 Measuring the perceived FOV. The subjects were asked to mark along the horizontal and vertical lines the extent one felt one was able to see through the display.

4.3 Experiment Results

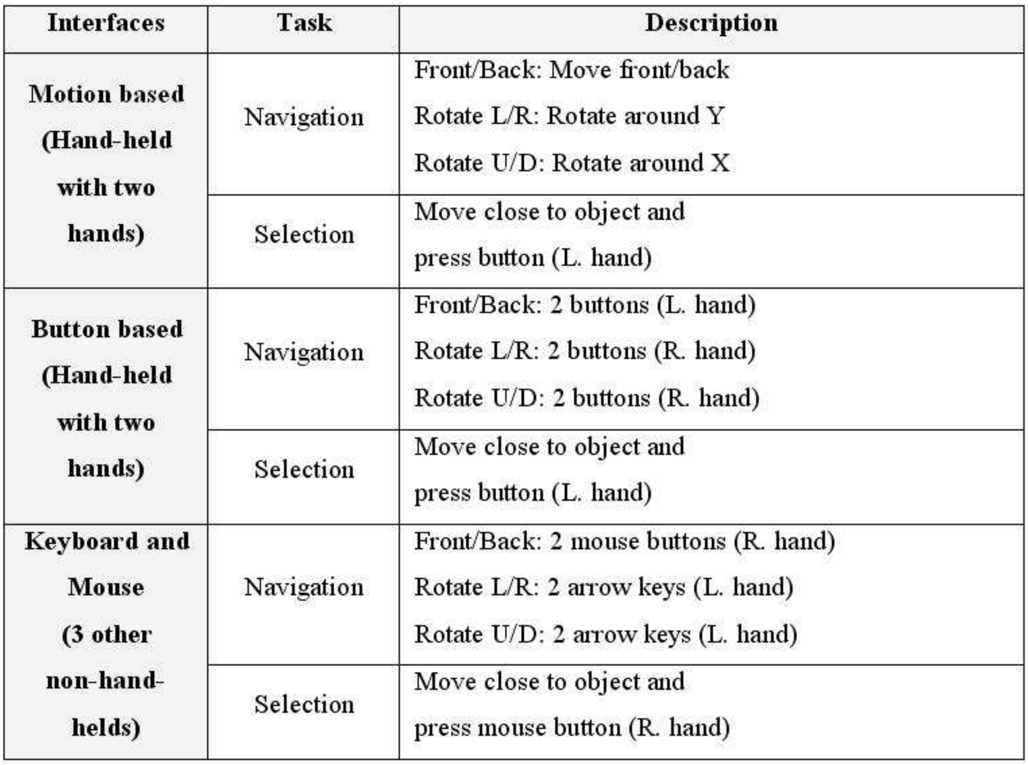
We used the ANOVA to verify the significance of conditions and the Student-Newman-Keuls test for grouping the test conditions with respect to the statistical results. We give a report to the major findings of our study with regards to the perceived FOV, presence, immersion, usability, task performance, enjoyment and cyber-sickness.

4.3.1 Perceived FOV and Presence (Collective)

There are many evidences that physical and software FOV has effects on the presence and immersion [83, 84]. But with hand-held device, due to the rela-

Category	Questions for each treatment
Visual	**How natural was the virtual environment?**
	How real was the virtual environment?
	Rate your depth perception.
	How large did you feel the "bird cage" was?
Auditory	**The sound effect helped me feel like I was in the environment.**
	Were you able to distinguish between different sounds?
	Were you able to tell where the sound was coming from?
Interface / Usability	The interface was easy to use.
	The interface was easy to learn.
	The interface was felt natural to use.
	The interface was intuitive.
Presence / Immersion	**Was the visual, auditory, and haptic stimulation felt consistent with one another?**
	How much disparate did you feel the virtual world was from the real?
	When carrying out the task did you think you were concentrated, focused or immersed?
	How much did you feel like looking at a real environment?
	How much were you involved in the environment?
	Did you feel like being in the environment?
Distraction	**How much were you distracted by the test environment?**
	Were you able to remember what environment objects were present?
Enjoyment	How much did you enjoy navigating through the environment?
Cyber-sickness	Did you feel sick navigating through the environment?
FOV	**Was the field of view sufficient for navigating through the environment?**

Table 4.2 Presence/Usability questionnaire



Interfaces	Task	Description
Motion based (Hand-held with two hands)	Navigation	Front/Back: Move front/back Rotate L/R: Rotate around Y Rotate U/D: Rotate around X
	Selection	Move close to object and press button (L. hand)
Button based (Hand-held with two hands)	Navigation	Front/Back: 2 buttons (L. hand) Rotate L/R: 2 buttons (R. hand) Rotate U/D: 2 buttons (R. hand)
	Selection	Move close to object and press button (L. hand)
Keyboard and Mouse (3 other non-hand-helds)	Navigation	Front/Back: 2 mouse buttons (R. hand) Rotate L/R: 2 arrow keys (L. hand) Rotate U/D: 2 arrow keys (L. hand)
	Selection	Move close to object and press mouse button (R. hand)

Table 4.3 The detailed description of the three interfaces used in the experiments

tively limited screen size, the SFOV is also limited. It is known that distortion in depth/size perception starts to occur with SFOV that is over twice that of the PFOV [64]. This limitation of FOV looks like impossible to overcome. But when we think about the human visual system, although the projected image onto the retina is limited in area and perceived in low resolutions outside of central parts, we still can perceive wider FOV with saccadic eye movements [85]. Inspired by this, we established the hypothesis that the perceived FOV could be widened with the motion based interaction. To verify this hypothesis, we assessed and measured the perceived FOV of the various VR platform conditions with the two methods as mentioned in Section 4.2.2, i.e. assessing the sufficiency of the FOV by score and marking on the pictorial snapshot of the virtual environment. Figure 4.6 shows the results for the case when subjects marked the extent of their perceived FOV, and it suggests that the perceived FOV is significantly widened compared to the Physical FOV ($F_{4,96} = 12.72, p < 0.0001$ in marking). The scoring method also produced a similar result with statistical significance ($F_{4,124} = 9.31, p < 0.0001$).

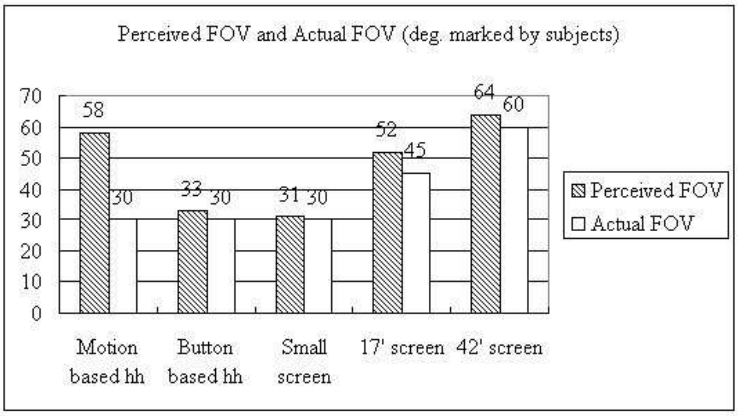


Fig. 4.6 Perceived FOV results

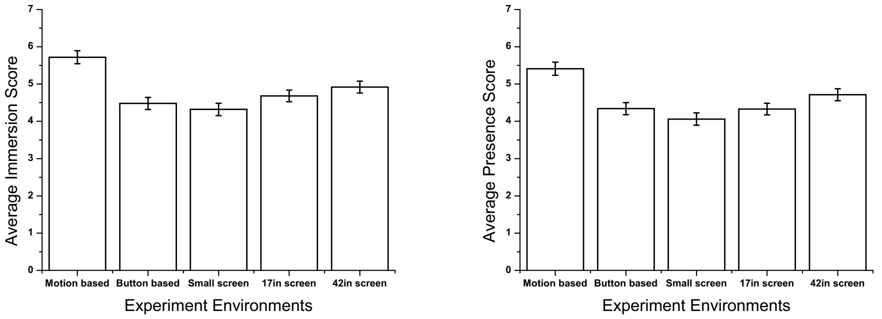
Also with Student-Newman-Keuls test, the perceived FOV in case of motion based interaction was grouped with desktop VR and large PDP which provided

	Motion based	Button based	Small screen	17in screen	42in screen
Mean	5.72	4.48	4.32	4.68	4.92
SD	1.061	1.122	1.314	1.180	1.222
SE	0.212	0.224	0.262	0.236	0.244

Table 4.4 The result of immersion score (Mean, standard deviation and standard error)

45° FOV and 60° FOV. This means the motion based interaction widened perceived FOV (for the small hand-held device) over 50% of the actual FOV. The result that this effect does not appear in other conditions (e.g. button based hand-held or small screen) and we can easily conclude that the motion based interaction was the factor in causing this phenomenon.

In addition to the support by the existing literatures [83, 84], the perceived FOV, in our study, also had a strong correlation with immersion and presence (Pearson correlation value was 0.301, $p = .001$ with immersion, correlation value was 0.475, $p < .0001$ with presence). Presence and immersion significantly improved with the motion based interaction (immersion: $F_{4,96} = 5.38, p = .0005$, presence: $F_{4,96} = 17.43, p < .0001$) (See Figure 4.7).



(a) The result of immersion score (b) The result of presence score

Fig. 4.7 Immersion and presence score

As already mentioned the presence score was computed by averaging the

	Motion based	Button based	Small screen	17in screen	42in screen
Mean	5.41	4.34	4.06	4.32	4.71
SD	0.876	0.807	0.828	0.779	0.794
SE	0.175	0.161	0.165	0.155	0.158

Table 4.5 The result of presence score (Mean, standard deviation and standard error)

answers to the presence-related questions with equal weights. This was done because there was no base for us to favor certain questions over others. Although not reported in detail here (for lack of space), the analysis with regards to the individual questions were consistent with the overall results.

4.3.2 Usability and Task Performance

We assessed the usability of the systems in four categories: ease of to use, ease of learning, naturalness, and intuitiveness (See Figure 4.8, 4.9). The motion based hand-held platform came out to be easier to use than all other interfaces ($F_{4,96} = 2.81, p = .028$). No particular results were found in terms of learnability probably because all interfaces were sufficiently simple and easy to understand. But in the motion based hand-held platform was superior in naturalness and intuitiveness (naturalness: $F_{4,96} = 7.99, p < 0001$, intuitiveness: $F_{4,96} = 24.25, p < .0001$) than the other four groups (which were grouped together as one by the SNK test).

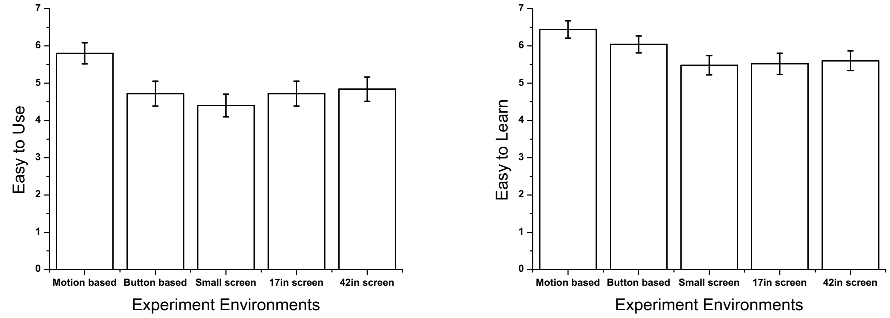
	Motion based	Button based	Small screen	17in screen	42in screen
Mean	5.8	4.72	4.4	4.72	4.84
SD	1.414	1.671	1.527	1.671	1.624
SE	0.282	0.334	0.305	0.334	0.324

Table 4.6 Easy to use (Mean, standard deviation and standard error)

Task completion time was the shortest (with statistical significance) with the motion based interaction platform, and with other interfaces the task performances were grouped as same. ($F_{4,68} = 8.88, p < .0001$) (Also see Figure 4.10).

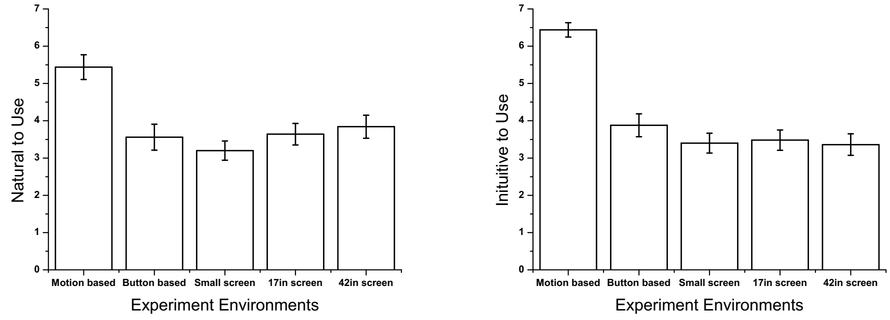
	Motion based	Button based	Small screen	17in screen	42in screen
Mean	6.44	6.04	5.48	5.52	5.6
SD	1.157	1.135	1.294	1.417	1.322
SE	0.231	0.227	0.258	0.283	0.264

Table 4.7 Easy to learn (Mean, standard deviation and standard error)



(a) The result of easy to use score (b) The result of easy to learn score

Fig. 4.8 Easy to use and easy to learn



(a) The result of naturalness score (b) The result of intuitiveness score

Fig. 4.9 Naturalness and intuitiveness

	Motion based	Button based	Small screen	17in screen	42in screen
Mean	5.44	3.56	3.2	3.64	3.84
SD	1.660	1.733	1.290	1.439	1.545
SE	0.332	0.346	0.258	0.287	0.309

Table 4.8 Naturalness (Mean, standard deviation and standard error)

	Motion based	Button based	Small screen	17in screen	42in screen
Mean	6.44	3.88	3.4	3.48	3.36
SD	0.960	1.536	1.322	1.357	1.439
SE	0.192	0.307	0.264	0.271	0.287

Table 4.9 Intuitiveness (Mean, standard deviation and standard error)

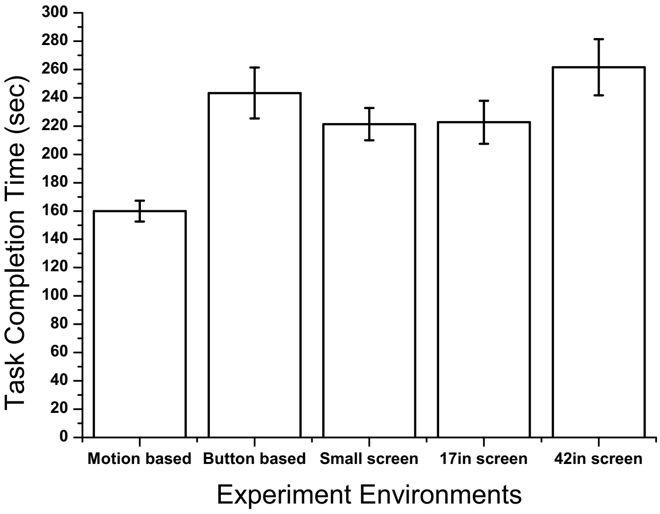


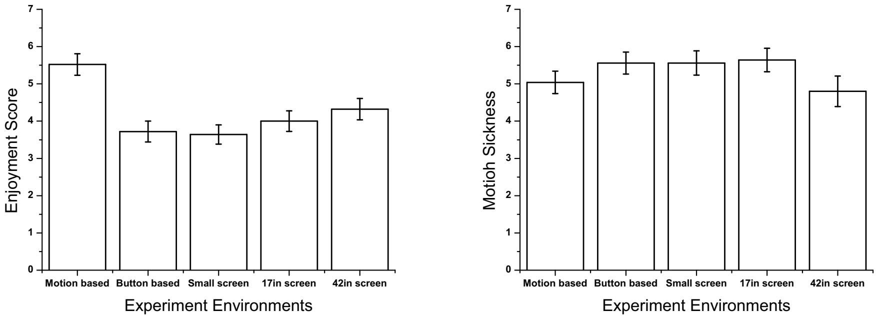
Fig. 4.10 Task completion time

	Motion based	Button based	Small screen	17in screen	42in screen
Mean	159.92	243.38	221.37	222.72	261.53
SD	31.379	76.222	48.560	64.384	84.044
SE	7.396	17.965	11.445	15.175	19.809

Table 4.10 Task completion time (Mean, standard deviation and standard error)

4.3.3 Enjoyment and Motion-sickness

Because entertainment is one of popular application areas for the hand-held platform, the enjoyment is another important goal for interface design of hand-held platforms. The level of enjoyment of motion based interaction platform was significantly better than the other four ($F4,96 = 7.58, p < .0001$). And the other 4 groups were not significantly different in their enjoyment level. (Figure 4.11).



(a) The result of enjoyment score (b) The result of motion sickness

Fig. 4.11 Enjoyment and motion sickness

	Motion based	Button based	Small screen	17in screen	42in screen
Mean	5.52	3.72	3.64	4	4.32
SD	1.446	1.4	1.287	1.384	1.435
SE	0.289	0.28	0.257	0.276	0.287

Table 4.11 Enjoyment (Mean, standard deviation and standard error)

	Motion based	Button based	Small screen	17in screen	42in screen
Mean	5.04	5.56	5.56	5.64	4.8
SD	1.513	1.474	1.635	1.577	2.041
SE	0.302	0.294	0.327	0.315	0.408

Table 4.12 Motion sickness (Mean, standard deviation and standard error)

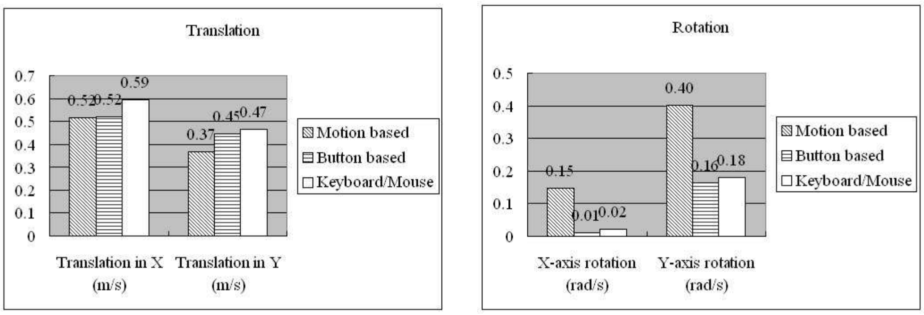
While one of our concerns was the possibility of an increase in motion-sickness with the motion based interface, no such results were observed in this experiment

4.4 Discussion

From the results in Section 4.3, it is clear that the two factors, i.e. "software FOV" and "interaction style," have affected the perceived FOV. In addition, if we compare the first three experiment groups (hand-held/motion-based, hand-held/button-based, small-screen/keyboard-mouse) which were set with the same sizes of software FOV, only the hand-held/motion-based exhibited the increase in the perceived FOV. The same results were obtained for the last two experiment groups, desktop-monitor/keyboard-mouse and large-PDP/keyboard-mouse, even though their relative software FOV was set to less than those of the first three experiment groups. Thus, simply manipulating the software FOV is not sufficient cause the increase in the perceived FOV, but rather the motion based interaction is more likely to do so.

To investigate further, we took a closer look at the pattern of the user's motion. Figure 4.12 shows the patterns of the user's motion for the three interaction styles, i.e. motion based, button based and keyboard-mouse based. The motion data were obtained and recorded (10 minutes) during the Experiment I (navigation). The top two graphs show the amounts of translational and rotational movements within the test virtual environment as invoked through the respective interfaces. The graphs show no significant differences in terms of translational motion, but a marked difference in the amounts of rotation of up to 0.4 rad/sec horizontally. The lower graphs essentially show the frequencies of the rotational motion and rotational direction change. For example, the probability of rotation represents the percentage of frames over all frames in which certain amounts of rotation had occurred. This shows that the user, when using a motion based interface, made many self-centered rotational movements, e.g.

left and right and up and down, in exploring and navigating the virtual environment. The user is much less likely to do the same using buttons, keyboard, or a mouse. The resulting pattern of motion resembles the saccadic eye movement which allows humans to perceive a wide field of view despite the very narrow (∼ 12 degrees) field of view offered by the eye ball [85]. There is also the same proprioceptive sense that is involved in both the saccadic eye movement and motion based navigation, the ocular muscles for the former, and the hand/arm movement for the latter. Note that the translation of the view point would not cause the similar phenomenon because a field of view is given respect to a fixed view point.



(a) The amount of translation (b) The amount of rotation

Fig. 4.12 Results from the motion data analysis

A comparison to the case of using head mounted displays (HMD) may be of interest as well. Even though most low cost HMD's only offer very narrow static fields of view, an immersive feeling is still possible by the head motion tracking and view dependent display. However, in general, the head motion is used for conscious view control rather than for changes in navigational direction (gaze directed travel is not considered very usable in most cases [76]). It is plausible that the perceived field of view of an HMD can be increased, by the same principle stated here, if the head motion (for view control) and navigational control (by other means) can be coupled. However, the natural coupling of view control and navigation is a unique characteristic of a hand-held interaction described in this paper. With an HMD configuration, the coupling of two tasks would be more difficult. We have not come across any study on this matter up to this point.

CHAPTER 5

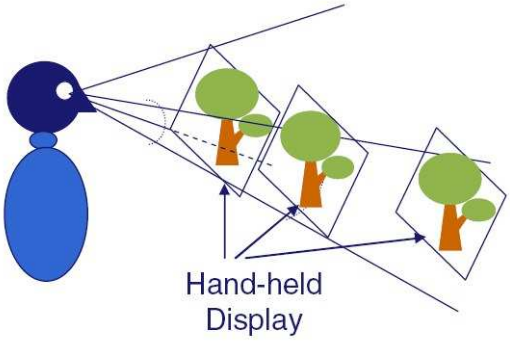
Visual Adjustment in Hand-held VR

5.1 Manipulating Visual Area

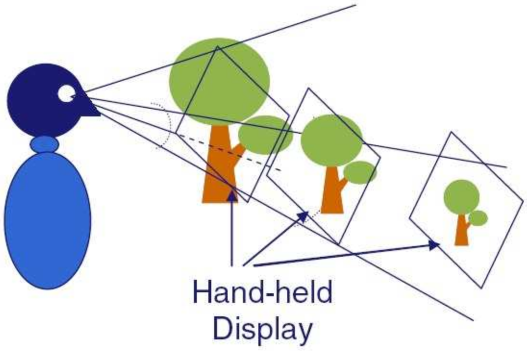
5.1.1 Dynamic FOV Adjustment for Hand-held Display

As already described, the narrow FOV and small size of the hand-held display (without any other provision) can cause lowered immersion in the hand-held VR. In addition, we claim that the fixed FOV despite changing viewing distance is also unnatural and can bring about similar effects (See Figure 5.1(a)).

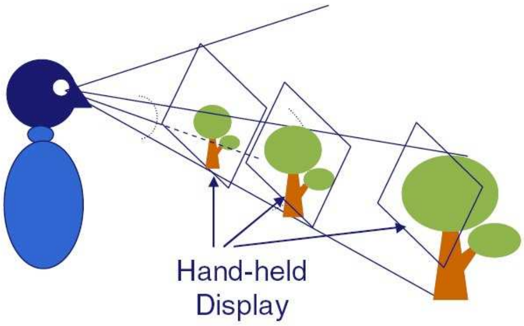
Therefore, to alleviate this problem, we suggest two different software FOV manipulation techniques using an approximate measurement of the eye (or head) position relative to the hand-held device. We attached and interfaced the SRF10 ultrasonic range finder to the hand-held device, and it can detect obstacles in the range of 3 cm to 6 m from the hand-held device screen. The first proposed FOV technique is to adjust the visual FOV to mimic the behavior of a magnifying glass (see Figure 5.1(b) and Figure 5.2). The FOV becomes narrower as the view distance is reduced. This method is useful for the applica-



(a) Nominal Hand-held VR

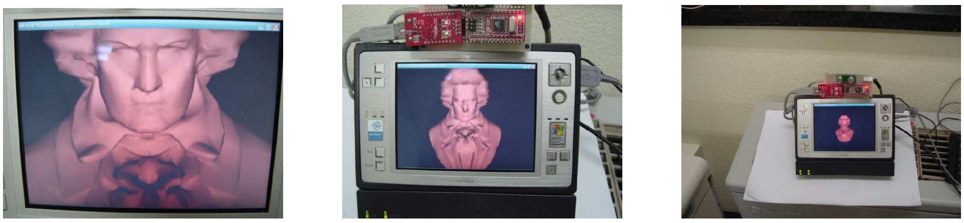


(b) Hand-held VR as a magnifying glass



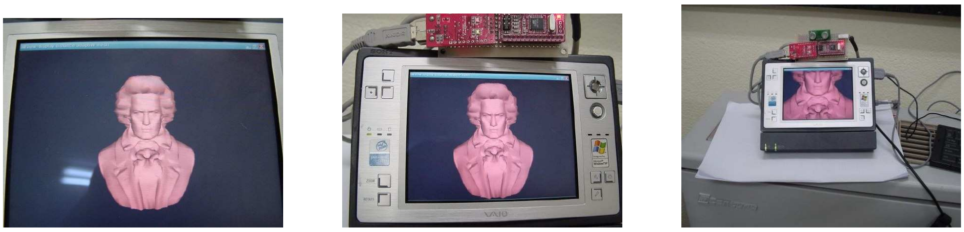
(c) Hand-held VR as a see-through window into VE

Fig. 5.1 Considering eye-display distance in hand-held VR



(a) Close (15 cm) (b) Medium range (30 cm) (c) Far (60 cm)

Fig. 5.2 Hand-held VR as a magnifying glass; the size of the virtual object looks bigger when the hand-held display is close to the eyes



(a) Close (15 cm) (b) Medium range (30 cm) (c) Far (60 cm)

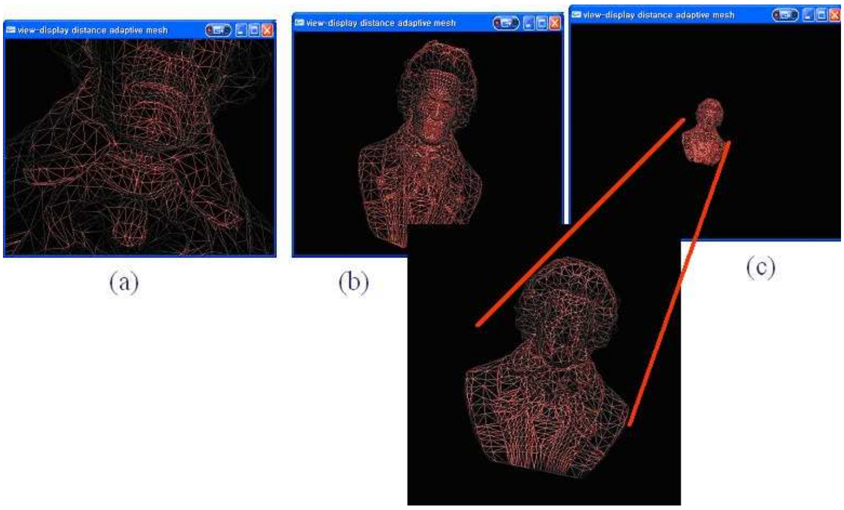
Fig. 5.3 Hand-held VR as a see-through window; the size of the virtual object looks same because we adjusted the software FOV using the eye-display distance tions in which the detailed views of the object are important but size perception is not. The second proposed FOV technique is to use the hand-held device in an opposite way, as a see-through window into the virtual environment (see Figure 5.1(c) and Figure 5.3). As the head gets closer to the screen (or window), there are more parts of the virtual environment visible, thus the FOV widens (and objects are drawn smaller). As you can see in Figure 5.3, the size of the virtual object “perceived to the user” is kept the same regardless to the eye-display distance. This approach is better suited for applications in which size or spatial perception is important such as medical training VR systems

5.1.2 Adjusting Display Decline

Some hand-held VR applications which has rolling motion of hand-held device itself makes the the visual decline happens. In this case, adjusting the declined image is necessary(See Figure6.3). The adjusting can be done using tilt sensing using acceleration sensor.

5.2 Model Simplification Depending User Distance

Hand-held devices are still not as powerful in terms of their graphic capabilities compared to the desktop environments that most users are accustomed with. View dependent simplification can be applied along with the varying the FOV to enhance the perceived quality of the target model and the system performance at the same time. In the case of a magnifying glass hand-held VR, as the view distance becomes larger and the FOV widens (objects smaller), the mesh can be simplified because the user’s detail perception will be trivial (See Figure5.4). In the case of the see-through hand-held VR, the opposite rule is applied. This technique can provide more visual detail and realism given the same amount of system resource. Such a system optimization is important for a reduced platform such as hand-held devices. We used GLOD(Geometric Level of Detail) Toolkit for mesh simplification [86].



(a) (b) (c)

Fig. 5.4 Simplifying the mesh with the changing eye-display distance. The case of hand-held VR as a magnifying glass: (a) close (15 cm), (b) medium range (30cm), (c) far range (60cm)

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CHAPTER 6

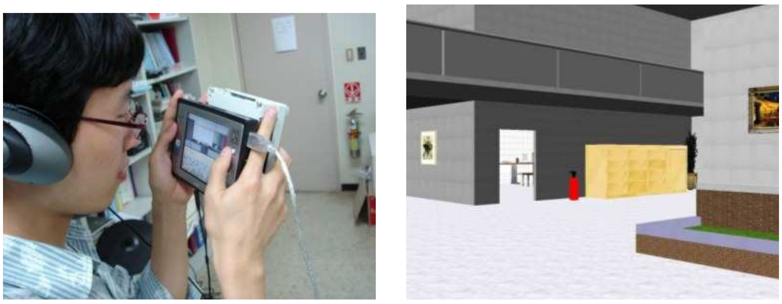
Applications of Hand-held VR

In the Chapter 3, we described the particular hardware and software design of a hand-held VR conforming to the proposed minimal requirements. In this section, we showcase three different applications of the hand-held VR platform and demonstrate its difference from the usual multimedia contents on hand-held devices. The suggested hand-held VR platform can be used in the various applications.

Among various candidates, we chose three major applications. The first one is virtual environment walk-through because it is most basic application in the VR. The walk-through application can be used as various evaluation testbed. The second one is the hand-held game. As mentioned in Chapter4, the enjoyment level is high when we used VR features such as motion based interaction. Moreover, the hand-held platform itself is useful as game platform. Therefore, we selected game application area and especially racing game. Current hand-held applications are mostly 2D based applications. Therefore, it is valuable the suggested hand-held platform is useful in the current 2D applications. So we applied our platform to the most popular hand-held application, multimedia contents browsing and manipulation. Not associated with our expectation, the feature of the hand-held VR platform such as motion-based interaction was not useful in this 2D application.

6.1 Virtual Environment Walk-Through

The most typical and natural application of virtual reality is the walk-through applications6.1. A VR walk-through application is to be different from simple, e.g. button-based, navigation in that it must be more experiential and realistic by employing such an interaction style. Table 6.1 shows the motion-based interaction that uses the motion of the device (or user's hand) to control navigation. The metaphoric use of the body is very natural and easy to learn for the users.



(a) Motion based interaction with hand-held device

(b) The virtual office

Fig. 6.1 A user navigating through a virtual office using the motion based interface. The motion based interface is realized by the hybrid relative device motion tracking

In fact, as briefly mentioned in Chapter 4, we carried out an extensive usability experiment and found out that the motion based interface induced a wider perceived field of view and increased sense of presence compared to the nominal button based interface. We described the evaluation results in Chapter4. As the results, the hand-held VR feature such as motion-based interaction was

Hand-held motion	Motion in the virtual environment
Roll	Slant head
Pitch	Look up/down
Yaw	Turn head left/right
Forward/Backward	Walk forward/backward
Button clicks	Selection

Table 6.1 Interaction method for navigation and selection in VE

usable, preferred, enjoyable and enhanced presence, immersion. Moreover, the suggested interaction method gave advantages in perceived field of view when it was used in the virtual walk-through application.

6.2 Hand-held Games

Games are another popular applications on hand-held devices as exemplified by the hand-held consoles and PDA/cellphone games. Furthermore, the motion-based games such as Nintendo's Wii™ or Samsung's Beat-box phones (Samsung SPH-S4000, SPH-S310) are gaining momentum. Our study also indicated a distinctively high level of enjoyment when a motion based interface was used. Our third application is a car racing game and Table 6.2 shows the mapping between the device motions to the various driving commands.

Hand-held motion	Driving commands
Roll right	Right-handed rotation
Roll left	Left-handed rotation
Pitch up	Brake
Pitch down	Acceleration (Throttle open)

Table 6.2 Mappings from the device motion to the driving commands

Shown in Figure 6.2 is the overall system architecture of the motion based racing game, consisted of three parts, the manipulator, the simulator and the

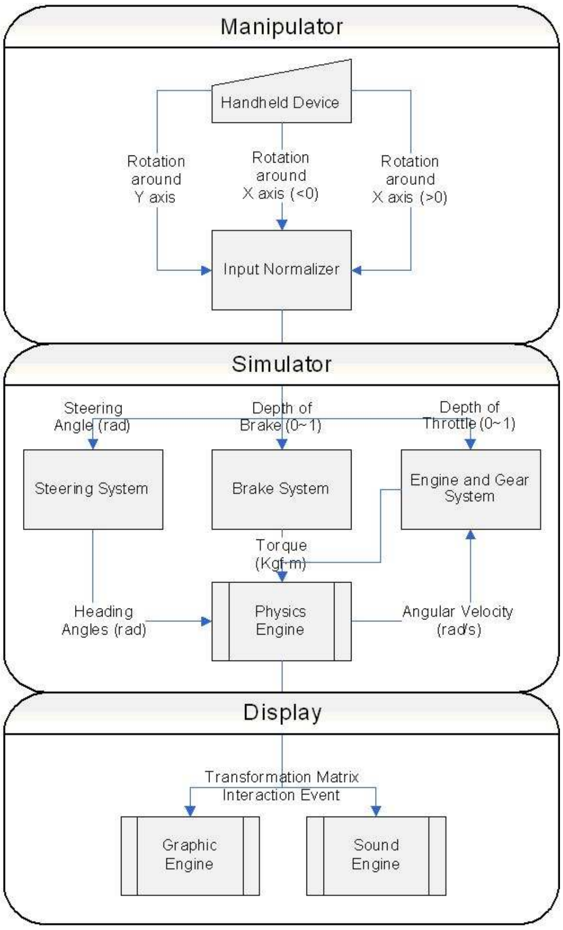


Fig. 6.2 System architecture of hand-held racing game

multimodal display. The manipulator converts inputs from hand-held device to a usable form in the driving simulator. Then, driving simulator applies the input to the brake system, steering system and engine/gear system. The simulated results are displayed to the user through three modalities. Figure 6.3 shows the steering interface.

(a) Right steering (b) Left Steering

Fig. 6.3 Using the hand-held device as a steering handle prop. Note that the orientation of the scene stays the same as the device is rotated

When using the hand-held motion as control command to the game, the mismatches between the virtual camera and actual user view direction occurs and results in the cybersickness and difficulties in the control. To adjust these mismatches, we used the roll motion of the hand-held device and changed the virtual camera as watching through the hand-held display. That is, the hand-held device acts as a steering handle prop, thus the orientation of the scene stays the same while the device rotates to the left or right for steering control (See Figure 6.3).

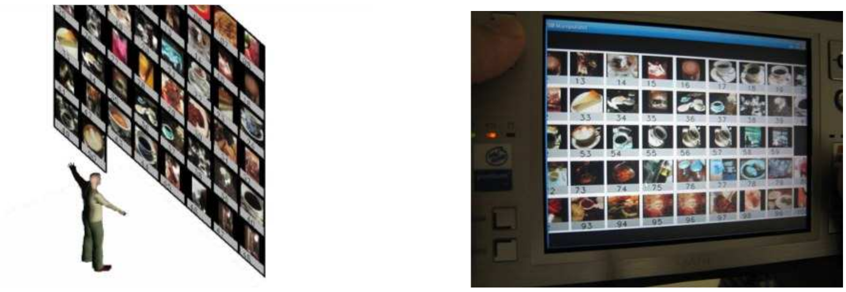
Hand-held motion	Motion for multimedia contents browsing and manipulation
Pitch up/down	Move camera up/down
Yaw left/right	Move camera left/right
Forward/Backward	Zoom in/out
Button clicks	Commands such as selection/cut/copy/paste/delete

Table 6.3 Interaction method for multimedia contents manipulation

6.3 Multimedia Contents Browsing and Manipulation

Hand-held devices, equipped with a camera, movie and music player, satellite TV receiver and memory cards, often holds an enormous amounts of multimedia data. This in turn makes the browsing and manipulation of the contents more difficult and time consuming. The limited screen sizes and unnatural interfaces also present difficulties for the associated multimedia tasks. Several proposals have been made to tackle this particular problem. Our proposal is to use 3D visualization and use a motion based interface. For example, we used two axis tilt (yaw and pitch) and forward/backward movements to browse contents. Table 6.3 lists the complete mapping between hand-held movements and multimedia contents manipulation command and movements. The mapping is similar to the interaction method in the walk-through application.

As for the display, we came up with three types of layouts for browsing and manipulation of the multimedia objects. There are researches related to display design and usability for mobile applications such as this [87], and likewise, we are still assessing the usability among the three. Our three layouts are planar, cylindrical, and fish-eye. The planar layout is generally used in the current hand-held devices (See Figure 6.4, a-1, a-2). The cylindrical layout is user-centered and the distances to the multimedia data is mostly the same (a spherical layout would be ideal in that sense, but spherical layout display results in distortion) (See Figure 6.4, b-1, b-2). The fisheye layout is gives emphasis to the content in the center. In the fisheye layout, the contents are laid

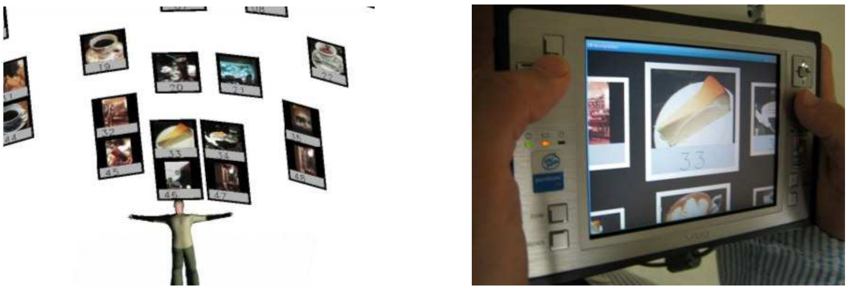


(a-1) Illustration of the planar layout of multimedia contents

(a-2) Snapshot of the planar layout

(b-1) Illustration of the cylindrical layout of multimedia contents

(b-2) Snapshot of the cylindrical layout



(c-1) Illustration of the fish eye layout of multimedia contents

(c-2) Snapshot of the fisheye layout

Fig. 6.4 Multimedia contents layouts in the hand-held VR in a cylindrical fashion and the object (in the middle), that the user is watching, moves towards to the user. (See Figure 6.4, c-1, c-2)

We performed experiment that evaluates which combination is best in usability, preference and task performance. The default setup (button interface + planar layout) was most preferred, usable and the task performance was also outstanding. We believe that the result shows the effect of the daily using interface. And the suggested motion interaction method was not adequate with 2D applications which does not needs multi-degree of freedom motion.

CHAPTER 7

Conclusions and Future Work

7.1 Conclusions

In this thesis, we have argued for and proposed requirements for hand-held VR platform for it to produce a minimum level of immersive and sensory experience. An actual hardware and software implementation, according to the proposed requirements, was carried out and tested on three different hand-held VR applications. We believe that such a platform offers an experience and enjoyment differentiated from the mere button-based nominal hand-held media devices. Some of the claims have been validated through our own usability study of the motion based interaction of hand-held VR. The results of the usability study have shown that the motion based interaction, a unique characteristic of hand-held platforms, can help improve the perceived FOV and presence/immersion up to a level comparable to the nominal VR platforms. The motion based interface also has shown promising results in terms of task performance leveraging on humans sense of proprioception. In the process of the study, a camera/accelerator based relative tracking technique has been developed to realize the motion based interaction on the hand-held device. From the user's motion analysis, we can explain that the motion based navigation causes the widely perceived FOV by the same principle of how human saccadic eye movement produces the same effect. This similarity was particularly effective because of the relatively small visual display. Also subjects experienced more enjoyment with motion based interaction without significant cyber-sickness.

With these results alone, it is plausible to conclude that hand-held VR is a distinct possibility and has good potential to provide sufficient immersion and presence (comparable to nominal VR systems) with other added factors such as multimodality (e.g. voice, tactile/haptic feedback, stereo display, etc), and environment binding/interaction (e.g. playing motion based golf on a grass field). Our motion based interaction technique works reasonably well in static environment, but not so in a dynamic (e.g. in fast moving car with the camera faced outside) or plain (no corner features) environments, due to the nature of the approach. And the zooming factor is only approximate to that of the real world scale.

We also believe the proposed system configuration is general enough to be applied to many application areas such as education, games, and mixed reality.

7.2 Future Work

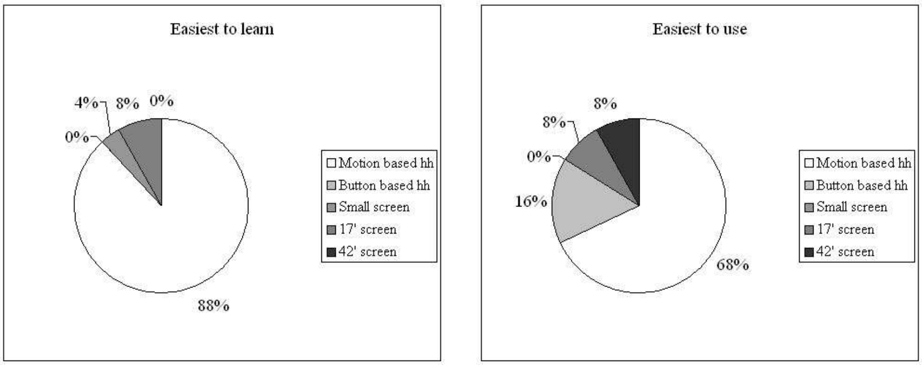
We are continuing to formally validate that user felt immersion or presence is possible with our proposed hand-held VR platform at a level comparable to desktop or even large scale VR systems. We are also improving both the hardware and software for various sensing and display, e.g. for creating illusory directional force feedback with multiple vibrators, view dependent display and resource optimization, environment sensing and mixed reality, and other types of multimodal interaction for hand-held VR.

We are continuing to improve the algorithm and would like to investigate how the inexact match between the amounts of movement between the real and virtual world affects the user perception. Moreover we are developing other multimodal displays for hand-held VR such as viewing-distance dependent display rendering and multiple vibro-tactile displays. Further validation is needed through exploration of various hand-held VR applications.

APPENDIX A

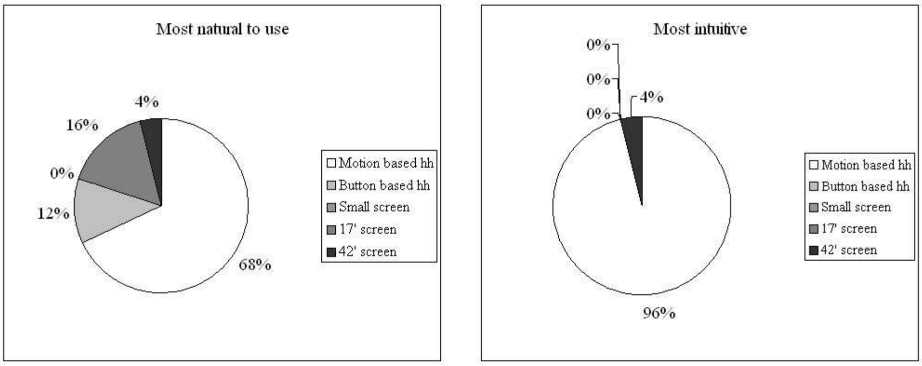
Additional Experiment Results

A.1 Ranked Data of Motion based Interaction



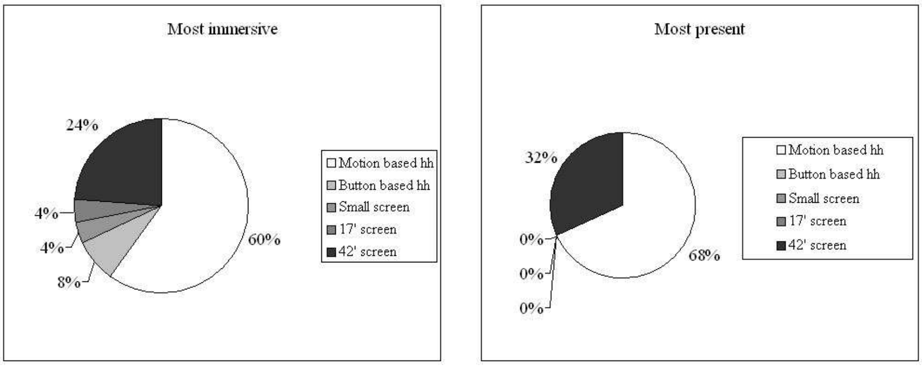
(a) Ranked data of easy to learn (b) Ranked data of easy to use

Fig. A.1 Rank of easy to learn and use



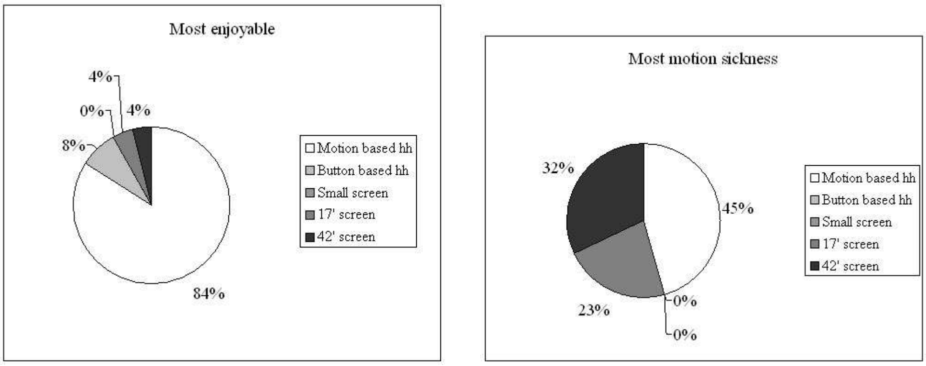
(a) Ranked data of naturalness (b) Ranked data of intuitiveness

Fig. A.2 Rank of naturalness and intuitiveness of the interaction method



(a) Ranked data of immersion (b) Ranked data of presence

Fig. A.3 Rank of immersion and presence



(a) Ranked data of enjoyment (b) Ranked data of motion sickness

Fig. A.4 Rank of enjoyment and motion sickness

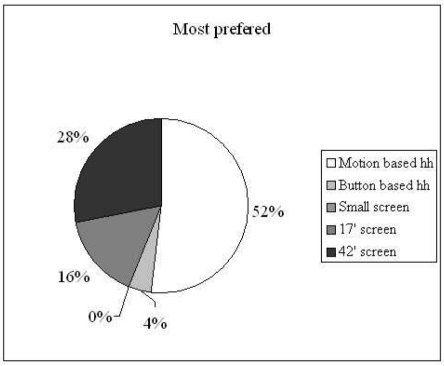
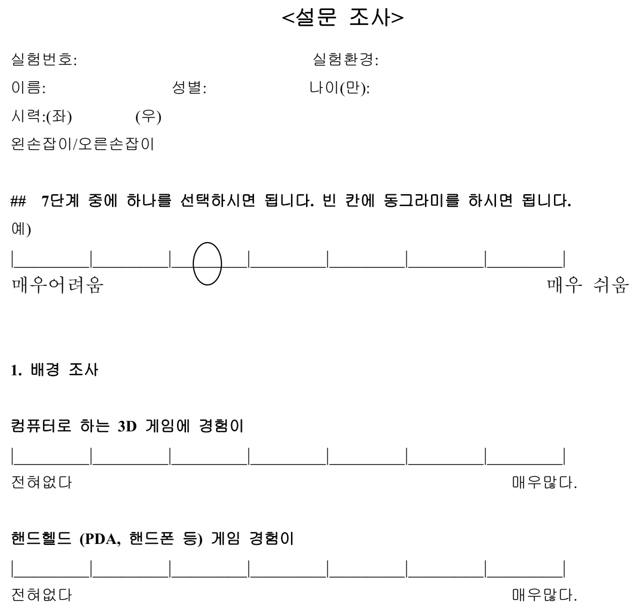


Fig. A.5 Rank of preference

APPENDIX B

Original Korean Questionnaires



<설문 조사>

실험번호: 실험환경:

이름: 성별: 나이(만):

시력:(좌) (우)

왼손잡이/오른손잡이

7단계 중에 하나를 선택하시면 됩니다. 빈 칸에 동그라미를 하시면 됩니다.

예)

|________|________|________|________|________|________|________|

매우어려움 매우 쉬움

1. 배경 조사

컴퓨터로 하는 3D 게임에 경험이

|________|________|________|________|________|________|________|

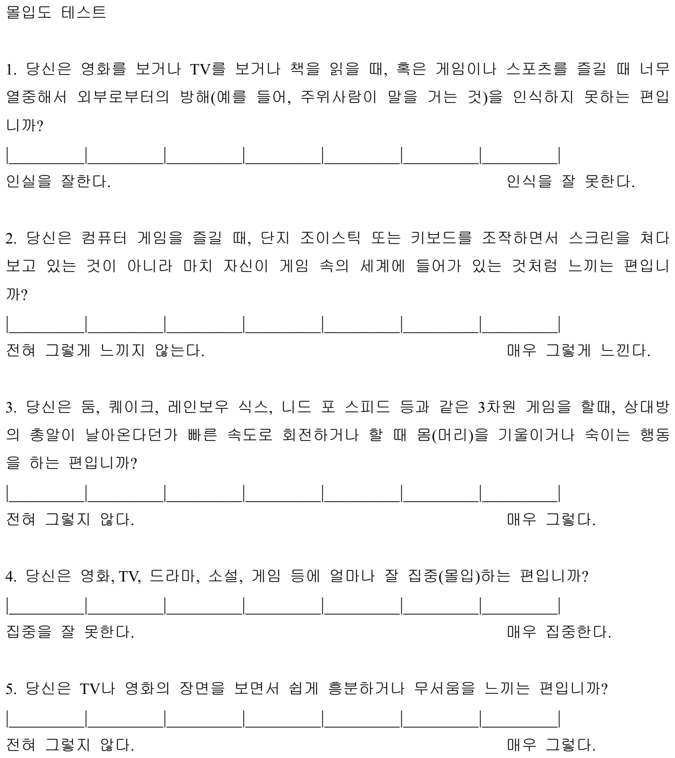
전혀없다 매우많다.

핸드헬드 (PDA, 핸드폰 등) 게임 경험이

|________|________|________|________|________|________|________|

전혀없다 매우많다.

Fig. B.1 The initial questionnaire



몰입도 테스트

1. 당신은 영화를 보거나 TV를 보거나 책을 읽을 때, 혹은 게임이나 스포츠를 즐길 때 너무 열중해서 외부로부터의 방해(예를 들어, 주위사람이 말을 거는 것)을 인식하지 못하는 편입니까?

|_________|_________|_________|_________|_________|_________|_________|

인실을 잘한다.   인식을 잘 못한다.

2. 당신은 컴퓨터 게임을 즐길 때, 단지 조이스틱 또는 키보드를 조작하면서 스크린을 쳐다보고 있는 것이 아니라 마치 자신이 게임 속의 세계에 들어가 있는 것처럼 느끼는 편입니까?

|_________|_________|_________|_________|_________|_________|_________|

전혀 그렇게 느끼지 않는다.   매우 그렇게 느낀다.

3. 당신은 둠, 퀘이크, 레인보우 식스, 니드 포 스피드 등과 같은 3차원 게임을 할때, 상대방의 총알이 날아온다던가 빠른 속도로 회전하거나 할 때 몸(머리)을 기울이거나 숙이는 행동을 하는 편입니까?

|_________|_________|_________|_________|_________|_________|_________|

전혀 그렇지 않다.   매우 그렇다.

4. 당신은 영화, TV, 드라마, 소설, 게임 등에 얼마나 잘 집중(몰입)하는 편입니까?

|_________|_________|_________|_________|_________|_________|_________|

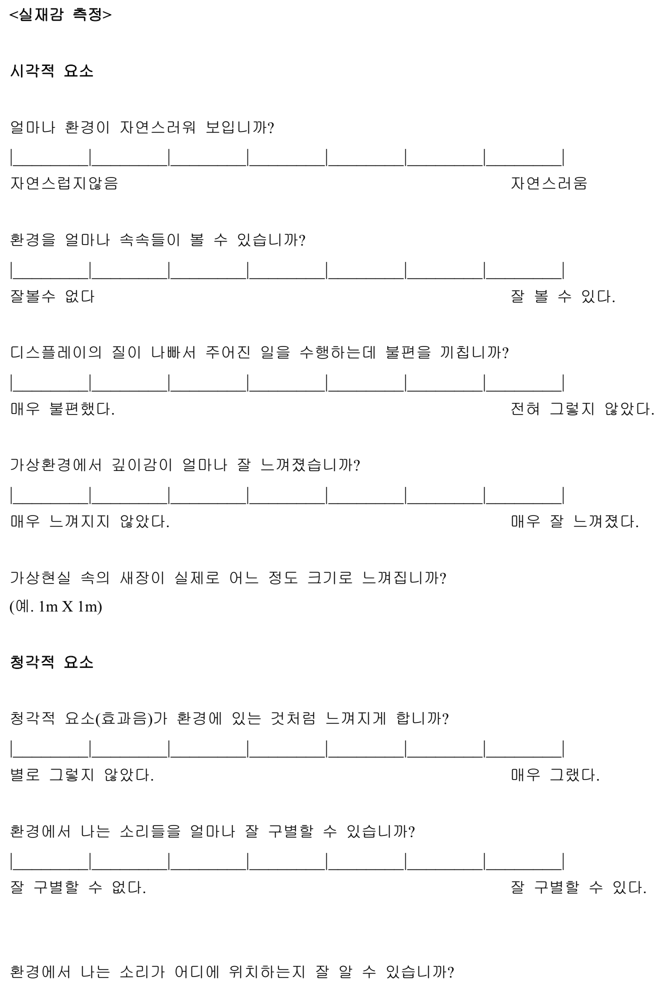
집중을 잘 못한다.   매우 집중한다.

5. 당신은 TV나 영화의 장면을 보면서 쉽게 흥분하거나 무서움을 느끼는 편입니까?

|_________|_________|_________|_________|_________|_________|_________|

전혀 그렇지 않다.   매우 그렇다.

Fig. B.2 The immersion tendency test



<실재감 측정>

시각적 요소

얼마나 환경이 자연스러워 보입니까?
|_________|_________|_________|_________|_________|_________|_________|
자연스럽지않음 자연스러움

환경을 얼마나 속속들이 볼 수 있습니까?
|_________|_________|_________|_________|_________|_________|_________|
잘볼수 없다 잘 볼 수 있다.

디스플레이의 질이 나빠서 주어진 일을 수행하는데 불편을 끼칩니까?
|_________|_________|_________|_________|_________|_________|_________|
매우 불편했다. 전혀 그렇지 않았다.

가상환경에서 깊이감이 얼마나 잘 느껴졌습니까?
|_________|_________|_________|_________|_________|_________|_________|
매우 느껴지지 않았다. 매우 잘 느껴졌다.

가상현실 속의 새장이 실제로 어느 정도 크기로 느껴집니까?
(예. 1m X 1m)

청각적 요소

청각적 요소(효과음)가 환경에 있는 것처럼 느껴지게 합니까?
|_________|_________|_________|_________|_________|_________|_________|
별로 그렇지 않았다. 매우 그랬다.

환경에서 나는 소리들을 얼마나 잘 구별할 수 있습니까?
|_________|_________|_________|_________|_________|_________|_________|
잘 구별할 수 없다. 잘 구별할 수 있다.

환경에서 나는 소리가 어디에 위치하는지 잘 알 수 있습니까?

Fig. B.3 The questionnaire filled out after each trial

|_________|_________|_________|_________|_________|_________|_________|

잘 알 수 없다.　　　　　　　　　　　　　　잘 알 수 있었다.

인터페이스

인터페이스가 사용하기가 얼마나 어렵습니까?

|_________|_________|_________|_________|_________|_________|_________|

매우 어렵다.　　　　　　　　　　　　　　하나도 어렵지 않다.

인터페이스 사용법 배우는 게 얼마나 어렵습니까?

|_________|_________|_________|_________|_________|_________|_________|

매우 어렵다.　　　　　　　　　　　　　　하나도 어렵지 않다.

인터페이스 사용하는 것이 얼마나 자연스럽습니까?

|_________|_________|_________|_________|_________|_________|_________|

자연스럽지 않다.　　　　　　　　　　　　　　자연스럽다.

인터페이스 사용하는 것이 얼마나 직관적입니까?

|_________|_________|_________|_________|_________|_________|_________|

직관적이지 않다.　　　　　　　　　　　　　　직관적이다.

전체적 실재감

가상환경의 시각, 청각, 촉각 정보가 서로 모순이 없이(consistent) 발생한다고 생각합니까?

|_________|_________|_________|_________|_________|_________|_________|

일치하지 않는다.　　　　　　　　　　　　　　일치한다.

가상환경과 실제 환경이 얼마나 서로 모순이 없다고 생각합니까?

|_________|_________|_________|_________|_________|_________|_________|

모순이 많다.　　　　　　　　　　　　　　모순이 없다.

가상환경에서 주어진 일을 수행할 때 얼마나 집중/몰두를 한다고 생각합니까?(immersion)

|_________|_________|_________|_________|_________|_________|_________|

집중을 하지 않는다.　　　　　　　　　　　　　　매우 집중한다.

Fig. B.4 The questionnaire filled out after each trial(continued)

가상 환경 속을 진짜로 바라보는 듯한 느낌이 어느 정도입니까?

|_________|_________|_________|_________|_________|_________|_________|

약했다. 강했다.

가상 환경에서의 경험에 실제로 참여하고 있는 느낌이 얼마나 듭니까? (involvement)

|_________|_________|_________|_________|_________|_________|_________|

안 들었다. 많이 들었다.

제시된 가상환경 안에 실제로 들어가 있었다고 생각이 되었습니까?

|_________|_________|_________|_________|_________|_________|_________|

전혀 그렇지 않았다. 매우 그랬다.

환경을 둘러보는 동안 당신이 실제로 빌딩 안에 있었다고 생각이 듭니까?

|_________|_________|_________|_________|_________|_________|_________|

전혀 그렇지 않았다. 매우 그랬다.

가상 환경이 실제 실험하고 있는 이 방과 얼마나 비슷한 느낌이 드십니까?

|_________|_________|_________|_________|_________|_________|_________|

안 비슷하다. 매우 흡사하다.

주의 흐림(distraction) 질문

가상환경에서 주어진 일을 하는 동안 주위의 실제 환경이 주의를 얼마나 흐리게 하는가? (distraction)

|_________|_________|_________|_________|_________|_________|_________|

주의를 흐리게 한다. 주의를 흐리게 안한다.

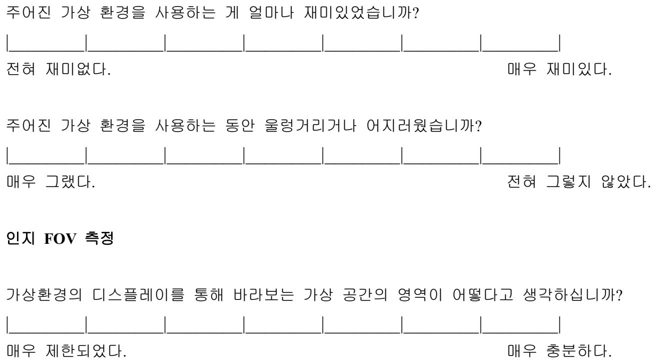
가상환경을 사용하는 동안 주위에 무엇이 있었는지 잘 인식 할 수 있었습니까?

|_________|_________|_________|_________|_________|_________|_________|

잘 인식할 수 있었다. 인식할 수 없었다.

기타 질문

Fig. B.5 The questionnaire filled out after each trial(continued)



주어진 가상 환경을 사용하는 게 얼마나 재미있었습니까?

|_________|_________|_________|_________|_________|_________|_________|

전혀 재미없다. 매우 재미있다.

주어진 가상 환경을 사용하는 동안 울렁거리거나 어지러웠습니까?

|_________|_________|_________|_________|_________|_________|_________|

매우 그랬다. 전혀 그렇지 않았다.

인지 FOV 측정

가상환경의 디스플레이를 통해 바라보는 가상 공간의 영역이 어떻다고 생각하십니까?

|_________|_________|_________|_________|_________|_________|_________|

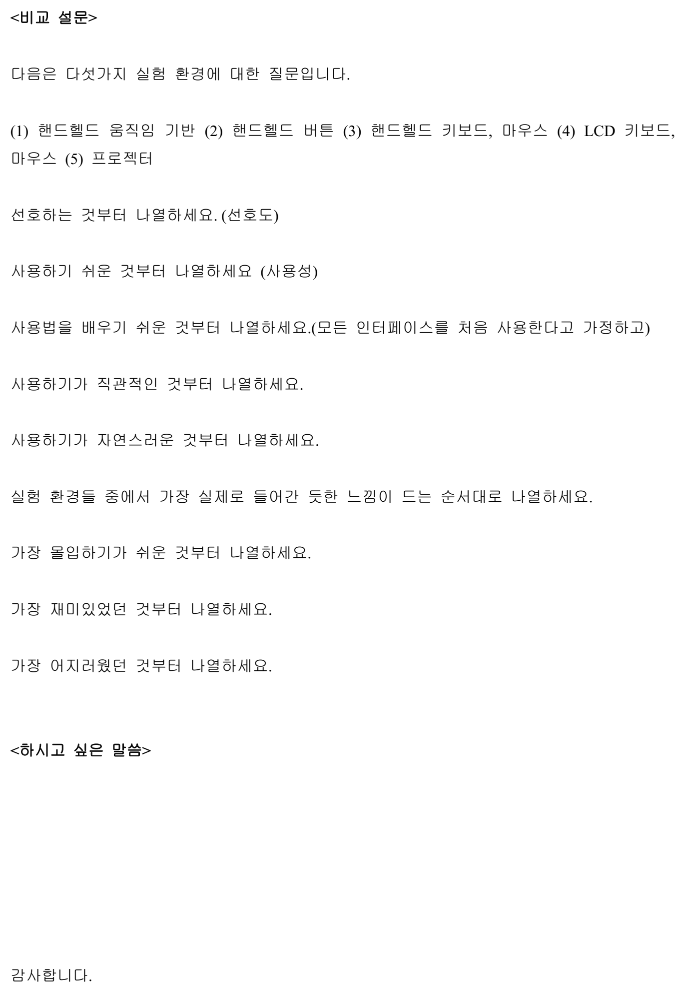
매우 제한되었다. 매우 충분하다.

Fig. B.6 The questionnaire filled out after each trial(continued)

가상환경의 디스플레이를 통해 바라볼 수 있는 영역이 그림에서 어느 정도라고 생각하십니까? (위아래에 표시)

(위까지의 설문을 각 환경에 대해서 조사한다. 그리고 나서 마지막으로 비교하는 설문을 한다.)

Fig. B.7 Perceived field of view measurement



<비교 설문>

다음은 다섯가지 실험 환경에 대한 질문입니다.

(1) 핸드헬드 움직임 기반 (2) 핸드헬드 버튼 (3) 핸드헬드 키보드, 마우스 (4) LCD 키보드, 마우스 (5) 프로젝터

선호하는 것부터 나열하세요. (선호도)

사용하기 쉬운 것부터 나열하세요 (사용성)

사용법을 배우기 쉬운 것부터 나열하세요.(모든 인터페이스를 처음 사용한다고 가정하고)

사용하기가 직관적인 것부터 나열하세요.

사용하기가 자연스러운 것부터 나열하세요.

실험 환경들 중에서 가장 실제로 들어간 듯한 느낌이 드는 순서대로 나열하세요.

가장 몰입하기가 쉬운 것부터 나열하세요.

가장 재미있었던 것부터 나열하세요.

가장 어지러웠던 것부터 나열하세요.

<하시고 싶은 말씀>

감사합니다.

Fig. B.8 Comparative questionnaire

APPENDIX C

Hand-held VR Platform Schematic

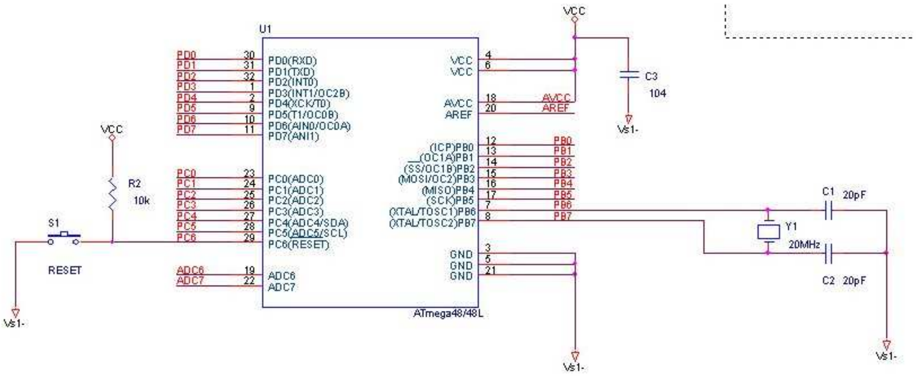


Fig. C.1 Microcontroller

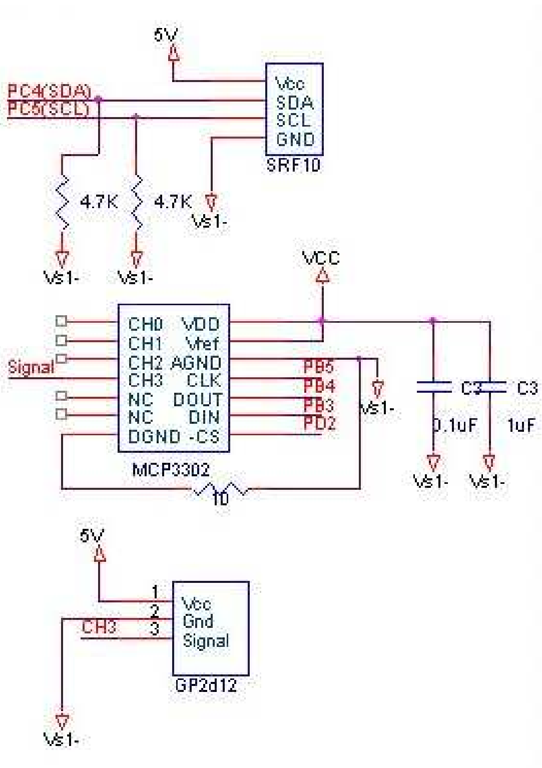


Fig. C.2 Distance Measurement Module (Infrared Sensor and Ultrasonic Sensor)

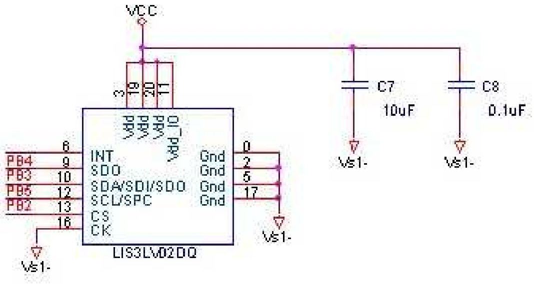


Fig. C.3 3 Axis Accelerometer

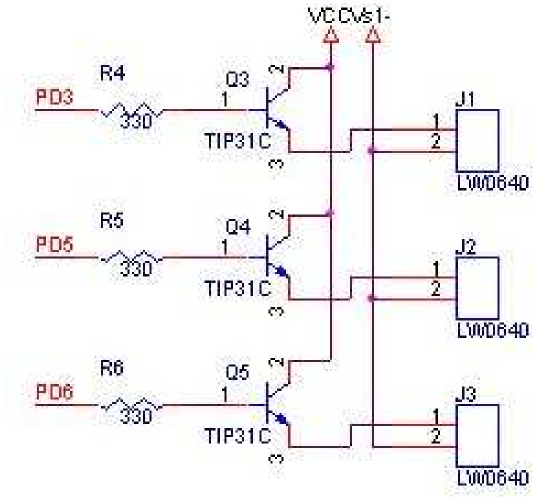


Fig. C.4 Multiple Vibrators

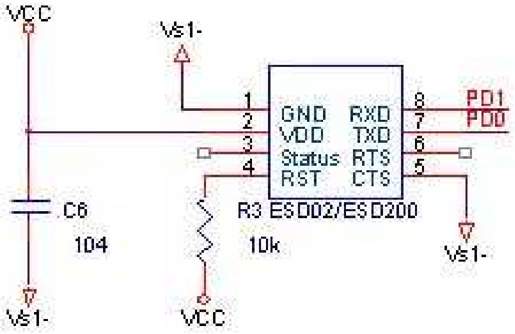


Fig. C.5 Bluetooth Communication Module

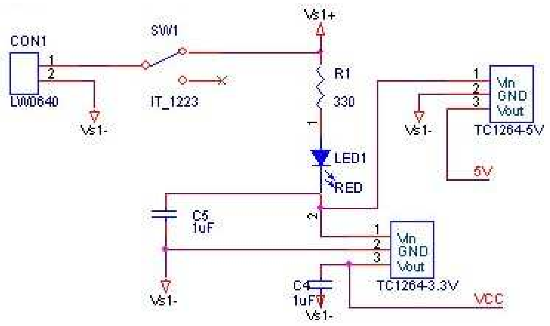


Fig. C.6 Power Supply Module

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요 약 문

핸드 헬드 가상 현실 시스템의 설계와 평가

근래에 들어 휴대폰, PDA, 휴대용 게임기 등의 핸드헬드 기기들의 성능이 향상되고 그에 따라 삼차원 그래픽스나 멀티미디어 데이터 처리 능력 또한 향상되어 여러 종류의 가상현실 응용물들이 현실화 되고 있다. 그러나 가상현실 시스템에서 핵심적인 요소라고 할 수 있는 실재감과 몰입감을 현재의 핸드헬드 기기를 통해서 제공할 수 있는지는 의문의 여지가 있다. 그래서 이 논문에서는 핸드헬드 기기를 통해서 실재감과 몰입감이 있는 가상현실을 제공하기 위한 요구사항들을 제시하고 그 요구사항들을 충족시킬 수 있는 저비용의 핸드헬드 가상현실 시스템을 실제로 설계하고 구현, 평가를 해 보인다. 이를 위해 핸드헬드 가상현실 시스템 구현을 위해 다양한 멀티모달 센서와 디스플레이를 핸드헬드에 장착하였다. 본 논문에서는 또한 구현된 핸드헬드 가상현실 시스템에서 3차원 인터랙션을 제공하기 위한 4 자유도의 핸드헬드 기기 추적방법을 제시하고 추적 결과를 사용한 동작 기반 인터랙션 방법도 제시한다. 그리고 구현된 시스템의 응용물로 세가지 가상현실 응용물을 제시한다. 이는 가상 현실 네비게이션, 핸드헬드 가상현실 게임, 3차원 멀티미디어 데이터 브라우저 이다.

논문에서 제시된 핸드헬드 가상현실 시스템이 작은 화면과 제한된 성능을 가지고 있음에도 불구하고 가상현실 플랫폼으로 충분한 실재감과 몰입감을 제공하는지를 알아보기 위한 평가를 수행하였다. 평가 결과에 의하면 기존의 방식인 버튼을 사용하는 방식에 비해서 유의하게 나아진 실재감과 몰입감을 제시하는 것으로

발견되었다. 또한 그 외에도 사용성과 선호도, 향유도(enjoyment) 등이 유의하게 나아진 것으로 밝혀졌다. 상대적으로 제시된 시스템을 사용시에 어지러움(motion sickness)은 증가하지 않는 것으로 나타나 제시된 시스템이 기존 시스템보다 가상현실 플랫폼으로의 가능성이 많은 것으로 나타났다. 또한 제시된 시스템의 인터랙션 방법인 동작 기반 인터랙션을 사용했을 시에 사용자가 인지하는 인지 시야각이 넓어 지는 것으로 나타나서 작은 화면의 단점을 극복하는데 도움이 되는 것으로 보여진다.

감사의글

저의 길었던 대학원 기간동안 연구와 제자에 대한 무한한 애정을 보여주신 김정현 교수님께 가장 크고 깊은 감사를 드립니다. 그리고 연구에 대한 많은 조언과 도움을 주셨던 최승문 교수님께도 감사를 드립니다. 바쁘신 중에도 시간을 내어 주시고 논문 심사를 해주신 이승용 교수님, 한성호 교수님 그리고 광주과학기술원의 우운택 교수님께도 깊은 감사를 드립니다. 인생과 학문의 큰 스승님의 모습을 보여주신 박찬모 총장님께도 감사를 드립니다.

대학원 생활동안 많은 선후배님들과 즐거운 시간을 가졌던 것 같습니다. 우선 졸업하신 남규선배, 상윤선배, 진석형께 고마운 마음을 드립니다. 연구나 인생에서 많은 조언과 도움을 받았습니다. 후배인 재훈, 성훈은 제가 졸업하는데 많은 도움을 주었습니다. 고맙습니다. 함께 고생한 그리고 고생하고 있는 성길에게도 고마운 마음을 전합니다. 동생같은 석희와 종현이도 고맙습니다. 꽃미남 재영, 완벽한 총무 이인, 황인욱 한갑종 커플, 개구쟁이 채현이에게도 고마움을 전합니다. 길고 긴 포항 생활에서 서로 위안이 되었던 그래픽스 연구실의 준호, 규만, 민수, 성열도 고맙습니다. 모두 세상 속으로 날개를 펴고 날아 가기를 바랍니다.

마지막으로, 항상 부족한 저를 믿어주신 부모님과 누나, 동생 재화에게 사랑한다는 말을 전하고 싶습니다.

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