Low-Cost Virtual Reality System*

PC-Driven VR system
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ABSTRACT
The concept of Virtual Reality has been around since early 1960s, but the availability and development of Virtual Reality systems were largely limited due to its nature of high cost and difficulty in maintenance. Until recently, thanks to the fast development of the modern technology, the idea of building Virtual Reality system using commodity-off-the-shelf hardware became feasible. By using Personal Computers, we have in this project developed a Low-Cost Distributed Virtual Reality system that is much cheaper, easier to maintain and mobile. In this project, the design of stereo vision, corner projection and distributed architecture had been discussed and applied in the implementation of the Virtual Reality system. User experiment had been conducted. The aim of the user experiment is to test the system for presence level, Slater, Usoh and Steed (SUS) questionnaire was used as an indication to the level of presence. Furthermore, network performance related to scene complexities were also evaluated. From these experiment, we have found that the Virtual Reality system developed creates a good level of presence to the participants and scene complexity would influence the roundtrip time of the network. Lastly, this paper concludes by discussing why the Low-Cost Virtual Reality system developed to be an effective Virtual Reality system.

Categories and Subject Descriptors
I.3.6 [**Computer Graphics**]: Methodology and Techniques - Interaction Techniques; I.3.7 [**Computer Graphics**]: Three-Dimensional Graphics and Realism - Virtual Reality

Keywords
Corner projection, distributed, Virtual Reality

1. INTRODUCTION
Virtual Reality (VR) is an emerging technology in computer visualization, but its development and availability was largely limited by its high cost in equipment and maintenance. With the fast development in technology in recent years, commodity-off-the-shelf hardware is capable of producing real-time rendering [6] of highly complex scenes while keeping the price within a range acceptable to average researcher and even home hobbyist.

Thus the idea of building distributed VR (DVR) system with commodity-off-the-shelf hardware becomes feasible. This type of system offers good performance in DVR and keeps the price at an acceptable range. In this paper, we will discuss how we have developed such a Low-Cost DVR system in detail. In order to measure the success of our implementaion, we performed a comparative study on the presence level between the DVR system and a single display system, as well as evaluation of network performance.

2. BACKGROUND
Virtual Reality is a system that models the real world where it is aiming to fool a human being into believing that he or she is physically located in a synthetically generated environment. In a perfect implementation of such system, a use would not be able to distinguish the virtual world from the real one. The virtual environment (environment created in the virtual reality system) can be very useful, especially when used in simulating expensive, difficult or even dangerous tasks [3]. Since the virtual environment need not obey the physics law and gravity, some impossible tasks can even be performed in the scene. Another important aspect of virtual reality is that it is possible for more than two parties to work collaboratively [2] in a virtual environment where they could be physically thousands of miles apart from each other.

There is no single way of constructing virtual environment, but the basic design of the technique is to simulate the human visual system, thus the environment created can be "life-like". In this background study, the method of how virtual environment can be constructed and different approaches used by various researchers around the world will be studied.

2.1 Generating Virtual Environment

Human has a extremely wide horizontal viewing angle, but a narrower vertical viewing angle. This means that we can sense objects better when it is beside us than when it is on top or below us. Thus the idea is to create a panoramic view that fills the horizontal view of human.

2.1.1 Corner Projection

A larger screen allows more information to be displayed and provides better navigability. It is also often stated that wide screen helps the user to be immersed in the virtual environment. Ronald Arsenaault and Colin Ware [7], in their research carried out in University of New Hampshire, pointed out that human's ability to resolve details falls off in the periphery of the visual field, so a wide screen does not necessary provide more amount of information to the perception. When the object that the user is searching for is more than 20 degrees away from the center of vision, the head movement will precede the eye movement.

Thus, in order to achieve the goal of having wide screen to improve the feel for immerse and at the same time, free the user from head movement, a technique called Corner Projection can be used. Corner projection uses two projectors where each projector will project onto one side of a corner. The user will then stand in front of the corner (without blocking the projection), and feel being *surrounded* by the panoramic view of the scene. In this type of projection, any point of the projection on the wall is about the same distance, where in contrast to the normal panoramic view where the edge is further to the user than the center, the user would have to turn his/her head when searching for certain object on the screen.

2.1.2 Torque Game Engine

Torque Game Engine is a rendering engine developed by GarageGames [4]. It uses C programming language and featured with scripting language which is also C-like. The engine was developed specifically for First Person Shooter[1] (FPS) game, but can also be used for developing other type of games.

Most of the known VR rendering engine does not have good support for network, while most of the game rendering engine in the industry, although provide good support for networking, has no features required for VR rendering purposes. In this project, Torque Game Engine will be used as the rendering back end for the virtual environment, those features that are required for VR will be implemented to the engine.

The network model of Torque Game Engine is an example of a Client-Server [4] connection model. It has multi-players support and especially designed to deal with low bandwidth, high latency and intermittent packet loss. It classifies data into different categories according to their delivery requirements: Non-guaranteed data, Guaranteed data, Most recent state data and Guaranteed Quickest data.

Although Torque Game Engine employs Client-Server network model, it can also be applied in peer-to-peer or multi-server architectures, due to its flexible network model.

[1]A type of shooting game which is played in first person perspective.

2.2 Cave Automatic Virtual Environment^{TM} (CAVE^{TM})

CAVE was first demonstrated in 1992 at SIGGRAPH by Electronic Visualization Laboratory (EVL), University of Illinois at Chicago. The people involved in the project were Carolina Cruz-Neira, Dan Sandim and Tom DeFanti[1], along with other students and staff of EVL. It was the first projected, immersive display.

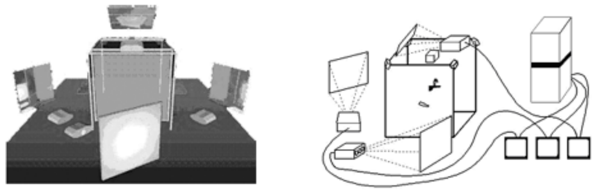

Figure 1: The look and setup of CAVE

The following are some of the specification:

Projection: Rear projection
Number of screens: 4 (front, left, right, bottom)
Type of stereo projection: Active stereo
Size of theatre: 3m X 3m X 3m
Motion tracking: Electro-magnetic tracking enabled
Audio: Surround sound
Render backend: SGI Reality Engine
Projector: Electrohome Marquis 8000 @ 1024X768, 96 Hz

They used four screens to surround the viewer where each screen has its own projector. The graphics workstation, SGI Reality Engine, is responsible for outputting the various video streams. The result of the system was spectacular. It well served as the prototype of virtual reality system.

2.3 Network Topology

The network architecture of PC-driven DVR system describes how hosts are connected. The design of the distributed topology depends on the number of participants expected in the environment, the amount and the form of data being shared. In PC-driven DVR system, all machines are connected in a shared centralized manner.

In shared centralized model, all shared data is stored on a central server (Figure 2). There is no direct communication between clients. Only one client can modify the database at a time. The advantages and disadvantages of the centralized model is summarized:
Advantages:

1. Simplifies the management of multiple clients, espe-

cially in situations where strict concurrency and consistency controls are required.

2. Allows server to process messages before propagating them to other clients culling, augmenting or altering the messages.

Disadvantages:

1. As an intermediary role for data delivery, additional lag can be introduced.
2. If the central server fails, none of the connected clients can interact with each other.

Despite these disadvantages, this architecture is still useful for supporting small group of collaborators. VISTEL [5] is an example that used this approach.

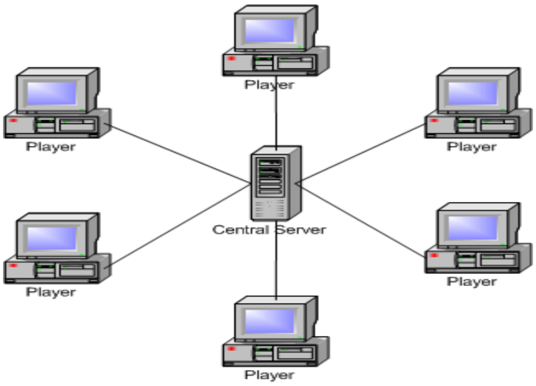

Figure 2: Shared Centralized Model

2.4 Summary

In this section, some of the concepts in designing DVR system were presented as well as the corner projection systems. Corner projection is about creating panoramic view by projecting onto a corner.

An example of the VR systems that implemented by the current industry was discussed. CAVE^{TM} serves as a guideline to the design and implementation of the VR system in this project.

3. DESIGN

In this section, the design of the PC-driven DVR systems will be discussed. For this project, one important issue is to make all the individual components to work together as a complete unit. These components are hardware and software components, consisting of virtual environment, distributed architecture, projection system and mini cave. Each of the components will be discussed in detail.

3.1 System overview

The main idea for the design of the DVR system was to make use of a network of three PC's as the system for generating virtual environment. The virtual environment running on the system uses distributed network model to exchange information. Thus in the virtual environment component, one PC (server) is responsible for the logic (control) and the other two for outputs (display client). Each of the display client then generates a half of the corner projection which then combined to be a panoramic view. Via the projection system, we project each half of the panoramic view to one corner of the wall, thus we created corner projection system. Lastly, placing all the components into a dark room of suitable size, we reached our aim of building mini Cave.

Figure 3 shows the general diagrammatic view of the VR system.

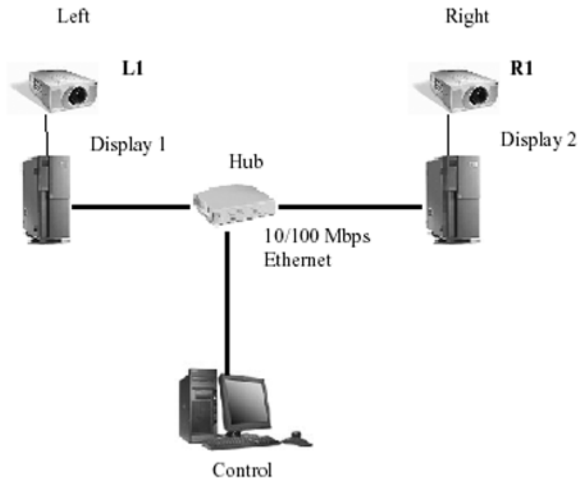

Figure 3: System overview of PC-Based VR

From Figure 3, we derived the design how data should be flowed in the system. Since server is the component with direct user interaction, it is the component that passes data to other components, i.e. display clients. Thus, the server will pass the data to both display clients, where each display client, by using the received data, generate the responsible half of the panoramic view.

3.2 Virtual environment

In the system, a game engine called Torque Game Engine[4] was be used. Torque Game Engine is written for First Person Shooter (FPS) game development, thus it suits our need in developing a DVR system to be interacted in first person perspective. Torque itself is a self-contained development platform, so the major issue in developing software for this DVR system was to get familiar with the Application Programmers's Interface (API) and alter the demo game code that came with the engine to the way we need it to be.

3.3 Distributed Network model

For corner projection to be possible, a distributed network (client-server) architecture must be designed. This is because the server need to pass information to the display client, so the display clients can generate the desired panoramic views from the perspective of the server.

3.3.1 Architecture

The system can be divided into three components:

- Two computers running act as client were used for corner projections. Each of these clients can be regarded as a transparent player which has the same view as the control player.

- A computer running both clients and server is used to capture inputs from user as well as controlling the movements of the other clients. In fact, every time the control player moves, server also updates its position to the other two clients so that they have the same camera view as the user.

Thus the basic idea is that the server being in control of the position of the clients by updating their position constantly.

3.3.2 Synchronization

Figure 4 illustrates how synchronization of movement is done in PC-based VR system. The server is responsible for synchronizing players' movement. Client's movement is controlled by a "movement handler" function in the script. When that function is invoked by client, it informs the server which updates the position of the other clients to the position of the server.

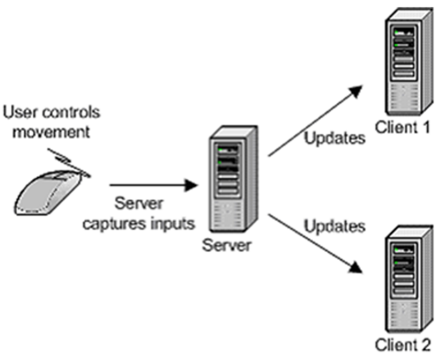

Figure 4: Synchronization process in Torque

3.4 Corner projection

Having a network architecture where server constantly updates the position of the client, the reason for doing this is because each client (camera) in the virtual environment has its own frustum[2], which is undesirable. It is desirable to create a panoramic view of the virtual environment from the perspective of the server, thus to enforce the clients to have the same perspective (same frustum) as the server, their position, as well as the camera rotation settings, need to be updated constantly.

To create the panoramic view after having the same frustum, we shifted the viewing port[3] of the frustum of the client camera half of the horizontal screen resolution to the left or right. Thus one client (camera) produces left half of the panoramic view and the other the right half.

[2]A rectangular or a pyramidal viewing volume where only objects within this volume will be rendered.
[3]A rectangular area that defines what is to be displayed to the window.

3.5 Mini Cave

A separate dark room was chosen to construct the mini CAVE. One corner of this dark room was used for the projection.

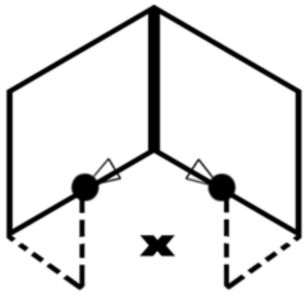

Figure 5: The setup of the mini CAVE

Figure 5 shows how the projectors were positioned. The mark "X" in the figure depict the position where the user stand when using the system. The position of the mark X will be such that the user is aligned to the outer edges of both the projected screens, so the projected screens can fill the horizontal viewing angle of the user as much as possible.

4. IMPLEMENTATION

4.1 Virtual environment

The design for the VR system is to have the server and clients exist in the same virtual environment where server constantly updates information to the clients. Thus Torque Game Engine (TGE) was modified to run multi-player mode on Local Area Network (LAN), which originally was only enabled if Internet connection exists. In the multi-player game, server is the player controlled by the user, and the display PC joins the network game as client.

The Virtual Reality that we constructed is essentially a multi-player game in TGE where all client players were controlled by the server.

4.2 Corner projection

The implementation of corner projection consists of two parts, server and client.

4.2.1 Server

A function was written in the script language, which is triggered whenever the server player moves. The function essentially updates the position of the server player and the camera rotation setting to all the clients in the game.

4.2.2 Client

To shift the view port of each camera, it requires alteration in the engine where it was set up. The goal is to shift the view port half of the horizontal screen resolution to the left or right.

By taking the difference of the X coordinate of both left and right edge, we get the size of the horizontal size of the view port. Then by either adding or subtracting half of the horizontal view port size to both left and right edge, the view port is then shifted to left or right the way we wanted. Thus for both clients, running different version of view port setting, the combined image of the two clients next to each other is the panoramic view.

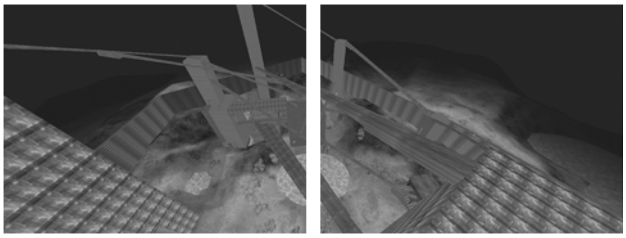

Figure 6: Left and right image created

4.3 Mini CAVE

4.3.1 Projector

Two projectors were borrowed from Computer Science Department of University of Cape Town to build this mini CAVE. The specification of the projectors are as follow:

Table 1: Projector specification

Make and Model	Ask C6
Brightness	900 ANSI
Lamp type	120W UHP
Maximum Resolution	1280 X 1024
H-Sync Range	15-100KHz
V-Sync Range	43-130Hz
Max Power	180W

4.3.2 PC used

Table 3 lists the specification for the PC used for running the VR system.

Table 2: Hardware specification of the Server

CPU	Intel Dual XEON 1.7 GHz
Motherboard	Intel motherboard
Memory	2.25 Gb RDRam
HDD	WD 80 Gb 7200 RPM
Graphics card	GeForce4 Ti 4600 128 MB DDR
NIC	10/100 Mbps
OS	MS Windows XP SP1

4.3.3 Others

A twenty-four port 10/100 Mbps switch hub was used to inter-connect the PC's to ensure the fast connection.

4.3.4 Setup

A dark room of the size of approximately 2.5 meters X 4 meters X 6 meters (length X width X height) was used for the setup of the VR system. Figure 7 shows the setups of the VR system. The two projectors were placed approximately 2.3 meters away from the wall. The projected images were then adjusted manually by shifting the position of the projectors to be aligned. Figure 8 shows the projected image. The position where the user stood is approximately 1.5 meters away from the corner in order to have the widest view and not blocking the projection.

Table 3: Hardware specification of Display PC

CPU	Intel P4 3Ghz 800FSB
Motherboard	Intel motherboard
Memory	1Gb DDR400
HDD	WD 80 Gb 7200 RPM
Graphics card	ATi Radeon 9700 Pro 128MB DDR
NIC	10/100 Mbps
OS	MS Windows XP SP1

The user interacted with the virtual environment using only a mouse, where left click for move forward, right click for move backward and middle click for jumping.

Figure 7: Setup of system

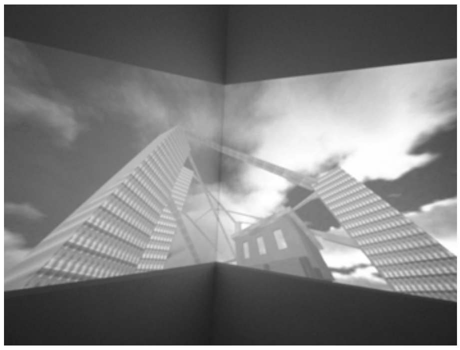

Figure 8: Corner projected image

4.4 Cost

One of the important issues of this project is to keep the cost of the whole system within an acceptable range. In this project, some of the components used, such as the Dual processor server and the twenty-four port switch, was borrowed from the Department of Computer Science. These components are not required for an actual VR system to be built. For the server, a normal PC, with same specification as the display PC, will be as good; and a normal eight port switch will also serve the job of providing fast connection between PC's.

The following shows what the realistic cost of the implementation of the VR system would be. The prices of the components were obtained on the same day as that of writing this section.

Table 4: Cost of the hardware

Component	Price
PC	R 15 550.00
Projector	R 15 000
8 port 10/100 Mbps Switch	R 1 000

For the DVR system we built, three PC's, two projectors and a switch is needed, thus the cost for such system would be R 77 650.00.

5. EXPERIMENT

Two experiment was conducted on the DVR system, one involves user test and the other on network performance.

The experiment involves user was designed to compare the corner projection system against the single display system. Then the participants were asked to first navigate projection system then single display system or vice versa. Then they were asked to do two set of questionnaires, one on each system.

The experiment on network performance was designed to run two different virtual environments in the mini CAVE, one have higher scene complexity than the other. In order to cover a large range of scenes. Figure 9 and 10 shows the screenshots of the complex scene and simple scene respectively.

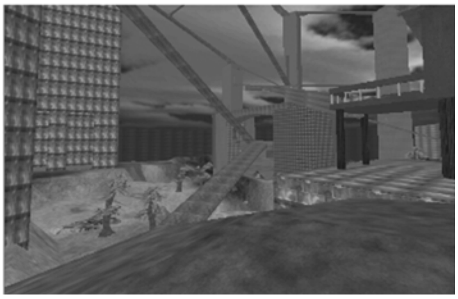

Figure 9: A screenshot of "Caotic Catwalk" VE

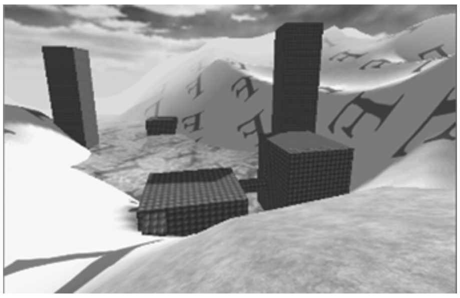

Figure 10: A screenshot of "One Texture" VE

5.1 Presence Experiment

5.1.1 Participant

Ten participants took part in the experiment. Out of the ten participants, four were females and six were males. Five were postgraduates and five were under graduates. Five of the participants were from Science faculty and five from engineering faculty.

The requirement for participation were not to have a lot of experience in gaming, especially First Person Shooter (FPS) game. This is to ensure that the participants has little previous experience in similar environment, which may affect the result.

5.1.2 The Questionnaire

Slater, Usoh and Steed (SUS) questionnaire was used to serve as an indication to the presence level felt by the user. Together with the SUS questionnaire, one extra question was attached to ask the user for their feeling about virtual environment.

5.1.3 Hypothesis

The primary hypothesis was that there would be better presence level from the participants on the corner projection than on the single display system.

The following hypothesis were established:

- ***H1:Corner Projection DVR system is more enjoyable than the single display system***

  The enjoyment level of the DVR system on the corner projection system was suspected to be higher than the single display system.

- ***H2:Corner Projection DVR system provides higher presence level than the single display system***

  The presence level of those participants who did corner projection system first was suspected to be higher than those who did single display system first.

- ***H3:Participants without prior experience of the VE will have higher presence level on corner projection system***

  It was suspected that participants to have higher presence level in corner projection system without any prior knowledge of the VE used, when compared to the presence level of those participants who did first single display system then corner projection system.

- ***H4:Participants doing corner projection system will take longer time to complete the task than those doing single display system***

  For the difference in size of screen and possibly in level of presence, it was suspected that participants would spend longer time in completing the task assigned in corner projection system.

5.1.4 Pilot study

A pilot study was done with three Computer Science students. The result was useful in finding defects in the system and led to changes to the experiment procedures. The result of the pilot study was however not considered for the final analysis of the result.

5.1.5 Procedures

An experiment session took approximately thirty to forty minutes and all procedures were identical for all participants. Each experimental session was divided into following phases:

- Introduction

  Before the participants were introduced to the virtual environment, they were briefed on the aim of the experiment and explained briefly on how the DVR system looks like and the task they have to complete.

- Training

  When the participants were introduced to the system, the observer explained the basic look of the virtual environment and the way how they can interact with the virtual environment through the mouse.

- Completing task assigned

  During the course of experiment, the observer did assist the user in any way. All possible interferences that might affect the presence were avoided. After the task was completed, a short conversation with the participant was done.

- Filling in Questionnaire

  Upon completion of both experiments (corner projection and single display), the participants were asked to fill in the questionnaires for both systems. The reason for filling in both questionnaires only after the completion of both experiments was to avoid the participants being affected by the questionnaire after the first experiment. So the result will not be biased.

5.2 Network Performance Experiment

5.2.1 Measure

The following variables were used in the experiment:

1. Roundtrip time
2. Scene complexity (Number of polygons)

Roundtrip time and frame rate are dependent variables of the experiment. Scene complexity is an independent variable.

5.2.2 Hypothesis

The following hypothesis was established:

- ***H5:Increase of scene complexity would increase roundtrip time***

5.2.3 Procedures

Fives minutes of random movement around the virtual world was carried out on both scenes of different complexity. Benchmarking results were recorded during the experiment.

6. RESULT AND ANALYSIS

6.1 Presence Experiment

Results from the questionnaires were analyzed to test the various hypothesis.

H1:Corner Projection VR system is more enjoyable than the single display system

Result: Eight of the ten participants gave positive comments on enjoyment level of the corner projection system while the questionnaire reflected that seven of ten participants gave positive comments on the feel of height and worried about falling down. No significant sign of physical uncomfortableness was observed.

Analysis and discussion: No conclusion can be reached from the above result concerning the enjoyment level. Observation shows that some of the user became anxious at some stage, but the questionnaire and the short conversation after experiment did not reflect what was observed.

H2:Corner Projection VR system provides higher presence level than the single display system

Result: The summary of the numerical analysis performed on the data is given in Table 5.

Table 5: Summary of numerical analysis of factor attributed towards presence level comparison

	Corner Projection	Single Display
Sample size	5	5
Total	139	90
Mean	27.8	18
Std. Dev.	8.167	2.916
Std. Err.	3.652	1.3
95% CI of Mean	17.659 - 37.941	14.38 - 21.62
Median	30	17
Min	15	15
Max	37	22

Discussion: A box and whisker plot was drawn and in the result, the two boxes did not overlap. Thus means that there is a significant difference in the result.

Related hypothesis: The result clearly indicated that the hypothesis can be accepted. Thus we claim that corner projection system does provide better presence level than the convention single display system.

H3:Participants without prior experience of the VE will have higher presence level on corner projection system

Result: The summary of the numerical analysis performed on the data is given in Table 6.

Discussion: A box and whisker plot was drawn and in the result, the two boxes overlapped. Thus means that there is no significant difference in the result.

Related hypothesis: The result of the experiment shows that the opposite is likely to be the true. The similar level of

Table 6: Summary of numerical analysis of factor attributed towards presence level comparison

	W/ VE exp.	W/o prior VE exp.
Sample size	5	5
Total	139	150
Mean	27.8	30
Std. Dev.	8.167	5.148
Std. Err.	3.652	2.3
95% CI of Mean	17.659 - 37.941	23.608 - 36.392
Median	30	33
Min	15	26
Max	37	34

presence is felt whether the participants had prior experience of the virtual environment or not.

H4:Participants doing corner projection system will take longer time to complete the task than those doing single display system

Result: The summary of the numerical analysis performed on the data is given in Table 7.

Table 7: Summary of numerical analysis of factor attributed towards time-efficiency level

	Corner Projection	Single Display
Total	92	50
Mean	18.4	10
Median	16	12
Std. Dev.	7.301	4.301
Min	11	5
Max	28	15

Discussion: From table 7, the total time spent by the participants is significantly higher than the other other group.

Related hypothesis: The result clearly accepted the hypothesis. The possible explanation for the result would be the presence level felt by the participants that influenced the task-completing efficiency.

6.2 Network Performance

Results obtained from the experiment were used for testing the hypothesis.

H5:Increase of scene complexity would increase round trip time

Result: Statistical results were calculated based on the data obtained from the experiment. The results are presented in Table 8. As a test of the relationship between scene complexity and roundtrip time, correlations were performed between these variables. Positive correlations were found between the variables (0.976).

Analysis and discussion: Figure 11 presents the relationship between scene complexity and roundtrip time in both VEs. As seen from the graph, there is a linear increase of scene complexity and roundtrip time for all VEs. This is because complex scenes require extra time for memory loading

Table 8: Summary of statistical results with average roundtrip time as dependent variable and average number of polygons as independent variable in the VEs

	Avg.	Mean	Std. Dev.	Max.	Min.
Caotric Catwalk	Round trip time	27.2	1.6	29.8	24.5
	Num. of polygons	8819.3	3055.6	14374.1	4806.4
One Texture	Round trip time	27.6	4.9	38.9	21.7
	Num. of polygons	1986.8	164	2338.5	1811.3

of data as well as rendering, thus the server will take longer to receive an acknowledgement packet. This hypothesis can also verified by the results obtained from the correlation matrices. Results have shown that there is a significant, positive correlation between the number of polygons and roundtrip time for all VEs.

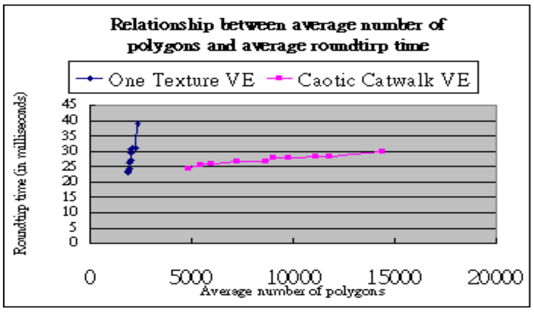

Figure 11: Graphical Representation of the avg. roundtrip time and number of polygons in Caotic Catwalk and One Texture VE

7. CONCLUSIONS

For this part of the project, a PC-driven Low-Cost distributed VR system was successfully implemented. A comparison on the presence level of this VR system and a single display system, as well as network related performance evaluation were conducted as experiments.

The result of the presence experiment have shown that the presence level of the VR system built for this project in deed provides higher level of presence to the user. The result have also shown that there is no difference in level of presence whether a user has prior experience in the virtual environment or not. However, the sample size of the experiment was not large enough, thus the result of the experiment is not significant enough to draw any scientific conclusion. Further test would be required.

Regarding the network performance of this system, various networking issues such as synchronization and latency have been addressed. Results have also shown that the increase of scene complexity would increase the round-trip time of the system. This is inevitable since the network model in Torque relies entirely on this, in order to provide consistency between hosts.

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