RESEARCH ANE EDUCATION MINISTRY

TECHNICAL UNIVERSITY
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FACULTY OF AUTOMATION AND COMPUTER SCIENCE
MASTER IN COMPUTER SCIENCE AND INFORMATION TECHNOLOGY
DOMAIN OF COMPUTER NETWORKS AND DISTRIBUTED SYSTEMS
COMPUTER SCIENCE DEPARTMENT

A CLUSTER-READY VIEWER APPLICATION FOR BUILDING SCALABLE HIGH-PERFORMANCE 3D VIRTUAL GEOGRAPHICAL SPACE SCENARIOS USING GRAPHICS CLUSTER ARCHITECTURES

MASTER THESIS

Author: **Cristinel Mihai MOCAN**

Project Supervisor: **Prof. Eng. Dorian GORGAN, PhD**

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Author: **Cristinel Mihai MOCAN**

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1. **The Problem:** *The task of this thesis is to find a scalable solution in order to demonstrate how can we integrate an object-oriented graphic rendering engine and a parallel rendering framework optimally to exploit the power of multi-GPU systems and visualization clusters when we build high-performance 3d Virtual Geographical Space (VGS) scenarios.*

2. **Content:** *The Problem Description, Introduction, Related Works, Theoretical Considerations, Technological Considerations, Implementation Considerations, Experiments and Testing, User Manual, Conclusions, References, Annexes*

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Project’s supervisor signature **_______________________**

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Author declaration,

I, *Cristinel Mihai MOCAN*, master graduate of Faculty of Automatics and Computer Science from Technical University of Cluj-Napoca, declare that the ideas, analysis, design, development, results and conclusions within this Master Thesis represent my own effort except for those elements which do not and will be highlighted accordingly in the document.

I also declare that from my knowledge this thesis is in an original form and was never presented in other places or institutions but those explicitly indicated by me.

Date: June, 28, 2010

Author: **Cristinel Mihai MOCAN**
Matriculate number: **601 / III**
Signature: ____________________

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SYNTHESIS

of the Master Thesis:

A CLUSTER-READY VIEWER APPLICATION FOR BUILDING SCALABLE HIGH-PERFORMANCE 3D VIRTUAL GEOGRAPHICAL SPACE SCENARIOS USING GRAPHICS CLUSTER ARCHITECTURES

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1. **Problem definition:**
   Evaluate the compatibility between graphics rendering engines and parallel rendering frameworks in order to build high-performance 3D complex scenarios on a distributed architecture. The main purpose is to develop and implement a cluster-ready application that allows the users to run different virtual geographical space scenarios using the graphics cluster.

2. **Proposed Solutions**:
   Graphics rendering engines: C++, an open source high performance 3D graphics toolkit called OpenSceneGraph, the object-oriented graphics rendering engine OGRE with CEGUI libraries and DotSceneLoader
   Graphics Cluster: C++ and Equalizer parallel rendering framework
   Video Encoding: MPEG-2 format

3. **Obtained Results:**
   A system that provides good performance for Graphical Modeling and Visualization of Interactive Virtual Geographical Space using the graphics cluster architectures.

4. **Tests and Verifications:**
   Experiments and testing ensure the correctness of the system implementation. They are presented in Chapter 7.

5. **Personal Contributions:**
   During the research activity presented in this Thesis, I have contributed to the application development and its functionalities that has the main purpose to integrate a graphic rendering engine with a parallel rendering framework optimally to exploit the power of multi-GPU systems and visualization clusters when we build high-performance 3d Virtual Geographical Space (VGS) scenarios. I evaluated the performance of load balancing for various cluster configurations by considering different combinations of distributed rendering algorithms over the graphics cluster and spatial data models. The research studies and experiments as well the flexibility related with the mesh data formats accepted by the graphics renderer, user interaction techniques with complex scenes in the context of graphics cluster rendering, and

solutions for data streaming and unit frame encoding. A few use cases of visualization of the virtual geographical model exemplify the achievements.

6. **Documentation Sources:**
   UTCN library, IEEE Organization Website, International Conferences proceedings, different user manuals and other websites.

Date: June, 28, 2010 Author signature ______________

Project's supervisor signature _______________

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1. THESIS DESCRIPTION

1.1. Task Statement

The task of this thesis is to find a scalable solution in order to demonstrate how can we integrate an object-oriented graphic rendering engine and a parallel rendering framework optimally to exploit the power of multi-GPU systems and visualization clusters when we build high-performance 3d Virtual Geographical Space (VGS) scenarios.

1.2. Functional Requirements

The task of integrating an object-oriented graphics rendering engine with a scalable parallel rendering framework is even more difficult if it should be generic to support various types of data and visualization applications and at the same time to work efficiently on a cluster with distributed graphics cards.

The performance of load balancing is evaluated for various cluster configurations by considering different combinations of distributed rendering algorithms over the graphics cluster and spatial data models. The research studies and experiments as well the flexibility related with the mesh data formats accepted by the graphics renderer, user interaction techniques with complex scenes in the context of graphics cluster rendering, and solutions for data streaming and unit frame encoding. A few use cases of visualization of the virtual geographical model exemplify the achievements.

From the interactivity point of view the solution is to allow the user to interact with the complex scenes. Using the object-oriented graphics rendering engine the user can add a camera in the application. In this situation the user is able to navigate throughout the scene interacting by the input devices - by keyboard keys to move the camera and by mouse for camera rotation.

1.3. Technological Requirements

The challenge is how to integrate a flexible object-oriented graphics rendering engine like scene-oriented with a parallel rendering framework in order to develop scalable graphics applications for a wide range of systems ranging from large distributed visualization clusters and multi-processor multi-pipe graphics systems to single-processor single-pipe desktop machines.

Related to this challenge we focused on finding an object-oriented graphics rendering engine that produces applications utilizing hardware-accelerated 3D graphics. Also we look for a toolkit based on OpenGL which provides an application programming interface to develop scalable graphics applications for our graphics cluster.

Increasing multi-core processor and cluster-based parallelism and the improvements concerning the CPU and GPU performances demand for flexible and scalable parallel rendering solutions that can exploit multi-pipe hardware accelerated graphics. In this situation, the scalable rendering systems are essential to cope with the rapid growth of data sets in order to achieve interactive visualization.

2. INTRODUCTION

2.1. General Overview

Rendering and interacting with high-resolution geographical data sets and complex models of virtual geographical space involves high power computation resources in networking environments. The solution of integrating graphics rendering engine applications in cluster based architecture and Grid infrastructure is the main concern of the research reported by this thesis.

In case of complex 3D models a single GPU cannot offer an adequate performance although the rendering devices performance has been the subject of a surge related to this aspect.

By visualization scenarios in a Virtual Geographical Space (VGS) we understand specific routines and algorithms created for the purpose to simplify and standardize the visualization methodology and add more useful details to visualization complexity. With the use of graphics cluster architectures, one can use these visualization scenarios on very complex VGS's.

The Virtual Geographical Space represents a tool in defining, modeling and simulating real life geographical environments. The virtual scene is composed of 3D object models (e.g.: polygonal models, NURBS surfaces, equation-based models)

In order to obtain a working visualization of such a complex scene, our system based on a distributed architecture provides the option to record what the user sees on the screen through the perspective of an avatar. The result that is obtained can be a video, an image or a sequence of images.

The main motivation is that most personal computers do not hold high-power computation hardware resources in order to be able to apply and use the visualization scenarios on locally stored 3D complex environments.

2.2. Objectives

The objectives of this research are listed in the following:

- Finding a solution for integrating graphics rendering engine applications in cluster based architecture and Grid infrastructure is the main purpose in this thesis. The result is an application that supports:
    - Rendering **multiple views** of the same scene graph, using software or hardware **swap synchronization**.
    - Parallel, multithreaded rendering on **multi-GPU** workstations and distributed rendering on multi-GPU **visualization clusters**.
    - **Scalable rendering** to aggregate the power of multiple GPUs for one or multiple views (supported modes: 2D, DPlex, 2D load-balancing, cross-segment load-balancing)
    - Any combination of the above due to the flexible **run-time configuration** of Equalizer, using a simple configuration file.
- Performance evaluation concerning load-balancing for various cluster configurations by considering different combinations of distributed rendering algorithms over the graphics cluster and spatial data models.

- Developing and testing a number of formats (scene graphs), executable on the graphics cluster, for the VGS description; Execute experiments as well in order to see the flexibility related with the mesh data formats accepted by the graphics renderer, user interaction techniques with complex scenes in the context of graphics cluster rendering.
- Testing the system for execution and visualization of a 3D static or dynamic environment that is existent on graphics clusters.

The next section highlights some related works concerning this subject.

3. RELATED WORKS

This section will present some of the existent software products which offer a similar functionality to the one of the current developed system, presented during the course of this project.

A great part of work has addressed issues recently in accessing, representing, and manipulating large data sets. The previous work can be summarizing as follows.

The paper [1] presents a few experiments on the solutions supported by the Chromium graphics cluster to provide fast distributed processing and remote visualization. It evaluates the performance for various cluster configurations and spatial data models. The research concerns as well with accessing the cluster based processing by web applications through grid and web services.

A solution of combining graphics cluster based computation, Grid infrastructure and Web applications appears in paper [2]. The paper explores and experiments the optimal architecture for remote graphics visualization considering different combinations of the sort-first and sort-last distributed rendering algorithms over the Equalizer graphics cluster.

Concerning the parallel rendering we found out that Equalizer [3] supports multi-view and scalable rendering, resource management, and planning of the transparent rendering layer. It enables application developers to configure their applications to take full advantage of multi-GPU workstations. In this case the applications provide better performance and allow visualizing complex data sets.

Equalizer and Chromium [4] solve similar problems by enabling applications to use multiple GPU's, but have disjunctive use cases and characteristics. In our experiments we have chosen to work using the parallel rendering framework because scalability, flexibility and compatibility are mainly required in our graphics cluster.

On the other hand, in order to build complex oriented-scenes applications we compared some graphics engines like [5], [6], [7] and [8].

From this point of view the problem was to find out which would be a better choice for a 3D engine. If we compare Ogre and OpenSceneGraph (OSG) we can conclude that Ogre has better documentation than OSG, supports D3D while OSG only supports OpenGL (not really important, but provide more options in the future). Ogre has more built in features, like skeletal animations (really important for the arm) and seems a lot easier to use.

Another important aspect about Ogre relates to the optimization for utilizing all the fancy GL features like hardware vertex buffers supported by mainly ATI, NV and mainstream cards while OSG is optimized for compatibility with scientific platforms like SGI, which generally have all kinds of peculiar bugs to work around.

The conclusion is that Ogre includes the features available in other graphics engines as add-ons. It offers more freedom to choose the components you want and has much better geometry and material formats and handling. Also the design is better, faster, and is much more feature rich. Irrlicht has mostly obsolete file formats that were never designed for real-time graphics and are extremely limited, often forcing you to use several separate formats to get the specific material and features you need.

Finally, I consider using object-oriented graphics rendering engine because it uses a flexible class hierarchy that allows us to design plug-ins to specialize the scene organization approach taken to allow us to make any kind of scene. Therefore, the object-oriented graphics rendering applications can be integrated with our parallel rendering framework.

Concerning the remote and collaborative visualization, the openVISSAR toolkit [9] sends the real-time generated visualizations.

Paper **Error! Reference source not found.** presents a method of remote cluster based visualization for 3D large medical objects obtained through direct modeling or 3D scanning in the context of eLearning applications. The teaching materials include 3D models, which is not actually a trivial action, since it requires skills for modeling, specific user interaction techniques and specialized hardware for implementation. The current project stands out by including a specifically implemented language for scenario manipulation in order to visualize a complex scene of objects (the VGS), whereas the application in the paper deals only with one object at a time. This being the case, some simple interaction functionalities are still included.

A similar work is done in paper **Error! Reference source not found.**. It details and presents the performance boosting of rendering applications by accessing remotely a graphical rendering system.

A solution that combines graphics cluster based computation, Grid infrastructure and Web applications is presented in paper **Error! Reference source not found.**. Its main focus is to explore and experiment different optimal architectures for remote graphics visualization while using combinations of the sort-first and sort-last distributed rendering algorithms over the Equalizer graphics cluster. It also deals with scalability issues: single and multiuser interaction against single and multi virtual geographical models.

The current application heavily relies on **Error! Reference source not found.**. The server part of the system is similarly implemented. The main ideas for analysis and implementation are used.

A different approach to distributed processing remote visualization is discussed in paper **Error! Reference source not found.**. It issues the problem of using the Chromium graphics cluster, which has a similar functionality with Equalizer. Various cluster configurations and spatial data models are being evaluated for performance.

Paper **Error! Reference source not found.** represents a similar implementation of the currently developed application, with the exception of the visualization scenarios. A major difference in the system is the use of the Chromium graphics cluster, whereas this project uses Equalizer.

4. THEORETICAL CONSIDERATIONS

4.1. Conceptual Architecture

Largely speaking, the proposed architecture for the cluster based visualization system uses the client-server model for the rendering part.

The main architecture components are the following: the visualization servers, the rendering clients and the resource manager component. The communication and the user interaction use a resource manager and a notification model.

The main conceptual architecture is described below (Fig. 4.1):

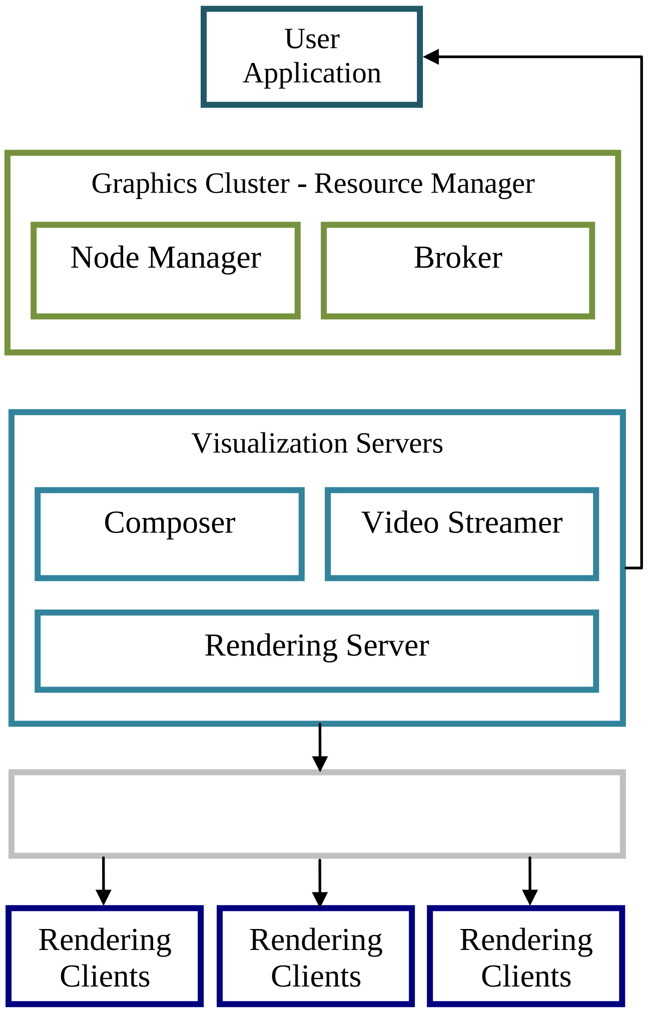


Fig. 4.1: System Conceptual Architecture

4.1.1. Rendering Nodes and Server

At the server and the rendering client level we used the modified parallel rendering framework based on Equalizer.

For our experiments we used multiple computers that were linked together in order to share computational workload. The requests initiated from the user are managed by and distributed among all the standalone computers to form a graphics cluster. In designing the graphics clusters we used different computing resources depending on the conducted experiment.

Each of the rendering client has a module which is responsible to execute the rendering tasks sent by the server. In conclusion, a rendering node application runs on each rendering client. After each rendering cycle, the result is sent to the composer node.

In order to achieve a good performance, the result data has to be compressed. For this purpose we use a compression plugin system supported by Equalizer. Currently the data is compressed using the RLE (Run Length Encoding) method. This is not the best option, a Huffman coding could achieve a better compression ratio. Another criteria for selecting other algorithm is execution time. From this point of view, the RLE execution time is linear with the raw data size.

The Rendering Server and the Composer application are running on the rendering subsystem's server. The server is responsible for managing the rendering nodes, transmitting messages to nodes and object distribution. The configuration of the rendering system is described in a configuration file [10].

The Composer module objective concerns on composing the final frame, compressing it, and streaming a continuous video stream to the client. For video compression we used the free library, which is a part of the FFmpeg project [11].

The communication between the streamer process and the rendering system uses pipe files. The composer node creates a child process, using the streamer binary and redirects its standard input to a pipe file. The streamer will permanently read the standard input and stream the data to the destination. The video streaming is made on a constant frame-rate, so the streamer process has to be feeded continuously, even if the rendering system's performance is lower as the desired frame-rate or it is not constant. This problem was fixed by a simple algorithm, which skips some of the frames, if the rendering FPS (Frames per Second) is greater than the streaming FPS or duplicates frames in the other case.

The networking layer provides a peer-to-peer communication infrastructure. It is used in order to communicate between the application node, the server and the render clients. This layer can also be used by applications to implement distributed processing independently or complementary to the core Equalizer functionality. It provides layered functionality, which means higher level functionality for the programmer. In our graphics cluster network layer the communication between nodes is accomplished using packets. There is a base class that allows the registration of a packets with a dispatch queue and an invocation method. Each packet has a command identifier, which is used to identify the registered queue and method. We can say that the node is the abstraction of a process in our graphics cluster. Using connections the nodes communicate with each other.

Based on the Universally Unique Identifier [12] standard each node has a unique identifier. For instance, in order to query connection information to connect to the node we use the identifier to address nodes.

4.1.2. Node Manager and Broker component

In order to achieve the desired experiments from this research we developed a node manager application. Using it we could enable or disable certain nodes in our graphics clusters depending on how many we need in each experiment.

We use this component for the cluster administration. By this tool the administrator may register new nodes that can be disabled or removed later from the system. It is important to notify that the nodes can be Server or Client nodes. This is a desktop application that connects to the database installed on the server and reads/modifies the database table which stores the information about the registered nodes.

The Node-Manager offers application file deployment. That means the application files are copied using Secure Copy Protocol before a new node is added in the system. In order to make it work, the host on which the Node-Manager is installed needs to have a password less SSH connection configured to the new node.

The administrator interest is to have access to a friendly user interface through which a new rendering node can be added to the rendering system. It is important to have access to the database and as an alternative scenario we assume the node could not be added successfully because of different reasons, like connection less or password less SSH connection errors.

On the other hand, the broker component receives requests from users and, depending on the rendering strategies and parameters it fetches the visualization to a rendering server. The rendering clients are receiving the rendering parameters from the rendering server together with the graphical scene.

Based on visualization requirements, the broker transparently selects the most suitable cluster for rendering. The cluster level resource manager is the local dispatcher that selects the visualization server in the cluster, and fetches the input data. This system level manages the existing clusters at a higher level.

Depending on the rendering attributes selected by the user, the visualizing service selects the appropriate read back component. The visualizing system provides three features: creation of video streaming visible in the user interface; image, when the cluster renders only one image frame; and video sequence, which is actually a movie as a set of image frames.

The client application is using the UI (User Interface) which allows the user to create a complex scene using the object-oriented graphics rendering engine library which uses a flexible class hierarchy. The UI allows the user to make any kind of complex scene we like with some limitations regarding the data formats accepted for the loaded objects. Using the camera feature from the UI, the user controls and manipulates the visualization scene. It supports the user interaction with the virtual scene, manly concerning with camera manipulation and interaction techniques to individual scene objects. The UI component receives commands from the user and forwards them to the rendering nodes using a communication channel.

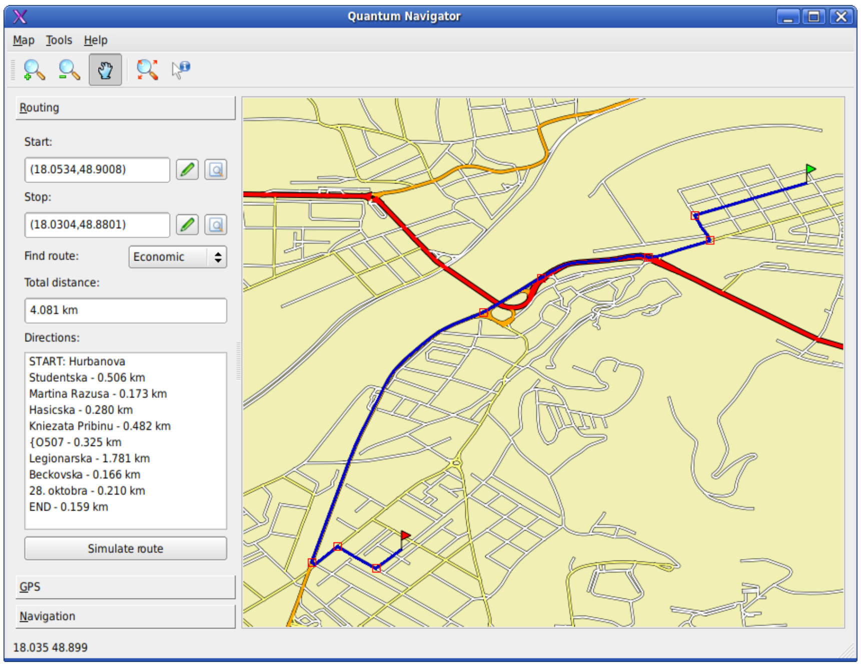
4.2. Virtual Geographical Space (VGS)

4.2.1. Geographic Information System (GIS)

GIS is mainly used to operate on spatially distributed data through a computerized process. The available operations that can be used to manipulate the spatial data are create, store, analyze and data processing. GIS technology is used in a wide variety of scientific domains, among which some important ones that are worth mentioning are resource management, cartography, and route establishment.

GIS is well known for its specific methodology used to organize its managed information. There are two types of information: graphical information, which describes the spatial placement of studied elements, and database-based information that is used to store the associated attributes of the elements (e.g.: a 3D model can have vertex number, edge number, polygon count, texture etc.).

We do not work on information stored in a database for the current project, so we will focus more on the first category of information, which is the graphical one. Graphical data can be represented in two modes: raster or vector. The vector graphical representation (Fig. 4.2) is quite different than the other one, since it represents images by the use of geographic primitives (dots, segments, polygons) which are mainly characterized by mathematical equations. The raster graphical representation of data (Fig. 4.3) is a method of describing images in software applications as matrices that contain pixel values as elements. Without depending on the graphical representation, GIS systems associate a geographical coordinate system to the pixel matrix in case of raster images and one to the vectors in case of vector images. Thus, an object that is represented by an image or a vector will always be associated to a unique position in the geographical information system that corresponds to a geographical position in the real world.



Start: (18.0534,48.9008)

Stop: (18.0304,48.8801)

Find route: Economic

Total distance: 4.081 km

Directions:
START: Hurbanova
Studentska - 0.506 km
Martina Razusa - 0.173 km
Hasicska - 0.280 km
Kniezata Pribinu - 0.482 km
{O507 - 0.325 km
Legionarska - 1.781 km
Beckovska - 0.166 km
28. oktobra - 0.210 km
END - 0.159 km

18.035 48.899

Fig. 4.2: Vector data in a GIS system

GIS takes advantage of all interrogation opportunities that today’s modern database systems have to offer, and can easily offer analysis possibilities based on specific geographical regions. The impact of GIS to the population is mainly known to be positive, thus GIS software evolved rapidly and at a high rate. There already exists a large number of products coming both from dedicated developers such as Autodesk, ESRI, Intergraph and from open source developers (Quantum GIS, GVSIG, OpenJump etc.).

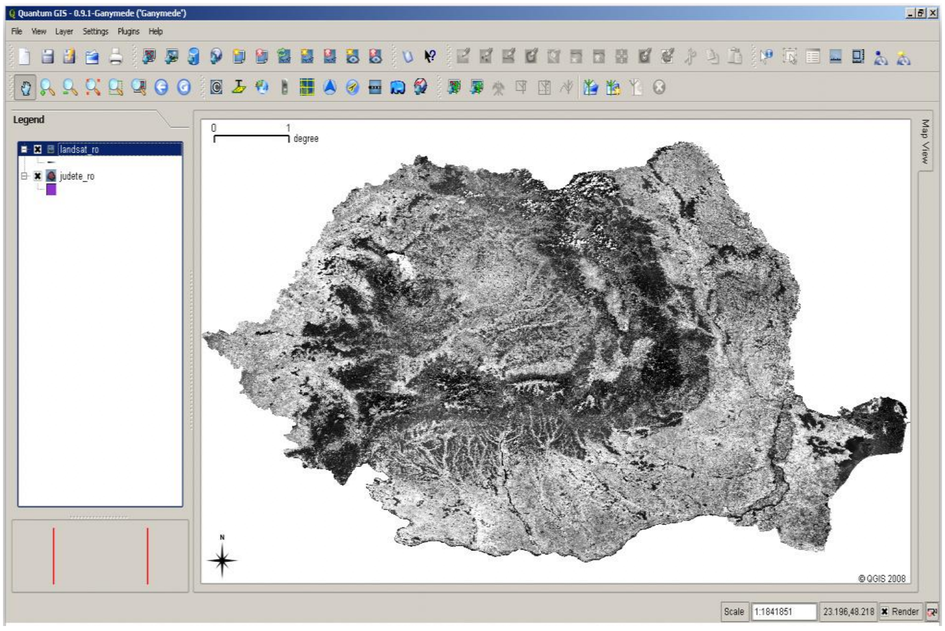


Fig. 4.3: Raster data in a GIS system

4.2.2. *Virtual Reality (VR)*

Virtual Reality represents a computer generated simulation of a 3D environment in which the user is able to visualize and manipulate its entire content.

The word “virtual” is frequently used in research studies/experiments/software products in computer science and the IT&C domain. It generally represents an entity/a medium that simulates/models an entity/a medium from our reality. By “reality” we understand the natural environment that is perceived by the human being through senses. With the use of this fact, it is possible to simulate/model the given environment through generating or providing data perceived by one or more of those senses. For this reasons, ***Virtual Reality*** (**VR**) refers to an entire system of concepts, methods, and techniques that are used for elaborating and building software products, having the purpose of using them through modern computing systems (*computers* and *special equipment*). They offer a different approach through which computers and special equipments modify the way the human being perceives the reality from a natural environment, this being by simulating or modeling of another reality. It is known that this system/medium, this computer simulated reality bears the name of *Virtual Reality*. During the last years, the grand development of *multiprocessor technology* produced, in terms of computer-market, more and more powerful *machines*. These *machines* come equipped with better graphics processing units than the previous releases at a lower price. Thus, it can be possible that even a non-frequent user uses the software products of **Computer Graphics**. The magic of a *new reality* usually begins with computer games and can expand ad infinitum. It allows us to view the world around us through another dimension. The advantage of this is that it lets us experiment different things that would be otherwise inaccessible or even non-existent in real life. Furthermore, the world of 3D graphics has got neither frontiers nor constraints and can be created and manipulated by any user in any way they wish. The wise move to be made is to stop and reflect for a few moments on the fact that this world is gifted with a fourth dimension, that being our imagination. This being known, regardless of the reached evolution stage, this will never be enough for its users. They will always feel the need for more. They wish to step into this world and interact with it, instead of just watching an image on the monitor. This technology becomes more and more popular and modern and is known as **Virtual Reality**.

The newly designed VR equipment tries to virtually recreate the normal functional behavior of the human being in such a reality. This equipment is represented by the following:

- 3D glasses, VR headsets (HMD – Head Mounted Display), 3D monitors;
- VR gloves, steering wheels, gamepads (with "*force feedback*", which means that they are able to communicate in both directions with the virtual environment);
- Trackers (which follow the movement of the human body).

The main applications that are considered to be the most important ones for *virtual reality* are the following:

- Modeling, simulating and visualizing in the scientific domain: among the obtained results are the image and study of different models or of phenomena that would be otherwise inaccessible to direct observation (information fluxes, atomic structures, meteorological systems, cosmic systems etc.); the results are mainly used in *educational software*;
- Experiments and simulations in the medicine domain: learning different procedures without the risk of losing the life of a patient (e.g. surgery);
- Simulation systems (simulators in general): used for training pilots, astronauts, drivers etc.; this way, difficult maneuvers can be done, without endangering the user's life or the security of the vehicle cabin (plane, helicopter, car, train, water ships, space ships etc.);
- Computer aided design (CAD): in different domains, such as construction, architecture etc.; the man in charge is able to see the results of the project in the form of an image representation in real time, to see the details, to check whether the criteria are met, to take decisions for modifications of parameters before the prototype is built;
- Create and design computer games and animation movies.

4.2.3. VGS Context and Definition

VGS was proposed in 1999. A big difference from GIS is that VGS is a human centric environment. From the Geography point of view, VGS is an environment that settles the relationship between human and 3D virtual worlds. From the information systems point of view, it is an advanced system that is able to combine GIS with VR technology.

The geographical space represents all that surrounds us, the world we actually live in. We can try to experiment many different things from our environment directly, but its huge size will not allow us to see an entire zone. It is pretty tough to do such experiments in such conditions. The experiments can be easily done if we could view the entire scene. Cartographic maps have been used throughout time for communicating the necessary spatial data, thus offering a visual representation of a world that is too big to be directly viewed. The problem with these maps is the fact that they are not able to contain enough information to represent an environment in its full 3D aspect. For this reason, certain visual elements which should have a greater importance are usually omitted.

A VGS is defined as a virtual representation of a real world that allows a person to explore and interact with a vast quantity of cultural and natural data. Compared to the 2D maps and the GIS system, VGS is a human-centric world. The geo-spatial information is different than other type of information because of its unique abilities to describe spatial/terrain modifications. Thus, dynamic and multidimensional analysis methods are very important in order to explore spatial problems.

VGS is a multidimensional describing space that includes almost any type of information: text, 2D maps, 3D GIS, 4D animations. It is proven to be the most efficient interface between human and computer for geographical data communication. The technologies of human-computer interface include visual/audio/tactile interfaces, user input, thus VGS can simulate the interactions from the real world. This leads to discovering new methods for understanding the real world and GIS. VGS supplies multidimensional and multisensory user-interfaces through which the intended purpose is to ease multidimensional datasets browsing and visual context exploration.

In order to create a 3D virtual environment, one can use **VRML** (**Virtual Reality Modeling Language**). The initial purpose of the language was the transition from a Web text-type interface to one with three dimensions, being in permanent interaction with the user.

Nowadays, VRML is rewritten in XML (Extensible Markup Language) terms, the new version having the name **X3D**. Instead of browsing pages with static images and following hyperlinks, the users are able, for example, to browse hallways and manipulate objects, using a special visualization helmet *(Head-Mounted Display)* and a VR glove for "communication" with the environment. Recently, the **Virtual Retinal Display** (**VRD**) made its way to the top of the 3D equipment tools in order to be used for a better exploration of the 3D virtual space.

4.2.4. Visualization Scenarios in VGS

Any real geographical space can be transposed to the virtual world in one way or another. But after the virtual world is created, it is important to be able to visualize it in the easiest way possible.

In order to experiment our integrated system, first of all we developed an object-oriented application used for building different VGS scenarios with different complexity. For this objective we used the object-oriented graphics rendering engine Ogre.

The most intuitive way is to allow the user to press some keys that resemble the arrows and move in the corresponding direction. This solves the movement part. But the application should also allow the user to view the scene from a single spot by rotating to the left or to the right or even up and down. This is done by implementing a mouse functionality that will allow these specific rotations to take place. The whole scene can be viewed from two perspectives: a 3rd or a 1st person perspective.

First person perspective refers to the perspective rendered from the point of view of the user. Applications with a first person perspective are usually avatar-based: the screen displays what the user would see with their own eyes if they were actually placed in the 3D environment. Thus, users do not see the avatar's body, although they may see some parts of it, like hands, feet, maybe a weapon if the application provides one. This viewpoint is generally used to display the perspective of a driver inside a vehicle. Considering this perspective type, the application does neither require sophisticated animations, nor complex model with lots of details for the avatar. This is a good way to make room for improving the details of the surrounding world. A first person perspective allows for easier aiming, since there is no representation of your avatar in the way. The disadvantage of the lack of a fully visible avatar is that it makes difficult to master the actual positioning in the virtual world. Some people also experience motion sickness from this perspective.

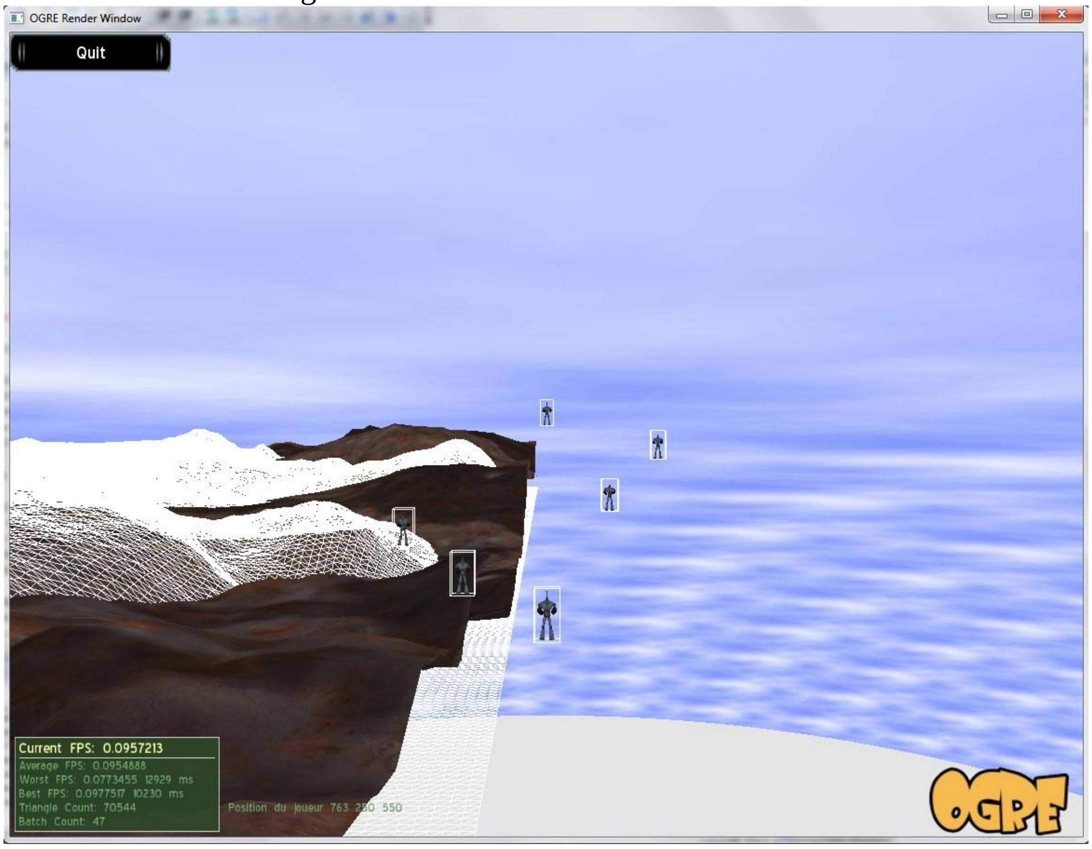
Third person perspective refers to the perspective rendered from a fixed distance behind and slightly above the avatar character. This viewpoint allows users/players to see a more strongly characterized avatar, and is most common in action or action adventure games. There are three types of third person camera systems:

- *Fixed* – the camera positions are set during project development
- *Tracking* – the camera follows the avatar character, usually staying behind it
- *Interactive* – the camera is under the user's control

The **avatar control** is done by using the mouse and the keyboard. The keyboard is used in order to move the avatar left, right, up, down, front and back and the mouse is used to control the camera so the user is able to visualize every part of the surrounding environment. The keys for controlling the avatar are the standard ones which are used in almost every computer game these days, i.e. W (front), A (back), S (left), D (right), Q (down) and E (up). Thus, every user will easily adapt to the avatar control of the project since it is a well known standard (Fig. 4.4). The camera is also the same as in most general computer games and similar applications: when moving the mouse left, right, up or down, the camera turns to face the corresponding direction.

The **avatar model** is represented by a 3D object (character), in this case, a robot. The robot has a few animations that represent the state it is currently in: idle, when the robot stays still and no scenario was selected, and walking, when the robot is executing a scenario and has to walk on the specified trajectory. The robot model is used only when a scenario is specified, so it will start walking once such a scenario was given. During the initial phase, when the user specifies a scenario or wants to simply walk around the virtual 3D environment with the directional keys and mouse movement, the avatar character does not follow; it will just stay still, as opposed to the camera which will execute the requested movement.

The **camera control** is generally set on free movement that is it can be moved freely around the environment without a specific relation to the previously mentioned robot. When the "Start scenario" button is pressed, the camera positions itself at the same point as the robot (avatar). The avatar starts walking following the scenario rules and the camera does the same. The camera is implemented as to be in a first person view at the start of the program – the user looks through the avatar's eyes – and if the user wants, they have a free hand into modifying it to a third person perspective. Thus, the keys and mouse control remain active during the scenario execution. If the user modifies the camera position, there is the possibility that they want to revert it back to a first person perspective, from the avatar's perspective. As a failsafe mechanism, the camera is programmed to go back to its original position (i.e. the position of the avatar) each time it meets a new point in the 3D environment where it must change direction.



```
Current  FPS:  0.0957213
Average  FPS:  0.0954888
Worst  FPS:  0.0773455  12929  ms
Best  FPS:  0.0977517  10230  ms
Triangle  Count:  70544
Batch  Count:  47
```

```
Position  du  joueur  763  250  550
```

Fig. 4.4: Visualization Scenario using Ogre

Scene selection can be done at any time during the application is running, with the exception of a scenario executing process. The GUI provides a list of existent scenes which can be loaded and the user will have to choose one scene file from that list. In order to get a friendly user interface, the

CEGUI library is used. *Crazy Eddie's GUI*, also known as CEGUI, is a graphical user interface C++ library. It was designed especially for video games, but since it has a large variation in terms of functionality, it can be used for other similar applications. The flexibility in look-and-feel makes it easy to integrate and adapt to the application purposes. The strong point of CEGUI's design is the configurability. It interfaces with windows, display text and similar components through user-defined code, though there is a number of modules included for using certain components and libraries. CEGUI can be used in almost any kind of resource management system or operating environment. The input is gathered by the user code and then it is sent to the CEGUI for processing. The rendering part is done by a back-end module. It is important to mention that the CEGUI source code comes with modules for Direct3D, OpenGL, OGRE 3D engine and Irrlicht engine, but if the user wants, they can write their own custom module for other engines.

When the user sets the parameters in the client application, one of the parameters implies the selection from three different **visualizing methods**: a video streaming visible in the interface, an image when the cluster renders only one image frame and a video represented by a sequence of images. When the visualization method is chosen, it can also be customized. For example, the user will be able to specify the resolution at which the output file is rendered, or if the result is a video, they can also specify the number of FPS (frames per second).

The data model of the application consists of the VGS scene files that are mainly stored on the server. The client application has to be aware of those scene files in order to know what the environment looks like, so it requests them in some form. Because of the low hardware resources, the previously mentioned request returns an XML file.

In order to be able to parse such a file, the program includes a special class, i.e. the DotSceneLoader class. The name comes from the extension of the input files (*.scene). Here is a sample part from an input file that represents the way an XML file should look in order to be compatible with the project:

```
 <node name="Ninja1" id="1">
        <position x="-800.0" y="0" z="0" />
        <rotation qx="0" qy="-1" qz="0" qw="1" />
        <scale x="1" y="1" z="1" />
        <entity name="Ninja1" meshFile="ninja.mesh" static="false" />
</node>
```

Every object that is included in the scene is represented by an entity. Each entity is attached to a node in the scene graph. As the code implies, each entity has a name which has to be unique from all other entities existent in the entire project. If an entity name appears more than once, the application prints an error message and crashes. Besides the name, the entity will be told what object to load. In this case, it will be an object with the "mesh" extension.

Besides the entity, which is the most important part of the node since it describes the actual object that is displayed on the screen, the XML file requires that each node has the name, id, position and rotation specified. The entity name restrictions are also applied to the node. This means that nodes must have a unique name, different from the rest of the nodes. This way, a node can be easily manipulated (translated, rotated, deleted etc.) if it is selected by its name. The nodes can also be manipulated by their id.

The position of each node is set by giving values to the corresponding x, y and z coordinates. The object will be placed at the specified position in the 3D environment. The rotation parameters are similar to the position ones. They represent the rotation on all axes. The rotation parameters allow the objects to face a specific direction in the VGS. The scale is always present in the node description of an object. This attribute specifies the actual size of the 3D model. The values can vary from 0, which represents the smallest size possible, up to 1, which represents the largest size possible. Real values should be set for each of the three axes.

Not only 3D objects can be attached to nodes, but also lights, spotlights, cameras, almost anything that has a position and can be rotated in the VGS. When attaching a light source to a node, the code is slightly different: it will not contain an entity and its attributes, but instead specific code is used. An example follows:

```
<light name="Omni01" type="point" intensity="0.01" contrast="0">
        <colourDiffuse r="0.9" g="0.0" b="0.0" />
        <colourSpecular r="0.9" g="0.0" b="0.0" />
</light>
```

Each light that is placed in the scene, must be given an intensity and contrast value. Another important setting is the specification of the diffuse and specular color. These set the RGB values for each of them independently.

The above sample code was only for demonstration purposes, thus it does not represent the entire complexity that can be done for the input scene files. An important and useful aspect is that each node can have children nodes. This means that when setting the position of the children nodes, they will be placed relative to the parent's position. The same goes for the rotation of the children nodes. When such a node is rotated, its rotation will be relative to its parent.

All these operations, tools and techniques represent an interactive language through which a movement scenario can be created.

4.2.5. Object-oriented graphics rendering engine integration

In order to render and interact with high-resolution geographical data sets and complex models of virtual geographical space, in the beginning the challenge was to find an object-oriented graphics rendering engine to make it easier and more intuitive for us to produce applications utilizing hardware – accelerated 3D graphics. The class library we found in object-oriented graphics rendering engine abstracts all the details of using the underlying system libraries like Direct3D and OpenGL and provides an interface based on world objects and other intuitive classes. It is very important to remark that this library uses a flexible class hierarchy allowing us to design plug-ins to specialize the scene organization approach taken to allow us to make any kind of complex scene we like.

On the other hand, from the point of view of the graphical cluster we modified the Equalizer framework which is an open source parallel rendering framework in order to solve the integration with the graphics rendering engine. The applications based on the framework we obtained after the modifications provide better performance and allow visualizing complex data sets.

The solution of integrating graphics rendering engine applications in cluster based architecture using the parallel rendering framework is the main concern of the research reported by this thesis.

4.2.6. 3D Objects Modeling

3D modeling is a process through which a mathematical or a wireframe representation is created for a 3D object with the help of a specialized software tool. The resulted product is known as the 3D model of the object. The 3D model can be viewed as a 2D image, by applying the process called *3D rendering*.

The 3D models can be created manually or automatically. By manual model creation we understand a basic process that implies manual placement of vertices, surfaces, and edges in order to create the desired model. It is similar with sculpting. The automatic way for building models implies the use of algorithms. This method is easier to use because when you apply such an algorithm, the model that will result will be identical every time. The only problem is to find or to implement one.

From the point of view of the representation, 3D models are divided in two categories. *Solid* models are the most realistic approach, but also the most difficult one to obtain. They represent an object with its entire volume, meaning that even the inside composition is built. The second category is *shell/boundary*. The main difference between this and the previous representation is that shell models are, as the name says, empty on the inside. Only the outer layer is designed. Most 3D animations and games use this representation, since it is less resource consuming and the viewer is not interested in seeing the interior part of the models.

There are five popular ways to represent a model:

- *Polygonal modeling* – the vertices are connected to each other through segments, thus forming a polygonal mesh. Many 3D graphics software programs use this technique (3D Studio Max, Blender). The advantage of this representation is that the resulted models are very flexible and are easily rendered by computers. The disadvantage is that the curved surfaces of real objects are only approximated by polygons (planar surfaces).
- *NURBS modeling* – NURBS surfaces are created by using spline curves. These curves have weighted control points that are used in order to pull such a curve closer to a desired point. Unlike the polygonal model representation, NURBS modeling offers really smooth surfaces of every detail of the model. No approximations are done. This technique is mainly used for organic modeling. From among the software programs that use NURBS, the most well-known are Maya, Rhino 3D and solidThinking.
- *Splines & Patches modeling* – they are similar to NURBS; they also use curved lines, but when talking about flexibility, patches are placed between NURBS and polygonal modeling.
- *Primitives modeling* – this way of modeling uses geometric primitives in order to build more complex models. Such primitives include spheres, cylinders, cones, and cubes. The main advantage for this procedure is that all the main primitives are well defined and can be mathematically represented, thus obtaining an exact replica of objects from the real world. It is mainly used for technical applications, where models have specific and well designed forms. There are software programs, like POV-Ray, that use this type of modeling representation.
- *Sculpt modeling* – it is the newest representation methodology from all of those mentioned in this section. Despite this fact, it is quite popular among the graphics designers. Currently, the sculpt-modeling technique exists in two types: displacement and volumetric. Sculpting is done in software programs like ZBrush. The result is a model with a very detailed design and having high resolution information.

4.2.7. The Scene Graph

A scene graph is a general data structure that is frequently used for vector applications, designed for graphical editing, and modern video games. Some examples of such programs that use this data representation model are the well known AutoCAD, Adobe Illustrator, Acrobat 3D, and CorelDRAW.

A scene graph is a hierarchical structure that manages the logic and spatial representation of a graphical environment in a collection of nodes. The nodes can be represented by graphics objects, lights, text, sounds, or even transformation operations such as rotation, and translation. Each node can have a number of children, and in most cases only one parent. A parent node can represent a transformation operation; in this case, its effect will be felt by all of its children.

For the implementation step, a transformation matrix is used. At each level in the graph, there exists such a matrix. In order to naturally and efficiently process such operations, one will have to multiply the required transformation matrices. The scene graph is a way to represent complex graphics environments by the use of elementary objects.

In order to implement a scene graph for a given 3D application, the easiest way is to design a list-type structure. Then, in order to show the graphics objects or to execute operations, the given structure is linearly iterated (one by one). As it can be deduced, when dealing with more complex environments, this methodology can become quite slow. Thus, another structure type is used, the tree-type structure, and the composite design pattern in order to maintain a hierarchical relation among the group/leaf nodes. Group nodes can have any number of children and represent transformation operations, while leaf nodes are the ones that actually get rendered and represent the results of the operations.

The graph traversal represents the strongest point and the reason for using such a scene graph. Each traversal operation begins from a start node (root node), the operation contained within is executed (usually, the update and render operations for an object are consecutive) and then all the children-nodes are recursively visited until a leaf node is reached. Currently, most scene graphs are traversed in a bottom-up fashion. For example, in the case of rendering, a Pre-Render operation is done while recursively reaching all the nodes and a Post-Render operation is executed when a leaf node was reached and the bottom-up traversal is started.

4.3. Virtual Geographical Space Model

A virtual geographical scene recreates a real environment by a subset of graphical models that simulates the physical objects. In the following paragraphs, we will define a conceptual model and an XML based representation.

The components that define a geographical space are the graphical models that represent objects from the real world and the dependencies between these objects. For example, we can define a virtual geographical space as a terrain that has some parameters such as geographical area coordinates (that implies some restrictions), and different objects such as trees, water areas, houses etc. All of these objects may have specific attributes and parameters.

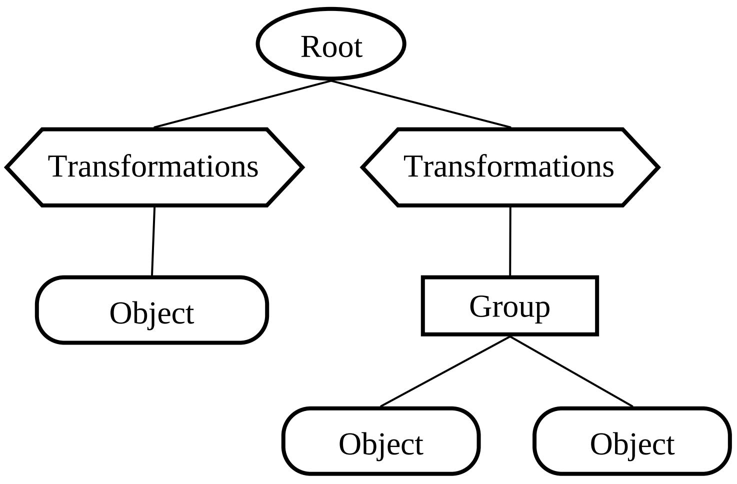


Fig. 4.5: Graph-based structure of the VGS model

The specification of a virtual environment must integrate the concepts of virtual objects, object space transformations, constraints and dependencies between virtual objects. The virtual object depicts a representation of real objects, which have attached different attributes. The object instance in the virtual space is the result of transformations, translation, rotation and scaling on the basic object definition. The system creates automatically the virtual model as a collection of object instances. In order to recreate a correct representation of the real world, we can use constraints. For example, a specific type of vegetation may appear only in conjunction with a specific geographical area.

A graph-based model (Fig. 4.5) describes the conceptual model. The graph nodes represent the objects and the arcs represent the dependencies between nodes. For example, the root node may represent the virtual space ground, or terrain, which is populated by different objects. The next level may represent a group of objects, for example a forest that is composed also by a set of different objects, like trees, flowers etc. The attributes that must be specified for every node are the name of the node, some textual description, an area in which are created the objects (that represent the space occupied by the objects, for example we can define an area in which are randomly generated trees) and also restrictions (for example in which limits we can generate the objects).

For storing this description, we use a XML based format that allows the description of nodes and arcs. As stated previously the nodes contain information about objects and the arcs describe the dependencies between objects. We have adopted the 3D graphical model representation to define the virtual objects. The polygonal representation of the objects, together with the associated textures, offers a quite good and economical solution for the representation of the real world environment. The major drawback of this solution is related with the high resolution. The model is very complex in terms of vertices and polygons and on a single machine the visualization can be problematic. On the other hand, in a cluster based visualization system it offers a very good performance related with the visual accuracy.

An important feature is that the scene graph must be able to integrate also dynamicity. By this way, that is the subject of future research, we could describe animation and simulation parameters. The physics processors support the simulation of real natural phenomena (e.g. wind, cloud movement, water flow etc). In order to include animation the scene graph must also include flow control structures.

4.4. Use Case Scenarios for building 3D complex scenes

The Ogre application we developed for building different 3d scenes with different complexity has an important purpose for testing the system architecture. This section provides information on how the current application is used by the user. Some use case scenarios will be described shortly, while others (more complex ones) will be presented with more details by presenting both the basic and alternative flows.

4.4.1. Visualization Scenarios

- *Use Case 1: Select Scene*

This use case scenario represents the situation in which the user must select a scene for the application. A list is provided by the system's CEGUI which contains all the available 3D scenes which can be chosen. After the user clicks on one scene name, it will be instantly loaded on the screen. The previous existent scene will be unloaded. Since the client machine may not have the necessary resources in order to render the entire scene, only the bounding boxes of all the objects will be loaded.

- *Use Case 2: Select Resolution*

When choosing the output result, the user has the possibility to select the resolution of the rendering material. There are three types of resolutions: small (320*240), medium (640*480) and large (1024*768).

- *Use Case 3: Start Visualization Scenario*

Primary Actor: Equalizer cluster

Secondary Actors: Broker component, Rendering server

Basic Flow:

1. The client application sends a start message with the name of the scene file to be visualized and the resolution at which the rendering must be done.

2. The broker component copies the file with the designated graphics environment on all the nodes where the partial rendering takes place.

3. The broker component starts the server node where the final rendering and composition operations are done.

4. The server node sends a message to all the necessary rendering clients, so they can start the parallel rendering application.

5. The graphics cluster executes in parallel the rendering operation of the scene and gets the final rendering result on the server node.

6. After obtaining the video result, the rendering server encodes it in MPEG-2 video format.

7. The rendering server sends the encoded video file to the client machine, where a video player will permit its visualization.

Alternative Flow:

1. One of the processes necessary to start the graphics cluster fails.

2. The file containing the scene graph is not represented in a valid format and it cannot be loaded in the application.

5. TECHNOLOGICAL CONSIDERATIONS

5.1. Object-Oriented Graphics Rendering Engine

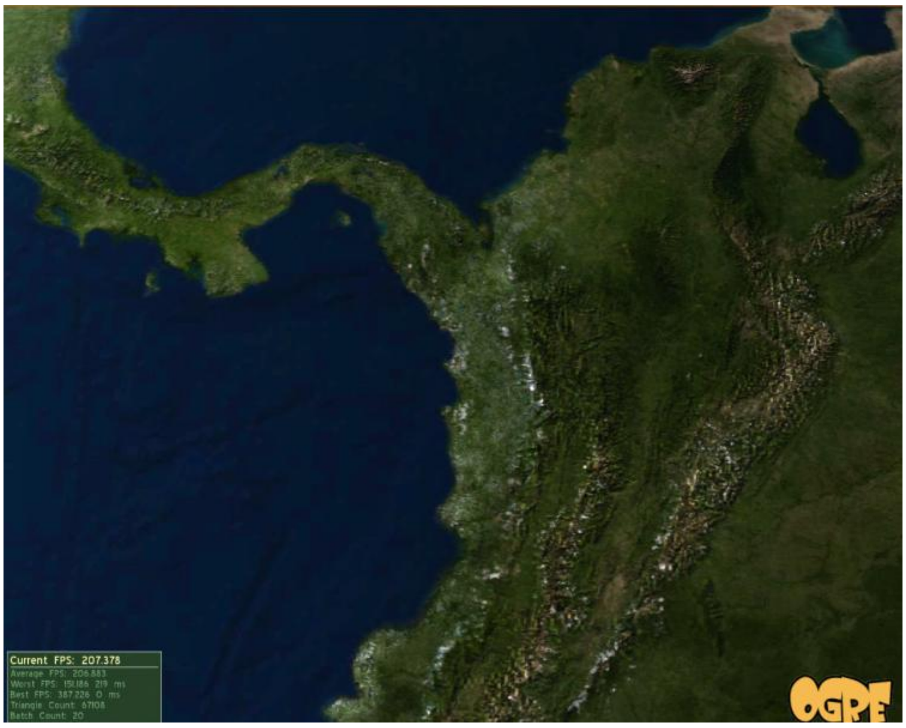
Object-Oriented Graphics Rendering Engine, also known as OGRE, is a scene-oriented, flexible 3D rendering engine written in C++. It is designed as being easy to use and learn by even the beginner programmers who want to create applications that use hardware-accelerated 3D graphics. The class library abstracts the details of using the underlying system libraries like Direct3D and OpenGL and provides an interface based on world objects and other high level classes.

OGRE has a very active community. It was Sourceforge.net’s project of the month in March 2005. It has been used in several computer games, such as Ankh and Torchlight. The first version of Ogre (1.0.0 named “Azathoth”) was released in February 2005. The current release is 1.7.1, named “Cthugha”, was released on the 25th of April 2010.

5.1.1. Introduction

OGRE is an open source rendering engine. Its main purpose is to provide a suitable option when dealing with graphics rendering. It includes several facilities, such as vector and matrix classes, or memory handling, but they are not the main part of it. Considering this fact, it does not have audio or physics support. Programmers which use this engine for creating their own games should also include frameworks for this kind of support.

Despite being excellent at what it does and providing a large number of features (Fig. 5.1), this is one of the main drawbacks of OGRE. Some people actually consider it as an advantage since they are free to choose the desired libraries for physics, audio or others. Even more, it allows the development team to focus on the graphics part of the project rather than distributing their efforts among several systems. It is widely known that OGRE supports the OIS, SDL and CEGUI libraries. They are used for key input events or user interfaces.



```
Current FPS: 207.378
Average FPS: 206.883
Worst FPS: 151.186 219 ms
Best FPS: 387.226 0 ms
Triangle Count: 67108
Batch Count: 20
```

Fig. 5.1: Screenshot from the official OGRE Demos pack. Rendering options: 1600*1200 pixel resolution, OpenGL renderer, 32-bit color depth

Shown below is a diagram of the core objects and their position in the grand scheme of OGRE (Fig. 5.2). This is just an example of the most significant structure, in order to give the user an idea of the big picture.

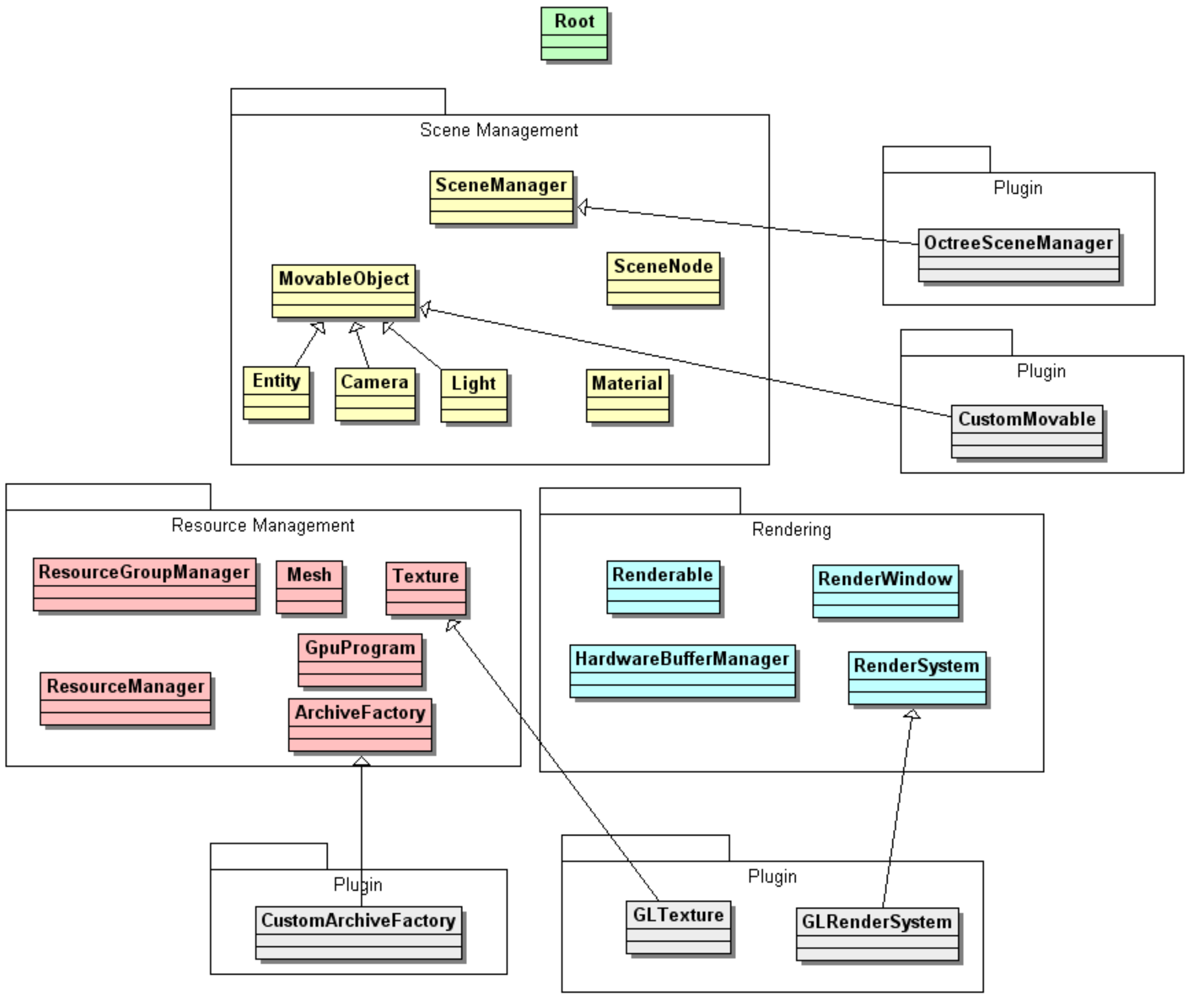


Fig. 5.2: Example of OGRE core objects UML diagram

The top of the diagram is represented by the Root object. This represents the “way in” to the OGRE system. It is where you create the top-level objects that you need, i.e. scene managers, rendering systems, rendering windows, loading plug-ins etc. It is considered as having the role of an organizer of the rest of the objects.

The majority of the other OGRE classes can be grouped in 3 main categories:

- **Scene Management:** it represents the contents of the scene, the way it is structured, how it can be viewed from cameras etc. The objects which are created here offer an “interface” of the world you are building.
- **Resource Management:** this is the place to store the needed resources, whether they refer to geometry, texture, fonts or any other resources.
- **Rendering:** takes care of the actual representation of visuals on the screen.

There is also a number of plug-ins scattered around these three categories. OGRE was designed to be extended, and plug-ins are the usual way to go about it. This way, OGRE is not just a solution for one specifically defined problem; it can be extended to about anything you need to do in terms of graphical applications.

5.1.2. Features

OGRE, as its name implies, is an object oriented engine. It was previously mentioned that it was designed with a plug-in architecture that allows the easy addition of features, thus making it highly modular. OGRE is also a scene graph based engine that supports a large variety of scene managers, some of which are octree, BSP and a Paging Landscape scene manager.

It is fully multi-platform, supporting both OpenGL and Direct3D applications. It is able to render the same content on different platforms while the programmer does not have to mind the differences between them. This reduces the complexity of deploying an application on multiple systems. There exist pre-compiled binaries for most operating systems, i.e. Linux, Mac OS X and all major versions of Windows.

The animation engine supports hardware weighted multiple bone skinning, which can be fixed across several poses for full pose mixing.

The libraries feature memory debugging and loading resources from archives. There are content explorer tools available for most 3D modelers including 3D Studio Max, Maya, Blender, LightWave, MilkShape, Sketchup and others.

5.2. The parallel rendering framework – Equalizer

The main purpose of the Equalizer Graphics Cluster is to be used in applications in order to accelerate the rendering process of a 3D environment, using more than one machine/graphics accelerator. With the help of Equalizer, one can create parallel OpenGL applications, i.e. it allows the applications to use several graphics cards, processors and computers in order to increase the rendering performance. An Equalizer-based application runs identical on a simple computer or on a large specially designed cluster.

5.2.1. Introduction

As we know, hardware performance used for graphical rendering has reached high evolution levels in the past decade. But we cannot say the same thing about the CPU hardware performance. When talking about 3D complex objects rendering, one video card cannot achieve the desired result.

Distributed processing by the help of clusters has become a key technology with respect to high speed computing. Equalizer is used in order to help graphics visualization applications so that they can make use of this key technology. It was described by Stefan Eilemann, the project leader, as being a "GLUT" for multi-GPU systems and visualization clusters.

An application that uses the Equalizer framework will have following advantages:

- Runtime configuration: the rendering system is configured at runtime, by using a standard configuration file.

- Runtime scalability: an application can use the entire computing power of more than one processor, video card, or computer in order to achieve high performance and high quality.

- Distributed execution: an application can benefit from parallel execution on a cluster.
- Stereo-rendering and head-tracking support: an Equalizer application may be configured for stereo rendering, thus simulating a 3D visualization process.

Equalizer is a cross-platform solution, available for Linux, Windows XP, Mac OS X for both 32 and 64 bit versions. It offers graphical scalability on three fundamental axes: data quantity, rendering and displaying capacities.

- Data scalability: a larger data quantity for a larger cluster.
- Rendering capacity: rendering performance enhances when the number of video cards increases in order to display a single image.
- Displaying capacities: large images can be shown using tiled displays.

Equalizer is the result of more than 10 years of experience in parallel and scalable rendering domains, easily integrated in other applications.

5.2.2. Use Case

The Equalizer framework is used in the following situations (as described in **Error! Reference source not found.**):

- **Display-walls (Fig. 5.3):** display-walls are one of the most frequent use cases. The configuration executes an instance of an application for each screen. The rendering processes are done locally and the result of the node rendering is sent directly to the screen, without passing them through the network.
-

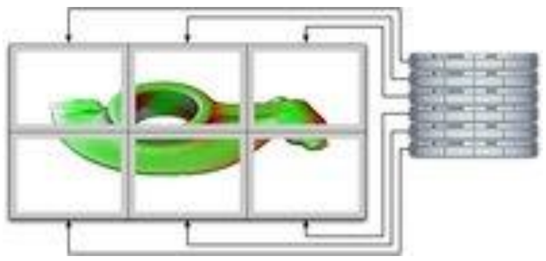


Fig. 5.3: Display-wall for Equalizer

- **Virtual Reality (Fig. 5.4):** these systems simulate reality by using many non-planar screens. The screens are rendered in stereo mode, offering a reality sensation to the user. Equalizer offers support for head-tracking.

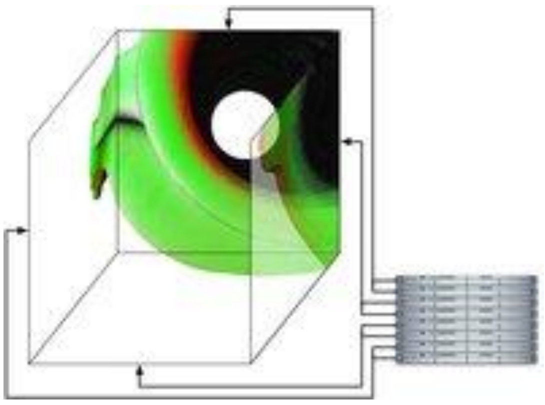


Fig. 5.4: Virtual Reality with Equalizer

- **Rendering using more GPUs (Fig. 5.5):** Equalizer offers support for workstations with more than one GPU.

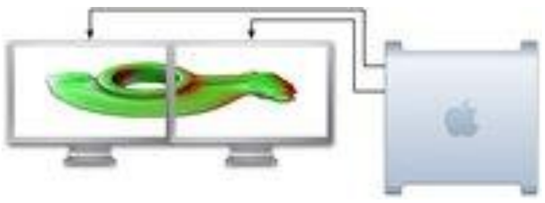


Fig. 5.5: Multi-GPU rendering with Equalizer

- **Scalable rendering (Fig. 5.6):** for scalable rendering for a single view, more than one processor, video card, workstation is used. Algorithms such as 2D, DB, Dplex, Eye can be used in these situations.
-

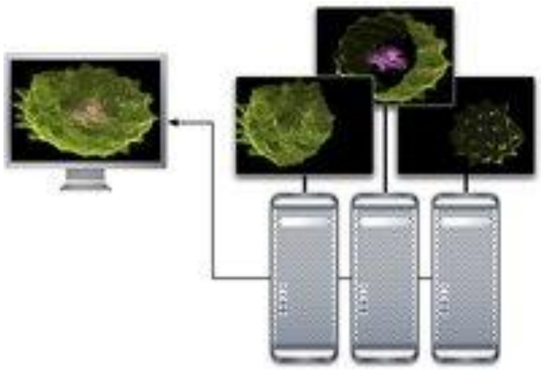


Fig. 5.6: Scalable rendering with Equalizer

5.2.3. Execution Model

A rendering Equalizer-based system is composed of the main application, a server and a number of rendering nodes.

The main application is responsible for the global logic, for handling events, for modifying the data model, for sending rendering requests to the server which assigns rendering tasks to the clients, depending on the system configuration.

The simplified execution model is presented in the following figure (Fig. 5.7):

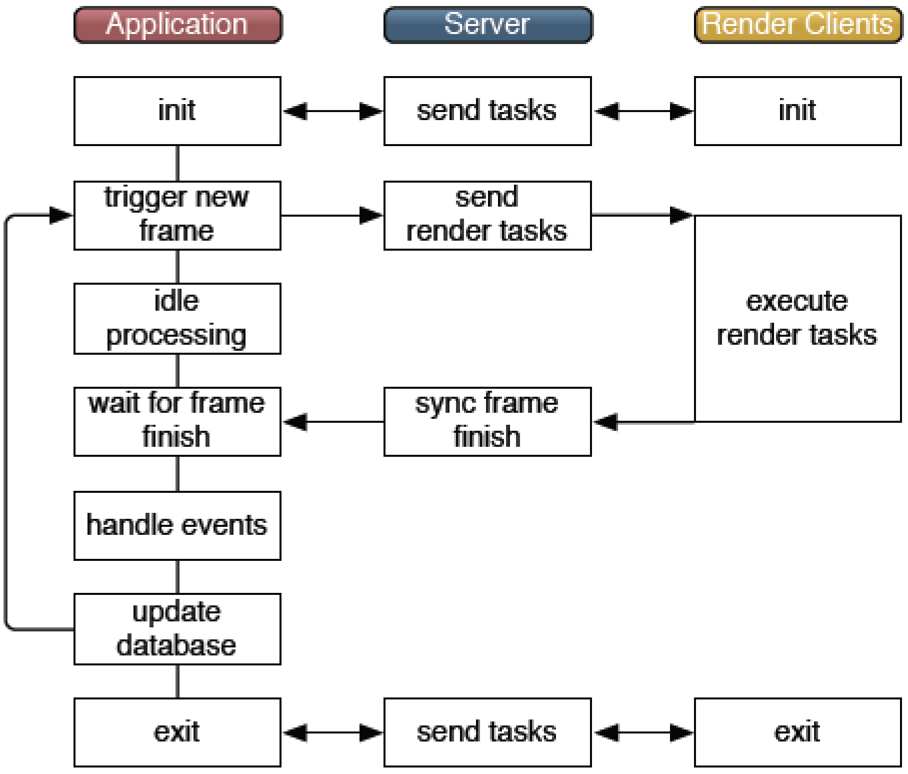


Fig. 5.7: Simplified execution model for Equalizer

5.2.4. Configuration

The system configuration is done through configuration files. The rendering resources are represented through a tree hierarchy. The resource management model is configured with the help of the component tree, which is a hierarchical representation of decomposition and recomposition across the resources.

The configuration elements are presented below:

- **Node:** represents a machine in the cluster.
- **Pipe:** represents an abstraction of the graphics card in each machine, so each node will have one pipe. For each pipe, a separate execution thread is created.
- **Window:** encapsulates an OpenGL rendering context, which can be a window in the OS, or a virtual window, i.e. a PBuffer.

- **Channel:** represents an abstraction of the viewport in the existing window. It executes the actual rendering.

Each of the previously described elements is mapped to their corresponding classes in the Equalizer implementation. A configuration example for a VR system is represented in Fig. 5.8.

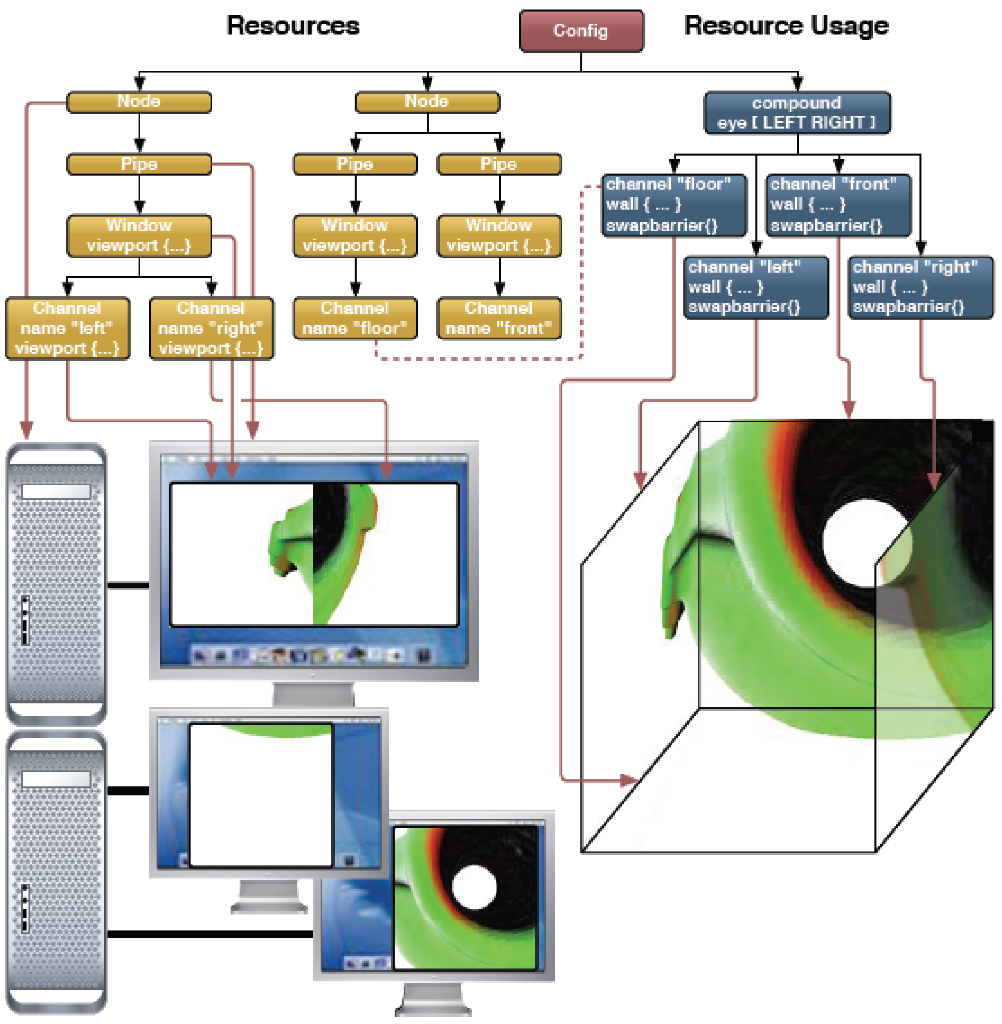

Resources
Config
Resource Usage
Node
Node
compound eye [LEFT RIGHT]
Pipe
Pipe
Pipe
Window viewport {...}
Window viewport {...}
Window viewport {...}
channel "floor" wall { ... } swapbarrier{}
channel "front" wall { ... } swapbarrier{}
channel "left" wall { ... } swapbarrier{}
channel "right" wall { ... } swapbarrier{}
Channel name "left" viewport {...}
Channel name "right" viewport {...}
Channel name "floor"
Channel name "front"

Fig. 5.8: An example configuration

5.3. Scalable Rendering

The parallel rendering framework used supports many important rendering algorithms (i.e. the process of generating an image from a model – mathematical wireframe representation of 3D objects - by means of computations). Choosing the right mode for the application profile is critical for performance and actual execution. The traditional methods used for rendering, like ray-tracing or ray-casting work extremely slow on one computer so, using Equalizer they are reconstructed in parallel rendering algorithms. The parallel rendering exectution relies on the subdivision of work in many processes that run in parallel and using cluster machines compose the results.

The main rendering methods we used in this thesis and supported by the Equalizer framework are:

5.3.1. 2D/Sort-First Rendering

2D or sort-first method decomposes the rendering in screen-space, that is, each contributing rendering unit processes a 2D "piece" of the final view. The recomposition simply assembles the tiles side-by-side on the destination view.

This mode has a limited scalability due to the parallel overhead caused by objects rendered on multiple tiles.

The advantage of this mode is a low, constant IO overhead for the pixel transfers, since only color information has to be transmitted. It is also defined as a "2D – space division rendering".

An Equalizer-based application was create for the purpose of explaining this type of rendering. Figure 5.9. presents this rendering mechanism on such an example.

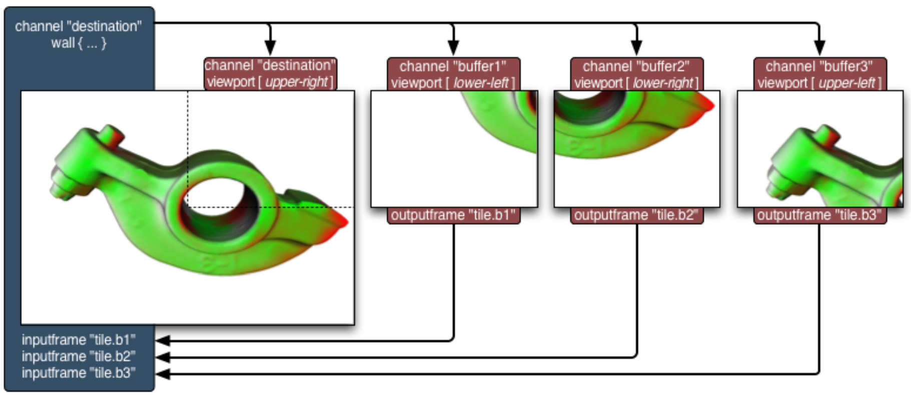


Fig. 5.9: Sort-first decomposition and Re-composition

5.3.2. Sort-Last Rendering

Sort-last rendering decomposes the rendered structure across all rendering units, and recombines the partially rendered frames. This allows lowering the requirements on all parts of the rendering pipeline: main memory usage, IO bandwidth, GPU memory usage and other performance measurements. Therefore, this mode scales the rendering very well, but the re-composition step is expensive due to the amount of pixel data processed during re-composition.

The image below shows an example of sort-last rendering. The computer in the top left corner is the master computer. This means it is responsible for receiving the images created by the other computers, and then compositing them into a final image, which it displays on its own monitor.

With Equalizer methods, the application has to portions the database so that the rendering units render only a part of it. Some OpenGL features do not work correctly (ant aliasing) or need special attention (transparency).

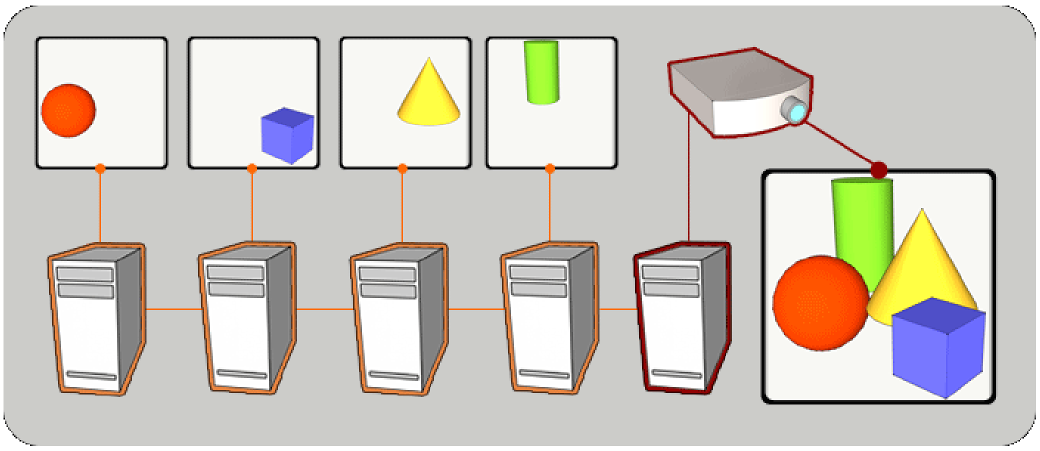


Fig. 5.10: Sort-Last Decomposition and Re-composition

5.3.3. Pixel Compounds

Pixel decompositions divide the pixels of the final view evenly, either by dividing full pixels or sub-pixels. The first 'squeezes' the view frustum, while the second renders the same scene with slightly modified camera positions for full-screen anti-aliasing or depth-of-field effects. The compounds are somehow similar in functionality with the 2D unit processes. Pixel compounds only work very well for purely fill-limited applications; techniques like frustum culling (the process of removing objects that lie completely outside the viewing frustum from the rendering process) do not reduce the rendered data for the source rendering resources.

In Equalizer, OpenGL functionality influenced by the raster position will not work correctly with pixel compounds (lines, points, sprites, glDrawPixels, glBitmap).

5.3.4. Other Methods

Stereo decomposition is used for immersive applications, where the individual eye passes are rendered by different rendering units. Passive stereo systems are a typical example for this mode. In Equalizer rendering framework, the number of rendering resources used by stereo compounds is limited by the number of eye passes, typically two.

5.4. Load-Balancing – Rendering Strategies

Using the load-balancing we can increase the performance of our graphics cluster systems, because this results in balanced computational work among different machines.

For optimal rendering performance sort-first and sort-last compounds often need load-balancing while pixel and stereo compounds are naturally load-balanced.

Some applications do not support dynamic updates of the database range, and therefore cannot be used with sort-last load-balancing. Using a sort-first or sort-last load-balancer will adjust the sort-first split or database range automatically each frame.

There are three modes in which the sort-first load-balancer works: sort-first using tiles, horizontal using rows and vertical using columns.

Sort-first load-balancing increases the frame-rate over a static decomposition in virtually all cases. It is very important to remark that we obtained the best performance if the application data is relatively uniformly distributed in screen-space. In order to fine-tune the algorithm we can use a damping parameter.

From the point of view of the sort-last load-balancing it is known that this rendering strategy is beneficial for applications which cannot precisely predict the load for their scene data. For example when the data is non-uniform.

On the other hand a static sort-last decomposition typically results in a better performance if we have a volume rendering example with uniform data. Considering that a segment represents a single display (a projector or monitor) and that it references a channel (has a name, viewport and frustum) is important that each segment of a multi-display system has a different rendering load and it depends on the data structure and model position. The channel referenced by the segment defines the output channel. In the case we use a static assignment of resources to segments the overall performance is determined by the segment with the biggest load. The solution is presented in our experiments related to load-balancing performances.

Regarding the wrong balancing, some configurations require a smoothing of the frame-rate at the destination channel, otherwise the frame-rate will become periodically faster and slower. Using a frame-rate we will smooth the swap buffer rate on the destination window for optimal user experience.

On the other hand the dynamic frame resolution trades rendering performance for visual quality. In order to keep the frame-rate constant the rendering for a channel is done at a different resolution than the native channel resolution. The solution is that dynamic frame resolution adjusts the zoom of a channel, based on the target and current frame-rate. For instance, volume rendering and ray-tracing which are fill-rate bound applications are usually using dynamic frame resolution. For example, the key for obtaining ten frames per second instead of five is that the model is rendered at a lower resolution and upscaled to the native resolution for display.

Concerning the rendering quality we have to note that it is slightly degraded, while the rendering performance remains interactive. It renders a full-resolution view when the application is idle. The dynamic frame resolution will also upscale the resolution if the parameters allow for it. In conclusion, it does not have a limitation in order to downscaling the rendering resolution. Beside this upscaled rendering which will down-sample the result for display, provides dynamic anti-aliasing at a constant frame-rate.

5.5. Video Compression

Video coding necessity in the case of remote viewing is obvious. Without video coding, it would be necessary to use a very large bandwidth. We also need a method that helps us transmit in real-time. MPEG-2 was chosen, because it is a widely used standard, even in TV industry.

5.5.1. MPEG-2

MPEG-2 is both a video and audio compression standard developed by Moving Picture Experts Group (MPEG). It resembles a combination of compressions with audio and video loss that allow video storage on reduced space media.

The MPEG-2 format is used in digital TV transmissions and for video compression on DVD. MPEG-2 actually represents an addition to the MPEG-1 standard, supporting variable bit-rate and interlaced module.

Elementary Streams (ES) are audio or MPEG video bit streams. An ES can have just one type of information: video or audio. These files can be distributed in this manner, just like in the case of MP3 files. Moreover, the elementary streams can be made more robust by packing, independent piece division, and by adding a cyclic redundancy check (CRC) to each segment for error detection. This structure is called Packetized Elementary Streams (PES).

Program Streams (PS) combines more Packetized Elementary Streams into a single stream, thus assuring their simultaneous and synchronized delivery. In order to generate Program Streams, a multiplexer interpolates two or more PESs. Thus, the packages of simultaneous streams can be transferred through the same channel and will reach the decoder at the exact same time.

A complicated and an important task is to determine the data quantity of each stream that must exist in each interpolation segment (interpolation size). The improper interpolation can lead to the overloading of the buffer; in this situation the decoder will receive more than it can store (e.g. audio) before receiving enough data in order to decode the other simultaneous streams (e.g. video).

Before encoding a video to the MPEG-2 format, the color space must be transformed to Y'CbCr (Y' = Luma, Cb = Chroma Blue, Cr = Chroma Red). This color space is used to separate out a luma signal (Y') that can be stored with high resolution or transmitted at high bandwidth, and two chroma components (Cb and Cr) that can be bandwidth-reduced, subsampled, compressed, or treated separately by improved system efficiency.

The human eye is less sensible to color than it is to luminance. Thus, the chroma components can be partially eliminated. This procedure is called *chroma subsampling*. There are many schemes for the subsampling procedure, such as 4:4:4, 4:2:2, 4:1:1, 4:2:1, and 4:2:0, the last one being used for MPEG-2 encoding. For 4:2:0 subsampling, the Cb and Cr component resolution is cut in half both horizontally and vertically, thus having for each 4 value grup of Luma, only one value of Cr and Cb (Fig. 5.11).

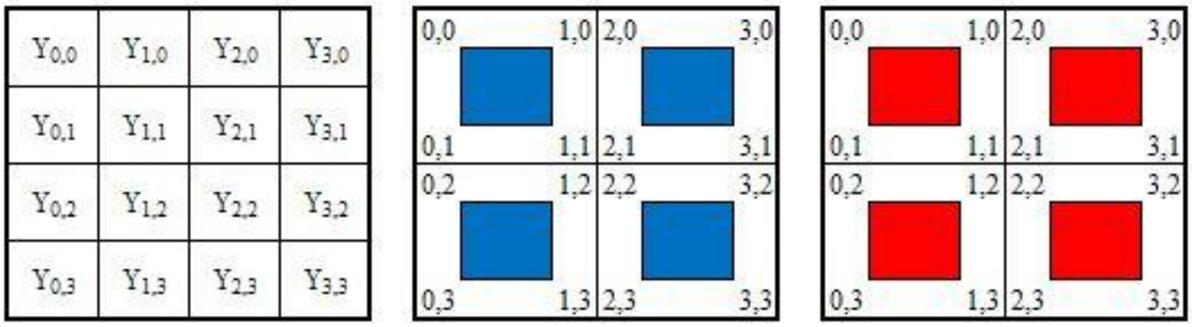


Fig. 5.11: Example of Y'CbCr subsampling

MPEG-2 contains many types of frames, each serving its own purpose. The most important of them are the *I-frames* (**intra-frames**). Their name comes from the way they can be decoded, i.e. independently. I-frames can be considered identical with JPEG images.

High speed navigation in a MPEG-2 video is possible only to the closest I-frame. Videos containing only I-frames are used in editor type applications. Their compression is done very quickly, but the result is a very large file – it can reach up to 3 times the size of a normal MPEG-2 file. The distance between two I-frames is called *Group of Pictures*. Usually MPEG-2 uses a GOP size of 15-18, which means that there are 14-17 frames which are not if type I-frame, but a combination of P-frames and B-frames, which will be discussed in the following.

P-frames (**predicted-frames**) are used in order to improve compression, and are based on the fact that not all pixels are changing from one frame to another. P-frames store only the differences from the previous frame, which can be also a P-frame or an I-frame. If there is not a large difference between frames, the most efficient solution is that the new frame should be an I-frame.

The third type of frames is the *B-frames* (**bidirectional-frames**). They are similar with P-frames, but they can refer both previous and next frames, so, before displaying it, a player has to read the next I or P frame after it has read a B-frame. This requires a more complex computational logic, and larger size buffers, which slows down the process by increasing the time necessary to encode and decode a video.

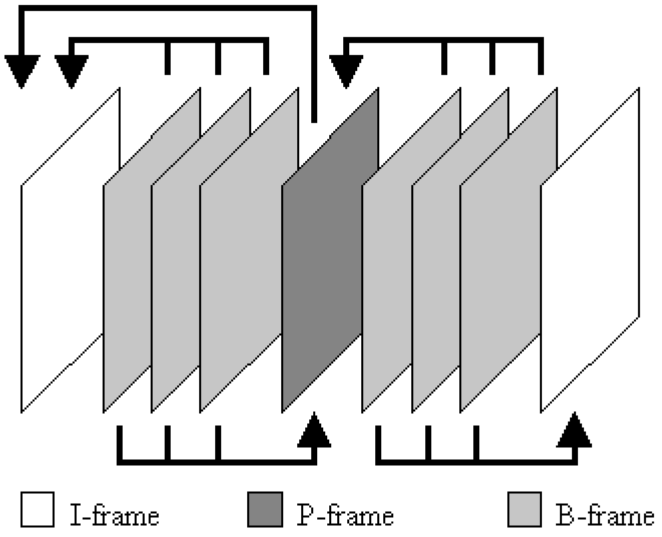


Fig. 5.12: An example of frame types and references in MPEG-2 compression

A **macroblock** represents a 16x16 pixel region from an image and it is the smallest independent unit within a video. If the size of the video does cannot be divided to 16, there will be a row of macroblocks which should be encoded, so the information contained in those regions is not lost. This phenomenon should be avoided because it leads to a waste in the encoding.

In order to eliminate spatial redundancy in a video, only changing blocks are memorized. This procedure is called conditional overwriting. The sudden movement of the camera, or of other objects, would lead to a large number of blocks to be changed. This problem can be overcome by motion estimation through vectors, resulting in the elimination of a large volume of redundant information. Motion vectors operate at the macroblock level.

The encoder compares macroblocks from the previous frame with macroblocks from close I-frames or P-frames situated at a predefined distance. In case the macroblock is found in these frames, only the motion vector is memorized, which is composed of direction and distance. The inverse operation of this process is done in the decoding phase and is known as **motion compensation**.

Each 8x8 pixel sized block is encoded by applying the Discrete Cosine Transformation (DCT), followed by a quantization method. Theoretically speaking, the DCT process is without losses and reversible by applying the Inverse Discrete Cosine Transformation (IDCT). Practically speaking, in the quantization phase during coding, a number of rounding errors can arise. The DCT process transforms an uncompressed block of size 8x8 in another block of the same size with values of frequency coefficients. DCT can be computed by the use of the following formula:

$$X_{k_1,k_2} = \sum_{n1=0}^{N_1-1} \sum_{n2=0}^{N_2-1} x_{n_1,n_2} \cos\left[\frac{\pi}{N_1}\left(n_1+\frac{1}{2}\right)k_1\right] \cos\left[\frac{\pi}{N_2}\left(n_2+\frac{1}{2}\right)k_2\right]$$

Formula 5.1: DCT computation

When this method is applied, an algorithm with O(n^2) complexity is resulted. There is a more efficient method, called Fast Cosine Transform (FCT), using Fast Fourier Transform (FFT). The quantization process consists of reducing the accuracy of the signal by dividing the values with a number. The quantization matrix contains these values, expressing the importance level of an image frequency component. The result after this method is applied is that many values of 0 will make an appearance. The following figures represent the DCT and quantization operations and also the final result (Fig. 5.13, Fig. 5.14).

$$\begin{bmatrix} -415 & -30 & -61 & 27 & 56 & -20 & -2 & 0 \\ 4 & -22 & -61 & 10 & 13 & -7 & -9 & 5 \\ -47 & 7 & 77 & -25 & -29 & 10 & 5 & -6 \\ -49 & 12 & 34 & -15 & -10 & 6 & 2 & 2 \\ 12 & -7 & -13 & -4 & -2 & 2 & -3 & 3 \\ -8 & 3 & 2 & -6 & -2 & 1 & 4 & 2 \\ -1 & 0 & 0 & -2 & -1 & -3 & 4 & -1 \\ 0 & 0 & -1 & -4 & -1 & 0 & 1 & 2 \end{bmatrix}$$

Fig. 5.13: An example of an encoded 8x8 FDCT block

$$\begin{bmatrix} 16 & 11 & 10 & 16 & 24 & 40 & 51 & 61 \\ 12 & 12 & 14 & 19 & 26 & 58 & 60 & 55 \\ 14 & 13 & 16 & 24 & 40 & 57 & 69 & 56 \\ 14 & 17 & 22 & 29 & 51 & 87 & 80 & 62 \\ 18 & 22 & 37 & 56 & 68 & 109 & 103 & 77 \\ 24 & 35 & 55 & 64 & 81 & 104 & 113 & 92 \\ 49 & 64 & 78 & 87 & 103 & 121 & 120 & 101 \\ 72 & 92 & 95 & 98 & 112 & 100 & 103 & 99 \end{bmatrix}$$

Fig. 5.14: An example of quantization matrix

$$\begin{bmatrix} -26 & -3 & -6 & 2 & 2 & -1 & 0 & 0 \\ 0 & -2 & -4 & 1 & 1 & 0 & 0 & 0 \\ -3 & 1 & 5 & -1 & -1 & 0 & 0 & 0 \\ -4 & 1 & 2 & -1 & 0 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

Fig. 5.15: An example quantized DCT matrix

The DCT block contains the most important frequencies in the top left corner (Fig. 5.15). The coefficients closer to the bottom right corner tend to 0. As it can be seen, the quantization actually eliminates a large amount of data.

6. IMPLEMENTATION CONSIDERATIONS

6.1. Graphics Cluster Description

The current application is mainly divided in two parts: the client part, and the server part. As it can be seen, there are some nodes (node1, node2, … node n) which are actually other computers in the network that can take the role of both servers and clients. Fig. 6.1 presents the diagram of the entire application:

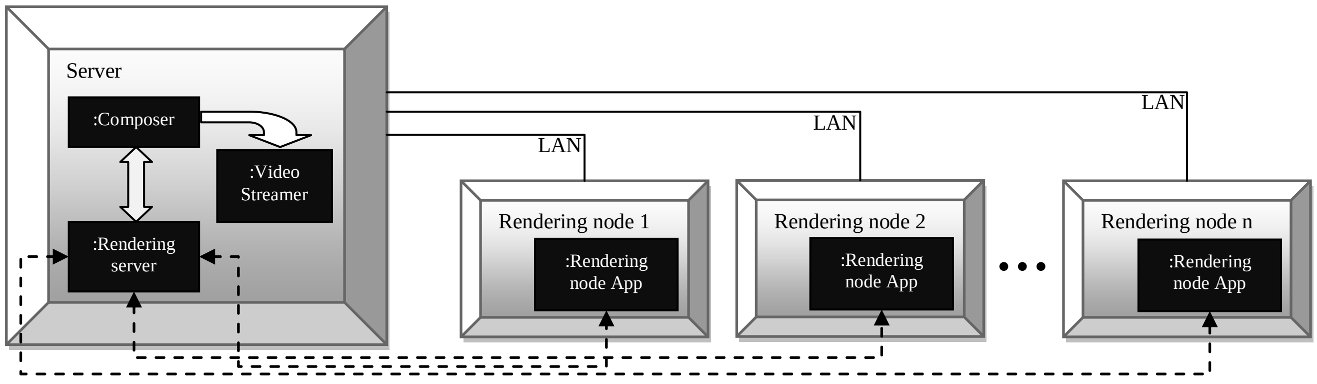


Fig. 6.1: Graphics Cluster Diagram - Rendering nodes and rendering subsystem's server

The main advantage of Equalizer is that it allows applications to be run on several machines, thus taking full advantage of all their GPU computation power. So, if a scene is too complex for just one computer, it can be rendered if more computers are used. The main components included on the server machine are the *rendering server*, the *rendering clients/nodes*, the *broker component* and the *node manager*. Besides them, the server is in the need of a DBMS which contains information about the enabled nodes required for a specific task.

6.2. The solution for integrating an object-oriented graphics rendering engine and a parallel rendering framework

6.2.1. Implemented application

The parallel rendering framework - Equalizer is the standard middleware for parallel rendering. It enables OpenGL applications to benefit from multiple graphics cards, processors and computers to scale rendering performance, visual quality and display size.

The implemented C++ application is a cluster-ready viewer application which is based on the modified Equalizer parallel rendering framework. It is providing the ideal basis for building scalable high-performance 3D applications using multiple GPU's. Also, it is an example application integrating a graphics rendering engine and a parallel rendering framework. Its purpose is to demonstrate the optimal approach for this integration and to serve as a basis for developing scalable, high-performance graphics rendering applications.

6.2.2. Parallel Architecture

The architecture of the implemented application is designed for optimal performance and parallelization, while providing a straightforward programming model.

Each **process** in the cluster is represented by an **eq::Node**. The node instantiates one copy of the scene graph in Node::configInit.

Animation updates and other scene graph modifications are applied at the beginning of each frame in Node::frameStart.

Each **GPU** on a node is represented by an **eq::Pipe**. Each GPU runs its own rendering **thread** in parallel to the other pipes and the node main thread.

Each on-screen and off-screen **OpenGL drawable and context** is abstracted by an **eq::Window**. To render the scene graph, a customized SceneView is used. The SceneView is initialized in eq::Window::config-InitGL(). Only the first window of a GPU, the shared context window, performs this initialization, while other windows reuse the scene view of their shared window.

All **rendering** operations happen in an **eq::Channel**, which represents a **2D viewport** in an eq::Window. Channel::frameDraw, which performs the actual rendering, sets up the SceneView with the rendering parameters provided by Equalizer and triggers a cull and draw traversal to render a new frame.

The rendering operations of all pipe threads on a single node are frame-synchronized, that is, they are synchronized with each other and the node's main thread.

Node processes and compositing operations for scalable rendering run asynchronous to this synchronization for optimal performance. Figure 6.2 depicts a possible synchronization when using scalable rendering to render one view using four GPU's.

The client component was built by integrating and customizing a large number of concepts which were presented in a previous section of the document from the theoretical point of view. The way they are actually implemented is presented in the current section.

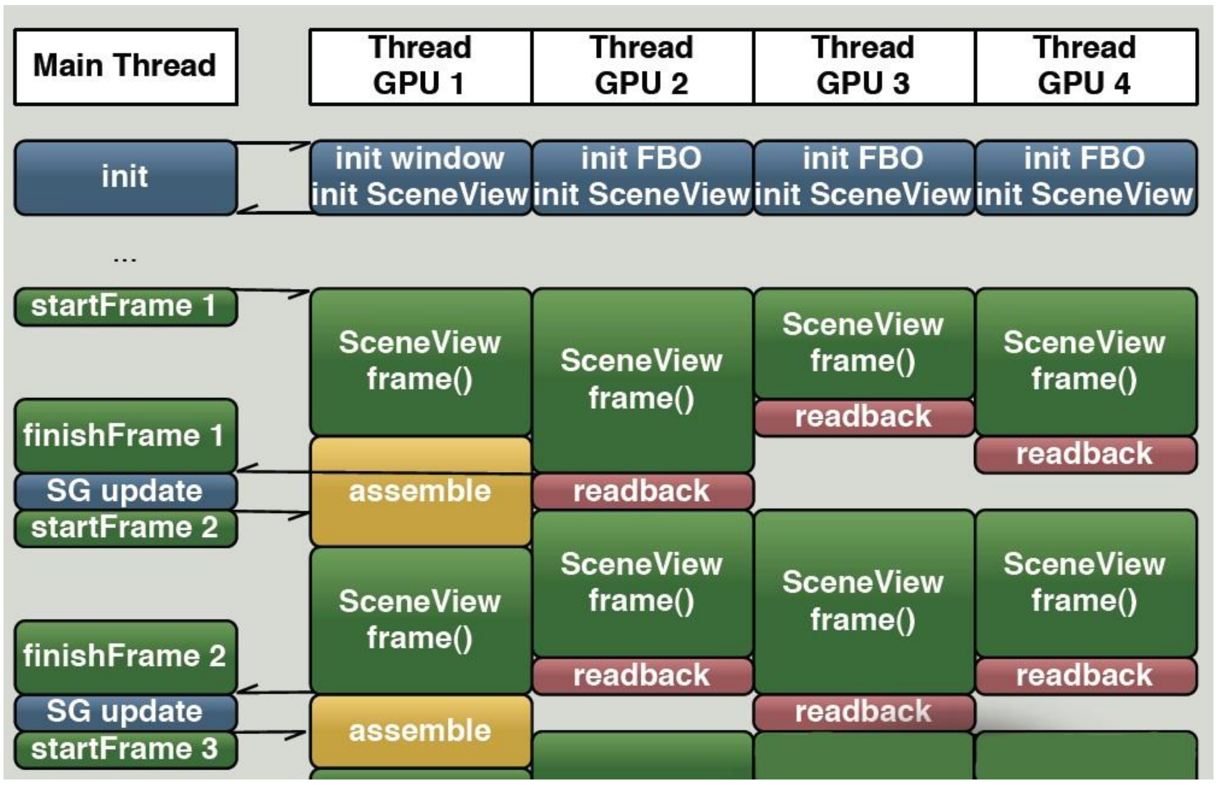


Fig. 6.2: Asynchronous rendering tasks when updating one view using four GPU's

6.2.3. Data Distribution regarding Equalizer framework

Equalizer provides simple, yet powerful data distribution based on the serialization of C++ objects. The objects are versioned, allowing efficient updates based on delta serialization. Object versions can easily be tied to rendering frames, keeping the database consistent across all rendering processes in a cluster.

For large clusters Equalizer provides optionally a reliable multicast implementation which efficiently distributes data to many cluster nodes.

The application we developed uses distributed objects to initialize the model filename on all processes and to synchronize the camera data. It does not need to implement a mechanism to distribute changes on the scene graph itself. The following sections outline different approaches which can be taken to implement distributed updates in the graphics rendering engine.

6.2.4. Scene Graph Updates

The Scen Graph viewer is a **multithreaded** rendering application, which applies all scene graph modifications in the main thread, between rendering frames. This is the preferred design pattern for optimal performance and memory usage. The default thread synchronization of Equalizer simplifies this implementation. All scene graph changes are done in the node process at the beginning of a frame, before the pipe rendering threads are unlocked, as shown in Figure 6.2.

Some applications tightly integrate data updates with the rendering traversal. In this case, a **multiprocess** approach may be used. For each GPU, a separate rendering process using an Equalizer node, is instantiated. This provides protection against conflicting data updates, but increases memory requirements.

The multithreaded approach of our implemented application fully exploits multi-GPU systems for multi-view and scalable rendering. All data modifications are done in a thread-safe manner and are directly available to the rendering threads through shared memory.

For graphics clusters applications need to implement a mechanism to update the different scene graph instances on all cluster nodes. In the following sections, two different paradigms to synchronize the databases are outlined.

6.2.5. Event Distribution

The least invasive, but code intensive and more fragile approach, is to apply the same operations to each scene graph instance. The initial scene graph is available to all processes, e.g., through a shared file system.

The relevant commands to modify the scene graph are distributed to all processes in the cluster. The FrameData object of from our application is the ideal place for this, since it provides frame-specific data correctly to all nodes. Each node reads and applies the commands in Node::frame-Start to keep the data consistent.

6.2.6. Data Distribution regarding the graphics rendering engine

Data distribution for the graphics engine nodes is the most versatile and robust approach. The application process holds the master instance of the scene graph. Any changes
on the scene graph are tracked internally.

At the beginning of each frame, the application commits all pending changes. The render clients receive a change list and update the data in Node::frameStart.

Several design patterns can be employed to implement data distribution. Subclassing, proxies or multiple inheritance are the most common (Figure 6.3) .

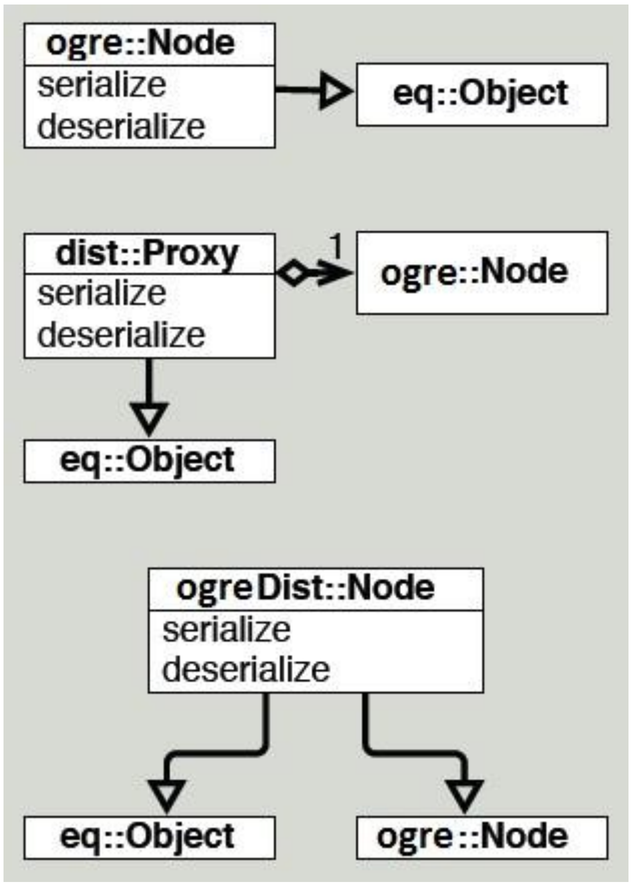


Fig. 6.3: Subclassing, proxies and multiple inheritance for OGRE data distribution

6.3. Rendering Component

The rendering component architecture is composed of the visualization server, the rendering nodes (clients) and the resource manager.
For the *server* and *rendering nodes,* a framework based on Equalizer was used. The reason behind this is because Equalizer is specialized in dealing with parallel rendering.

The rendering nodes are represented by multiple computers linked together and their main job is to divide the workload among themselves. The user's rendering requests are sent to the server which distributes them to the nodes, thus forming a graphics cluster. In order to handle the distribution and execution of the given task, each node contains a module responsible for this operation. Knowing this, it must be said that there is an application which runs on each rendering client. When the rendering cycle is completed, the result is sent further to a node called composer node. The result is then compressed, thus achieving a better performance. This is done by the Equalizer graphical engine, since it has a compression plug-in: the RLE method (Run Length Encoding).

The server holds the applications for the rendering server and composer parts and manages the rendering nodes by transmitting messages to them. The messages contain information about the way the distribution of operations is done among the clients. A configuration file is needed in order to configure the presented system. The purpose of the composer application is to combine the parts received from the clients in order to obtain the final result. It also compresses the result and sends a continuous video stream to the client application which is handled by the user. The video compression is done by the use of a free library which is part of the FFmpeg project [16] .

In order to establish a way to communicate between the streamer process and the rendering system, pipe files are used. The way this communication works is explained in the following. The composer node creates a child process, using the streamer binary. The input of the child process is redirected to a pipe file, while the streamer will continuously read the standard input and stream the data to the destination. The streamer process must be given input values continuously because of the constant frame-rate. The same applies, even if the rendering system's performance is lower or if the frame-rate is not constant. An algorithm comes to fix this problem: if the rendering FPS is greater than the streaming FPS, it skips some of the frames; if the rendering FPS is lower than the streaming FPS, it duplicates some of the frames.

The whole rendering component uses a networking layer (Fig. 6.4) that provides a peer-to-peer communication infrastructure. This solution was integrated so the client application, server and rendering clients are able to communicate easily between one another. It provides a layered functionality, thus the programmer can benefit of higher functionality level. In the current application, the nodes communicate using packets. The packets are managed by a base class.

Each node must have a unique identifier. For example, if you want to connect to a node, you must specify the identifier to find it. If there is more than one node with the same identifier, the application will not know which of the nodes is desired by the user.

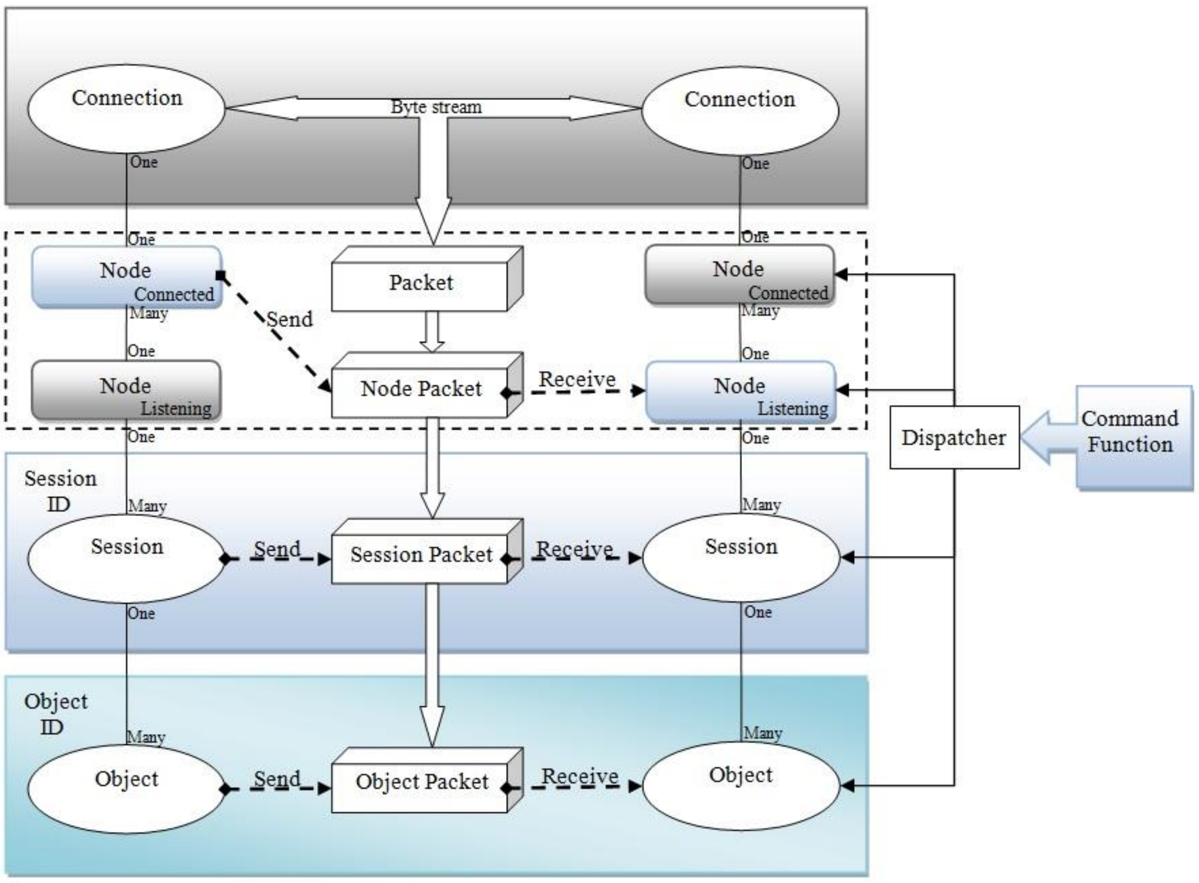


Fig. 6.4: Communication between nodes, sessions and objects in the Graphics Cluster

Besides the described parts of the rendering component, there are still the *node manager application* and *the broker component*.

By the help of the node manager, the administrator is able to enable or disable specific nodes in the cluster graphics architecture. The number of enabled nodes depends on the type and complexity of the application and the needed resources. The nodes in the cluster can be considered either as server or client nodes. The current project contains a database which is placed on the server. The database holds enough information about the registered nodes. The node manager application provides file deployment: before adding a node to the system, the files are copied using Secure Copy Protocol. The host that houses the node manager is required to have a password less SSH connection configured to the new node (view ANNEX).

The administrator is interested in having an application that can be easily used in order to do such operations, as previously discussed. Thus, the interface must be user-friendly and should provide instant access to the database. The alternative solution to be considered is to directly manipulate the tables from the database if some error occurs during the addition/deletion of a new node.

The purpose of the broker component is to handle the requests received from users. Its functionalities are: receiving requests and fetching the visualization to a specific rendering server. After the fetching operation is completed, the rendering nodes receive the rendered graphical scene together with its necessary parameters. The work of the broker component must be transparent to the user, so it must know at each step which is the most suitable cluster to be enabled for a given job.

For the implementation of the whole project, a system composed of 12 computers was built: 10 rendering nodes and 2 servers. The remote rendering system can be used at the same time by more clients. The computers that were used in the graphics cluster have the following configuration:

- Processor: Intel® Core™ 2 Duo E7300 @ 2666GHz
- RAM memory: 2GB
- Graphics card: GeForce 9600GT
    - Version driver: 178.13
    - Stream processors: 64
    - Core clock: 450 MHz
    - Memory clock: 756 MHz
    - Memory interface: 256 bit
    - Memory: 512MB
- OS: Windows XP SP2

6.4. Collaboration Diagram for OGRE::DotSceneLoader

The *DotSceneLoader* class collaboration diagram is presented in Fig. 6.5. The full functionality and implementation method is presented in the “Data Model” subchapter.

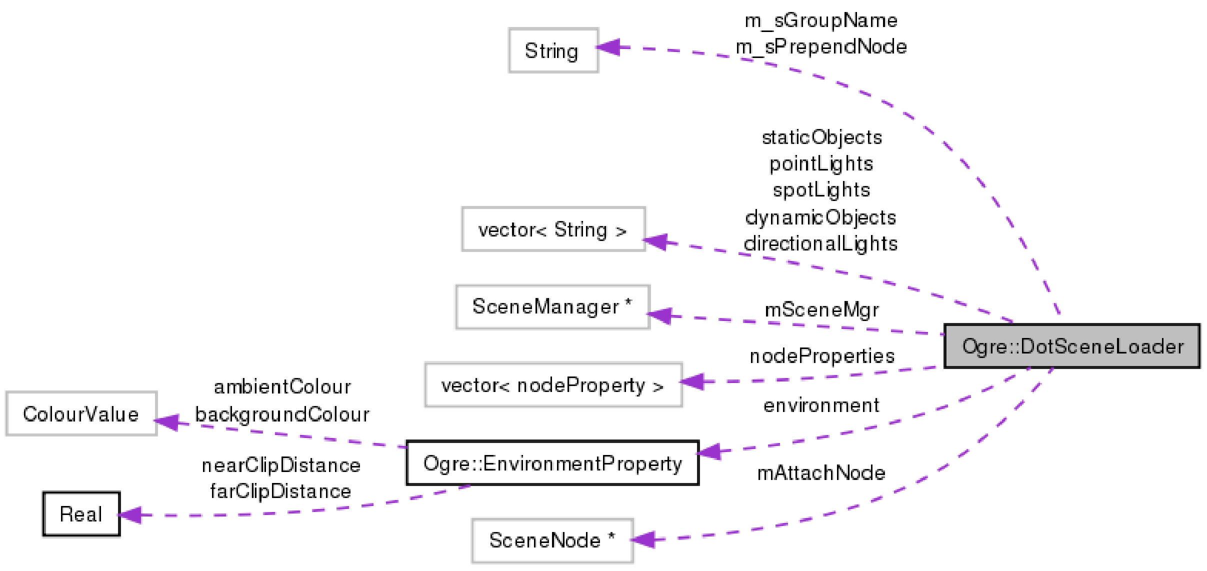


Fig. 6.5: Collaboration diagram for OGRE::DotSceneLoader

Here are some of the main functions and attributes that were needed for the implementation of the application for building object-oriented complex scenarios. The function names are pretty self explanatory, so no complex explanations are given.

- Public member functions:
  - **DotSceneLoader()**
  - virtual **~DotSceneLoader()**
  - void **parseDotScene(const String &SceneName, const String &groupName, SceneManager *yourSceneMgr, SceneNode *pAttachNode=NULL, const String &sPrependNode="")**
  - SceneManager* **getSceneManager()**
- Protected member functions:
  - void **processScene(TiXmlElement *XMLRoot)**
  - void **processLight(TiXmlElement *XMLRoot, SceneNode* pParent=0)**
  - void **processCamera(TiXmlElement *XMLRoot, SceneNode* pParent=0)**
  - void **processNode(TiXmlElement *XMLRoot, SceneNode* pParent=0)**
- Protected Attributes:
  - SceneManager* **mSceneMgr**
  - SceneNode* **mAttachNode**

6.5. Data Model

In order to parse the implemented scene file format, to be able to manipulate the nodes and to load the entire scene, the DotSceneLoader class provides suitable methods. Some of the most important ones are:

- *processEntity(xmlNode, parent):* takes care of the entity being loaded. It has information about its corresponding node and parent. It sets the attributes (name, id, mesh file etc.) and then builds the entity.
- *processNode(xmlNode, parent):* processes each node from the scene file.
- *processLight(xmlNode, parent):* handles a light node and its parameters.
- *processCamera(xmlNode, parent):* handles a camera node and its parameters.
- *processSkyBox(xmlNode)*
- *processSkyDome(xmlNode)*
- *processSkyPlane(xmlNode)*
    - the last three methods are available if one wants to add a sky object. The sky object can be of three types: box, dome and plane. Each one has its own functionalities and advantages/disadvantages.
- *parseDotScene(sceneName, groupName, sceneManager):* this is the most important method of the class. It is called from the client program in order to load and display the entire scene. The rest of the methods are practically invisible to the user, because they are applied from the inside of this method and are not needed to be applied separately. The sceneName parameter gets the actual *.scene file to be loaded, the groupName specifies the group which will represent the loaded models and the sceneManager is the one used by the client application which holds and manages the entire information about the scene.

7. EXPERIMENTS AND TESTING

Testing is an important part of the development process of any software application. Throughout the development, a series of tests were being made in order to check the correct execution of each component separately, and the functionality of the system as a whole. This chapter will focus on the methods in which testing operations were done.

7.1. Graphics Clusters Configurations

The architecture we proposed has been experimented on two local graphics clusters.
First configuration resources are shown in Figure 7.1

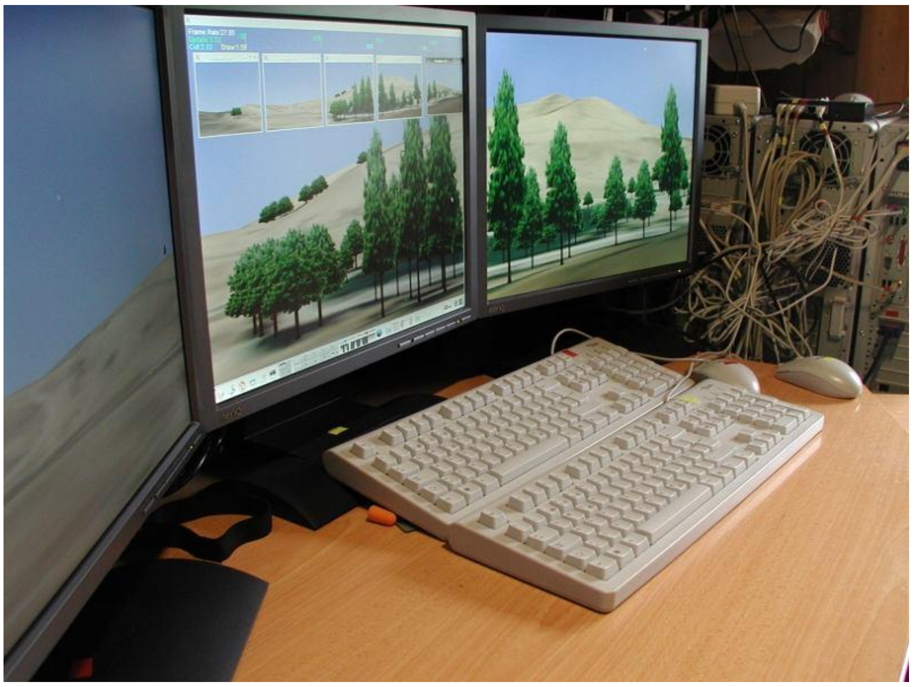


Fig. 7.1: Graphics cluster computing resources

The computing resources used for the first one consists of six Pentium 4 systems with 1 GB RAM memory, GeForce 8800 640MB graphic card, and running on Windows XP SP3. This graphics cluster was used for the first three experiments described in detail in the following paragraphs.

In terms of scalability, in the last experiment we used the second graphics cluster consisting of eleven Intel® Core™ 2 Duo with 2 GB RAM memory, GeForce 9600GT graphic card, and running on Windows XP SP2.

For evaluating the functional level of our architecture we have defined a set of test scenarios.

7.1.1. Scene-Oriented integration into Graphics Cluster

The aim is to evaluate the integration of all architectural components by using a very general use case scenario. For building complex scenes, we used an object-oriented graphic engine which we integrated in the parallel rendering framework based on Equalizer middleware. This use case refers to the graphics cluster based visualization and user interaction in a complex 3D scene.

For this experiment we used a graphics cluster consisting of two rendering clients and one server of which task concerns with scene data distribution over the rendering clients and the composition of the result received from each node.

Through the client application, the user builds up the graphical scene and sets the rendering parameters from the user interface. An example of the application we built is shown in (Figure 7.2). In this scenario, the user sets the positions for each of the selected scene model - the ground material and some complex models (a house and different types of trees). In order to create this complex scene, the client application used the scene management and the resource management classes from the library used in object-oriented graphics rendering engine.

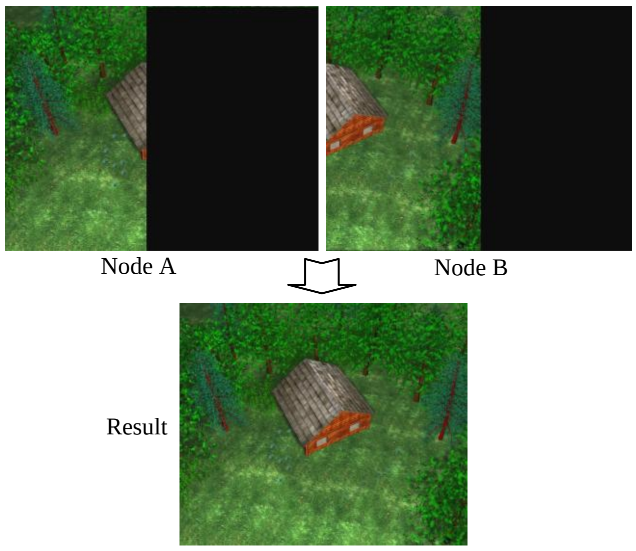


Fig. 7.2: Visualization by two rendering nodes. The sort-first configuration and the object-oriented graphics rendering engine are integrated into the graphics cluster.

In this use case the application load several ply complex models to hardware buffer and then render the scene with texture shadow. After the user sets the rendering parameters and configures the graphics cluster by the manager, the application can start the parallel rendering using the graphics cluster. It is a scene-oriented application that load ply files as mesh data and computes textured shadow for each object in real-time.

Regarding the graphical rendering, the UI allows the user to choose between these configuration modes of the system: multi-window, multi-channel or graphics cluster.

The user interaction is supported by keyboard, in order to move the camera, and by mouse for camera rotation.

Using our work for the integration of the object-oriented graphics rendering engine with the Equalizer framework, the user has the possibility to create the camera and to set its position.

By default we set the camera at 500 units on Z direction, and looking back toward –Z. Then the viewports are created as well. In our use case, we map the viewport over entire window.

Concerning our experiment with the object-oriented graphics rendering engine integration we can conclude that the visualization results show that the performance increases only for complex models.

For simple models, the performance declines by increasing rendering nodes. On the other hand, because of the object-oriented graphics rendering engine limitation, thread safeness is poor. Each node can contain only one GPU, which means we must change the Equalizer configuration file (two-window using sort-first strategy) to use one pipe that contains two windows.

In order to experiment the entire distributed architecture we built some 3D complex scenarios using an Ogre application that we developed for this purpose. (Figure 7.3)

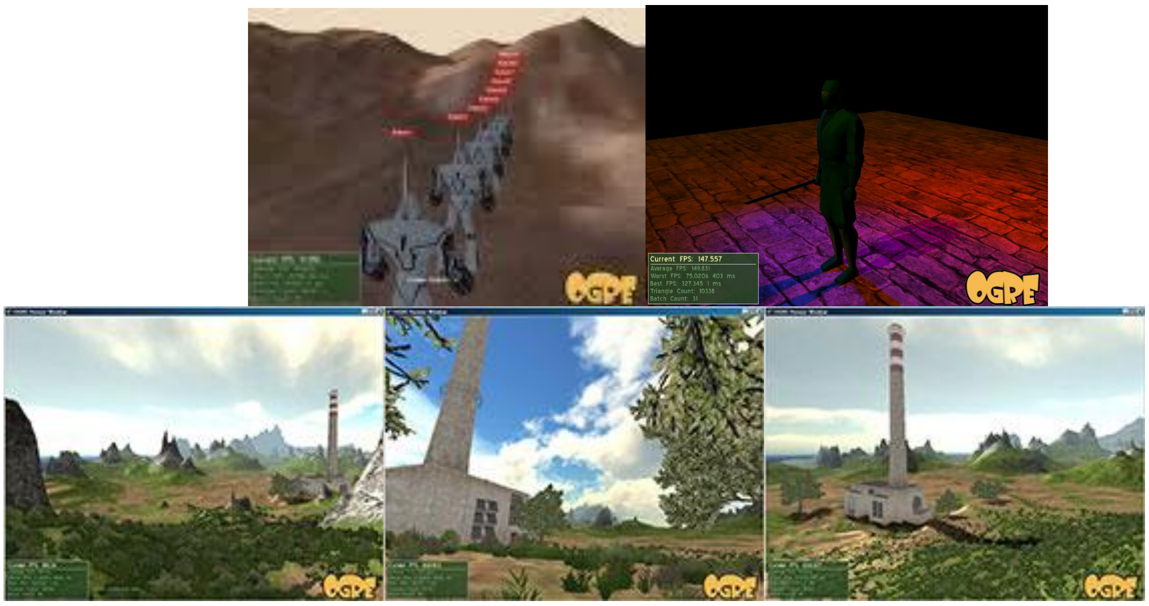


Fig. 7.3: Screenshots Results from the application we developed using Ogre

7.1.2. Component Testing – Building different complex scenarios in Ogre

The current application was developed iteratively, starting from the simplest parts, and going further to the more complex ones. During the development process, extensive testing and evaluation was done for this part.

The *vgsScenarioApp* class handles the visual part of the system, mainly the creation of the scene, adding the user interface, creating cameras, viewports, a scene manager and also creating an instance of *vgsScenarioFrameListener* class.

The *createScene* method is probably the most important one from the visual point of view of the application. As the method was beginning to receive functionality, testing was done after each part. The first part to be tested was the insertion of 3D models into the scene. At first, simple entities were created and scene nodes were added in order to include the models and test the behavior of the application. When the entities were correctly loaded, the DotSceneLoader class was included and tested in order to load an entire complex scene. The lights and sky were then added and tested in a trial and error manner. The same testing method was then applied for the CEGUI part. The positioning of the radio buttons, check boxes, text boxes and buttons were modified a lot throughout the development process.

The functionalities from the user interface were also tested in separate methods. In order to load a new scene, the current one should be cleared. The *eraseCurrentScene* method was tested for correct deletion of objects, entities and scene nodes. Several times, the application crashed when loading a new scene, because the erase scene method failed to destroy all components from the previous one. The *loadScene* method is not very complex. In order to test it, several scenes were created. Initially, some common scene nodes were overlapping between scenes and were not displayed correctly.

The scenario visualization process was intensively tested since it represents the main purpose of the project. In the method *frameStarted*, a large part was tested for the movement of the avatar. The rotation of the camera in real time was given specific attention since, the camera initially rotated to various directions, but the correct ones. Also, in order to get the correct vertex location, a new method was used (*nextLocation*). This was tested by adding points to the designed list and verifying if the avatar moved according to them. It was tiresome to use the application each time this part was tested, so dummy points were hardcoded inside the code. At the end of the development, these were eventually deleted, since they did not have any other specific use.

7.2. Graphics Clusters visualization performance using Load-Balancing strategies

The aim of our next experiments reported in this research concerns on evaluating the impact of scene complexity, image dimension, and rendering method using different load-balancing strategies on the visualization performance.

7.2.1. Resources assignments for optimal performances

In the next experiment we used our first graphics cluster configuration having all the computing resources available. Concerning the segment definition from chapter V, it is important that each segment of a multi-display system has a different rendering load and it depends on the data structure and model position. When using a static assignment of resources to segments, the overall performance is determined by the segment with the biggest load.

The solution is to analyze the load of all segments and adjusts the resource usage each frame. It equalizes the load on all segments of a view. This process is illustrated in (Fig. 3).
In this experiment we used a static assignment of resources to display segments on the left side. The right-hand segment has a higher load than the left-hand segment, causing sub-optimal performance. On the left side the configuration is using a view which assigns two GPU's to the left segment and four GPU's to the right segment, which leads to optimal performance for this model and camera position.

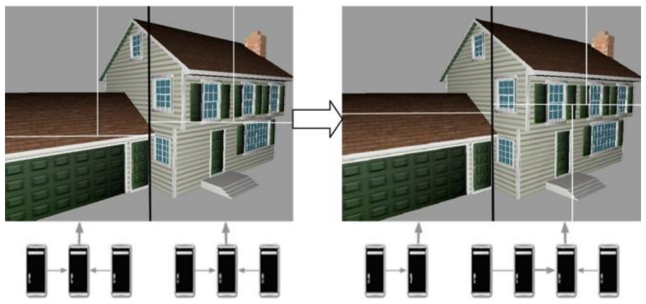


Fig. 7.4: Cross-segment load-balancing for two segments using six GPU's

7.2.2. *A relevant advantage in using load-balancing*

The third experiment use the computing resources from our first local graphics cluster described in the beginning of this chapter and have four active rendering clients. The number of frames per second (fps) was used as the measured parameter in order to evaluate the performances. First of all we compare and evaluate the visualization performances between sort-first rendering strategy and load-balanced sort-first rendering using objects centered in the middle of the screen. The differences between these modes are quite insignificant. For instance, if we upload a complex model without load-balancing we obtain 13 FPS. On the other hand, using the load-balancing, we obtain 17 FPS. In (Fig. 4) we show a demonstration regarding these results. For these measurements we load a complex model that has 10.000.000 faces and a total size of 183 MB.

From the measurements point of view, we have to conclude that the advantages in using load-balancing are relevant in the case the loaded model is covering a small part of the screen-space. In this case we obtained 17 FPS without using load-balancing and 25 FPS using it.

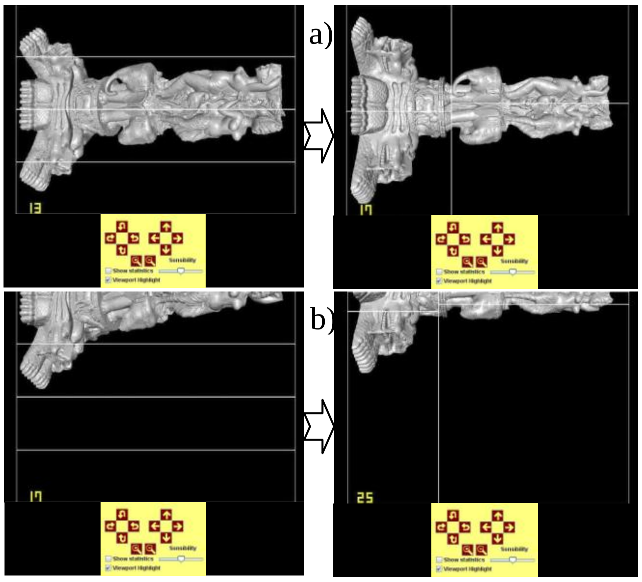


Fig. 7.5: Four nodes graphics cluster running sort-first rendering strategy using load-balancing. a) Full object visibility b) Partial object visibility

7.2.3. *Frame computation by the rendering algorithms*

For the last experiment we have used our second graphics cluster (one visualization server and ten rendering clients) in order to find out how much we can increase the number of rendering nodes and how this may influence the performances using the rendering algorithms with load-balancing on different resolutions. The test variables are the number of rendering nodes, the scene complexity (in term of number of triangles) and the rendering resolution.

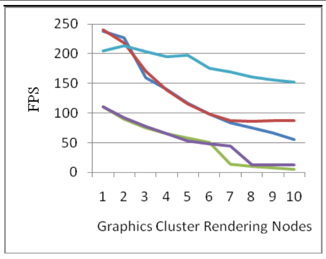
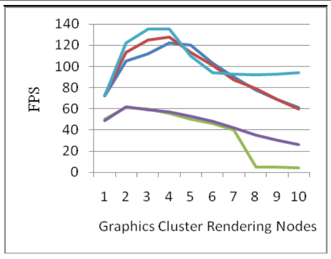
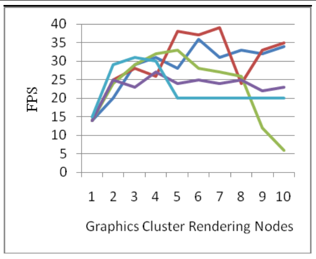
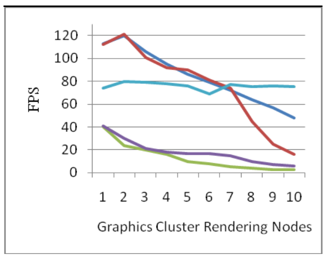
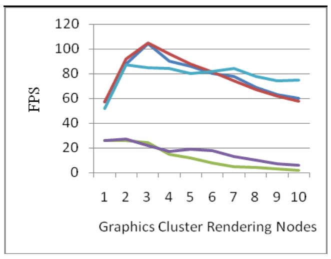
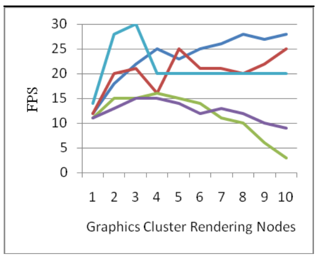
Our measurements results presented in (Table 7.1) were obtained by running the graphics cluster for each loaded model on different resolutions. For these measurements we used 3 models with different complexity level. In terms of rendering algorithms we used the sort-first, sort-last and DPlex decomposition strategies to compare the performances related to load-balancing improvements.

DPlex decomposition requires multiple frames to be rendered concurrently. DPlex mode assigns full frame rendering for each rendering client. This mode is known as the alternate frame rendering. It provides a very good scalability, but the disadvantage concerns the rendering system delay. In our experiment the DPlex is configured using a period and phase for each rendering node.

The network traffic and the rendering nodes load are variables that required our attention. The server node synchronizes the rendered frames at the composition stage. In this context the frame rate is influenced by the load of the rendering client nodes.

The results show that the performance increases only for complex models. For simple models, the performance declines with increasing rendering nodes. We can conclude that in the case of the sort-first strategy, the scalability may be applied, but in the case of sort-last, the network traffic cost is increasing with the number of rendering nodes. Concerning our measurements the advantages in using the load-balancing are relevant in the case the loaded scenes are complex and the rendering algorithm is sort-first.

TABLE 7.1
FRAME COMPUTATION BY THE RENDERING ALGORITHMS

Resolution	Model complexity level		
	Small	Medium	Large
320 x 240			
640 x 480			
	Legend: 🟦 Sort-first without load-balancing 🟥 Sort-first with load-balancing 🟩 Sort-last without load-balancing 🟪 Sort-last with load-balancing 🟦 Dplex		

7.3. Functional Testing

7.3.1. Generating Scene files

For testing VGS application, some complex virtual geographical scenes are required. In order to create such scenes, two programs were used. Ogitor is a plug-in based WYSIWYG editor environment for the object-oriented graphic rendering engine. It allows easy creation of scenes which can be loaded in an OGRE application for both rapid prototyping purposes and as final application content. This program mainly supplied the object models, their positioning, rotation and scale in the 3D environment. A group of objects were placed in a small scene which was later exported to a ".scene" file. In order to create several types of scenes (simple, of medium complexity and complex), a Java program was designed. Its purpose was to place the previously discussed objects on the scene in a specified number of times.

In order to test if the integration between the parallel rendering framework and the graphic engine works, we generated three files with having different complexity:

- *map_small.scene*: number of triangles: 189,192
- *map_medium.scene:* number of triangles: 1,158,801
- *map_large.scene:* number of triangles: 5,321,025

7.3.2. MPEG-2 Compression

The MPEG-2 compression is used and implemented from **Error! Reference source not found.**. After the inclusion of this part in the project, testing was still necessary in order to verify the correct usage. Similar tests as in the paper were executed. Testing the MPEG-2encoder module was done through saving the result of the rendering in a local file. In case the component operates as the specifications require, any player may read and display the content of the saved file.

The testing was executed with the use of VLC Player and Windows Media Player. Both applications rendered the content of the file with no errors.

7.3.3. Adding a Node to the System

In order to add a node to the system, the implementation from **Error! Reference source not found.** was used. The testing was still necessary in order to verify that the correct behavior is obtained.

The process of adding a node to the system can be done with the help of the NodeManager component. Before adding a node, a SSH password less connection between the server and the new node must be configured (view ANNEX).

After the configuration data is introduced, the user has to press the "Add" button. When this happens, the configuration of the new node is being done. In case the node is a server, the folder ServerFiles will be created on partition C: of the new node, otherwise, if the node is a client, the folder will have the name ClientFiles. These folders are used to store and copy the necessary files in order to fulfill the role of a client or server.

After the addition process is done, the files on the new node are verified of existence. For the file validation process, a complete test for rendering using the new node was also run.

7.3.4. Disabling a Node from the System

Since the addition of a node was done using the technology in **Error! Reference source not found.**, the same goes for the inverse operation, i.e. the removal of a node. The nodes registered in the rendering system may be disabled. The reason behind their disabling may be the detection of some error on that node, or any other factor that may result in an abnormal functionality.

The node is thus disabled. The test is represented by the initiation of a new visualization session. It can be observed that the removed node will not take part in the rendering operation.

7.3.5. Communication between the Client Application, Broker Component and the Rendering System

In paper **Error! Reference source not found.**, this part was implemented and tested. The current application that integrates Ogre and Equalizer also needs to integrate this functionality. In order to start/stop or send an interaction command to the graphics cluster, the user operates on the Client Application. The requested commands are sent to the Broker Component.

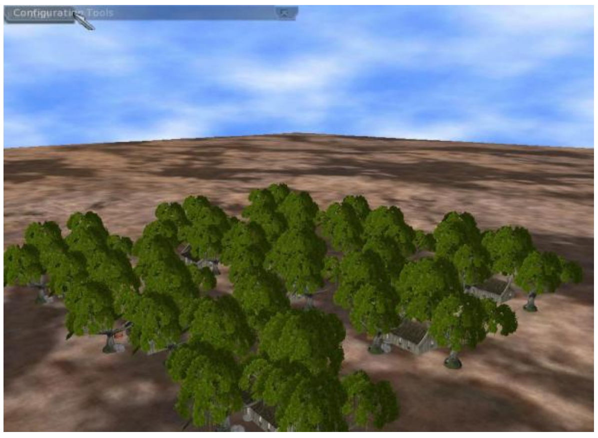
Scene interaction commands which are sent to the Broker Component are then sent to the session associated server. The testing consists of starting a new session, i.e. starting the client application, and executing commands by the use of the graphical user interface.

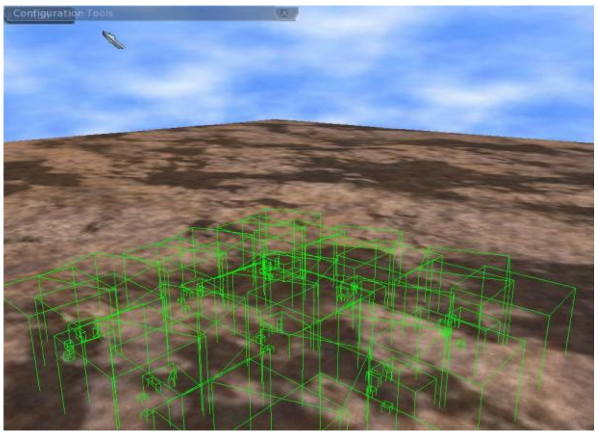
It can be seen that the functionality of these components is the expected one.

7.4. Performance Testing

In order to complete the experimental testing in this section, I have used the VGS that were generated as mentioned in subchapter 7.3.1., i.e.:

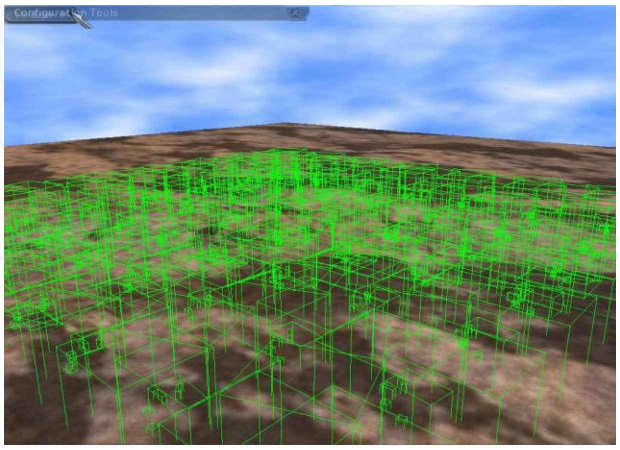
- *map_small.scene:* number of triangles: 189,192





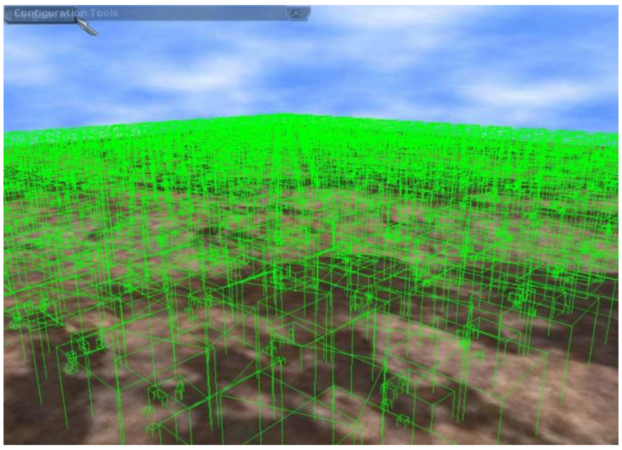
- *map_medium.scene:* number of triangles: 1,158,801

Configuration Tools



- *map_large.scene:* number of triangles: 5,321,025

Configuration Tools



In the number of possible processors and graphics cards, the graphic clusters are virtually unlimited. Compared to computing clusters, the software scalability on such cluster is a relatively new subject. Equalizer is pushing the boundaries on what is possible by bringing more applications to this environment.

The evaluation of the impact of scene complexity, image dimension, and rendering method on the performance of remote visualization are the aim of our experiments. As the measured parameter, we use for evaluation the number of frames per second (FPS).

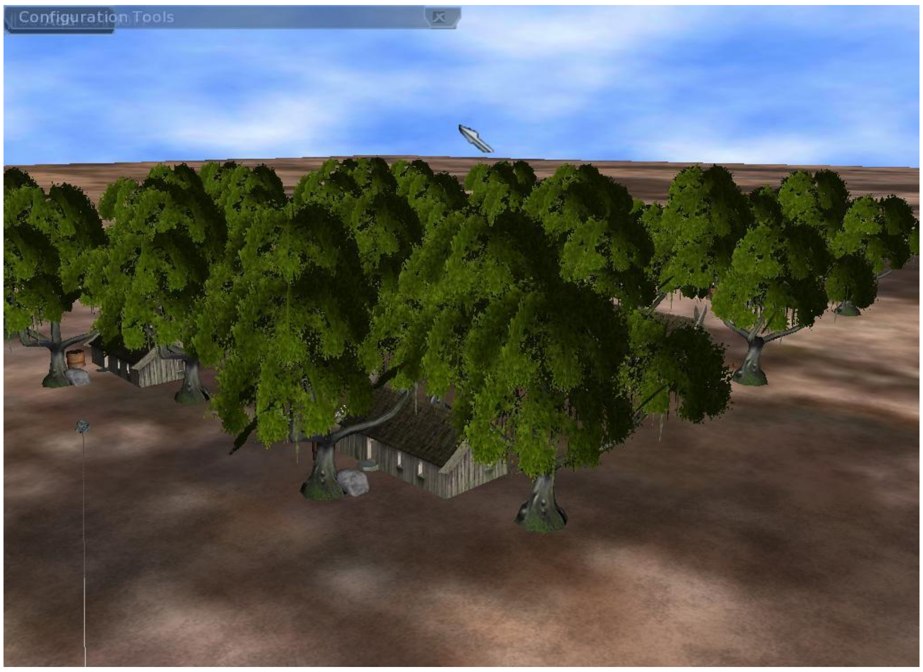


Fig. 7.6: Visualization result using the sort-first algorithm

We have defined a set of test scenarios to evaluate the functional level of our architecture. The aim is to evaluate the integration of all architectural components.

Another important subject is the scalability of the system. Moreover, the main question is how much we can increase the number of rendering nodes and how this may influence the performance. In the case of the sort-first strategy, every rendering client renders a subset of the original resolution. The network traffic cost will be mainly the same. The sort-last strategy renders a subset of the scene objects. The resolution on each of the rendering nodes is the same as the final image resolution and the rendering clients fetch back the depth buffer to the composition node.

The other tests consist on performance evaluation by measuring the frames per seconds. The test variables are the number of rendering nodes, the scene complexity (in terms of number of triangles) and the rendering resolution. The last two variables decrease very much the visualization performance. The higher the resolution, the better the final image, but the rendering time increases. In a similar way, the scene complexity influences the frame rate. By adding more details to objects, the rendered quality is better but the rendering time increases (Table 7.2).

Table 7.2: Frame Computation by the Sort-First Algorithm

Scene complelxity	Nodes	256 x 256 pixels	512 x 512 pixels	1024 x 1024 pixels
Low – small map	2	47	30	14
	3	40	28	10
	4	39	15	8
Medium – medium map	2	28	18	8
	3	20	14	5
	4	23	11	4
High – large map	2	14	10	5
	3	8	7	3
	4	11	6	1

Another measurement variable can be the network traffic and the rendering nodes load. The server node synchronizes the rendered frames at the composition stage. Therefore, the load of the rendering client nodes influences the frame rate.

The architecture we proposed has been experimented on a local graphics cluster. The computing resources consists of four Pentium 4 systems with 1 GB RAM memory, GeForce 8800 640MB graphic card, and running Equalizer middleware on Windows XP SP2.

Table 7.2 presents the frame computation rate on the Equalizer cluster by the sort-first algorithm for low, medium and high scene complexity, three node configurations, and three image resolutions. We use three different graphical scenes: one with low complexity, one with medium complexity and another one with more details (see Table 7.3). At middle image resolution (512 x 512 pixels, Fig. 7.63), we managed to obtain good frame rates without optimizations (fast network, frame encoding etc.). With higher number of rendering clients, the composition time tends to increase and this affect the obtained frame rate. The best performance related with image resolution and scene complexity is obtained by using two or three rendering clients and a middle image resolution both in the case of low, medium and high scene complexity.

Table 7.3: Number of Faces for the Small, Medium and Large Maps

Complexity	**Faces**
Low	189,192
Medium	1,158,801
High	5,321,025

Nevertheless, the performance already achieved is quite far of the required ones. The future research will mainly concern with performance enhancement by graphics cluster configuration, connectivity and communication among cluster nodes, rendering algorithm optimization, streaming, user interaction, virtual space modeling and distributed processing, and the modeling and simulation of the natural phenomena.

Ogre3D and Equalizer are the ideal combination for high-performance 3D visualization. While object-oriented rendering graphics engine focuses on rendering efficiently, the parallel framework provides scalability on multi-GPU systems and large-scale clusters. The application we developed is a template for applications combining the two open source solutions in an efficient way.

8. USER MANUAL

8.1. Installation Guide

A. OGRE

- Download OGRE SDK 1.7.0
- Unpack to a suitable location
- Build the project to get the necessary .lib and .dll files
- Go to the directory of the newly installed sdk and copy the full path
- Set the environment variable OGRE_HOME to point to that path.
  - One way to do this is to open a command window and set the variable using the following command:

    setx OGRE_HOME D:\OgreSDK\OgreSDK_vc9_v1-7-0

B. CEGUI

- Download CEGUI 0.7.1 and also the “Dependencies” files; copy the “Dependencies” folder into the root of CEGUI.

Remark: Since the Ogre 1.7 version, CEGUI is not an Ogre dependency anymore using its own basic interface for its samples now, instead of CEGUI. This means that from now on, you have to build CEGUI for your Ogre project yourself, in case you want to use the latest Ogre or CEGUI versions. Otherwise, you can grab the latest precompiled dependencies from the Ogre download section Webpage and the CEGUI download section Webpage.

- In your CEGUI folder there should be a folder called "**projects**" with a subfolder called "**premake**". Get a version of premake and extract the **premake.exe** file into this folder.
- Open **config.lua** in the premake folder and edit the Ogre and OIS paths accordingly, so they will point to your SDK files. In my case for example the 2 lines look like this:

OGRE_PATHS = { ".../Visual Studio 2008/Projects/Ogre 1.7/Ogre/VCBuild/sdk", "include/OGRE", "lib" }
OIS_PATHS = { ".../Visual Studio 2008/Projects/Ogre 1.7/Ogre/VCBuild/sdk", "include/OIS", "lib" }

Remark: Remember to use forward slashes here! Just copying the paths from the Windows explorer will give you backward slashes. Replace them!

Next, set all Renderers you do not need to "false", in this case we will only need *OGRE_RENDERER*. You can also set all samples to false, except maybe *SAMPLES_OGRE* if you want them.

- Next, we create our Visual Studio Projects - Execute **build_vs2008.bat** to create a Visual Studio 2008 project or execute any other .bat file for your respective Visual Studio version.
- This should create **CEGUI.sln** in the premake folder. Open it.
- If you have the Ogre lib files seperated into a Debug and Release folder, you will have to change the path in the Linker settings of the project so they will point to the **lib/Debug** or **lib/Release** folder for each configuration respectively.

- **Build** the **CEGUIOgreRenderer** in Debug and Release mode, copy the CEGUIBase and CEGUIOgreRenderer .dll and .lib files as well as the CEGUI include folder.

Remark: Add all **dll** files from CEGUI into the bin working folder of OGRE! Also, add all **lib** files from CEGUI into the lib folder of OGRE!

- Locate the file “resources.cfg” in OgreSDK, open it with a suitable editor and add the following lines at the end in order to set the CEGUI resources:

```
# CEGUI resources
[Imagesets]
FileSystem=[path]/datafiles/imagesets
[Fonts]
FileSystem=[path]/datafiles/fonts
[Schemes]
FileSystem=[path]/datafiles/schemes
[LookNFeel]
FileSystem=[path]/datafiles/looknfeel
[Layouts]
FileSystem=[path]/datafiles/layouts
```

Where [path] points to the installation folder of CEGUI, for example

E:/Work/Facultate/Licenta/CEGUI-0.7.1

C. *Equalizer framework*

Before I can describe how to run the software, you must understand how to use the configuration files of Equalizer. Depending how many nodes you’re running in your cluster all of this must be described in that file including the connection information.

Also, you must map one node to one GPU on the machine. You can’t run multiple nodes on the same machine if you don’t have enough GPUs.

First and foremost, you must specify all library paths to point to both Equalizer library binaries and Ogre library binaries. You need to start up all your render nodes first:

<u>Command window:</u>

```
>myapplication --model=<model filename> --eq-client –eq-listen <ipaddress>:<port>
Example: >myapplication --model=first_scenario.scene –eq-client –eq-listen 10.128.1.234:4243
<model filename> Name of the model to load
<ipaddress> Render node’s address
<port> Listening port
```

After starting up all the render nodes, you start the actual server. The server will automatically connect to all the render nodes as specified in the configuration file.

```
>eqServer <config-file>
```

Example: >eqServer config/2-node.2D.eqc
<config-file> Configuration file (.eqc)
Lastly, start the application and connect to the server.

```
>myapplication --model=<model filename>
```

Example: >eqOgre --model=first_scenario.scene
<model filename> Name of the model to load

For more details, see ANNEX.

9. CONCLUSIONS

The set of components and interactive software tools available to the user permit the visualizing and editing of complex scenarios in a VGS taking advantage of the Equalizer graphics cluster.

The system fulfills all the requested specifications, both the functional ones and non-functional ones. After testing and experimenting with this research, it was proven that all the use case scenarios were correctly executed and follow the necessary specifications.

One of the main objectives of the current project was to be able to interact with a 3D complex scene using a high-performance distributed architecture. Thus, an application was successfully developed for this purpose. Through it, the user is able to run on the graphics cluster any scenario built using object oriented graphics rendering engine.

The client application for building Ogre scenarios is mainly about the scenario creation and manipulation for walking inside a 3D geographical space. In order to have fully working scenarios, a standalone language was built. The application provides interactive techniques, and includes an easy to learn interface. Through it, the user has the ability to choose some operations and use the entire system functionality for the description of visualization processes.

When talking about the format of the scene graphs available for this application, the ".scene" format was developed and tested. It is an XML based format through which the 3D objects are placed in the virtual world. The ".scene" format is humanly readable and understandable.

In this application, a scalable system is developed, such that one can easily add new client nodes for the rendering part inside the graphics cluster, with the purpose of achieving better performance.

For future improvements, the application is wide open to new ideas for add-ons. One of the major improvements that can be brought is to include a curve-shaped trajectory for the visualization scenarios.

A new and improved scene file format can be documented and integrated in the project. There are lots of scene formats that can be used. The more formats, the better because this will mean a larger usability.

Since the Ogre implemented application includes several predefined scenarios, it may also have an option to create one from scratch and save it later.

Another possible major improvement is related to the frame compression when the client nodes send information to the rendering server where the final composition of the image is done. A better compression of the frames leads to a reduced traffic within the network and implicitly a visible increasing in performance of the entire system.

The MPEG-2 encoding is the one used for the project. In the future, one can probably implement a MPEG-4 encoding type which brings a better data compression, thus the necessities of the internet connection bandwidth for the user would get considerably low. The MPEG compression algorithms are parallelizable and thus a GPU implementation would result in the increase of performance.

The future research will mainly concern with performance enhancement by graphics cluster configuration, streaming process improvements, communication and connectivity between graphics cluster nodes, rendering algorithm optimization and more data formats accepted by user interface.

REFERENCES

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ANNEX

- **Equalizer configuration files**

A configuration for two rendering nodes, at resolution 640*480 pixels, using 2D mode with load balancing may be generated using the following command:

```
configtool –c 3 –n nodes –x 640 –z 480 -m 2D –a –l –o config.eq
```

The execution result, i.e. the config.eq file contains:

```
global
{
   EQ_WINDOW_IATTR_HINT_FULLSCREEN    OFF
}
server
{
   config
   {
      appNode
      {
        pipe
       {
                  window
                  {
                      viewport [ 10 10 640 480 ]
                      attributes{ hint_fullscreen OFF }
                      channel { name "channel0"}
                  }
         }
      }
      node
      {
          connection
          {
                  hostname "hostname1"
                  TCPIP_port 4243
          }
          pipe
          {
             window
             {

                attributes
                {
                   hint_drawable     pbuffer
                }
                channel
                {
                   name     "channel1"
```

```
            }
         }
      }
   }
   node
   {
      connection
      {
               hostname "hostname2"
               TCPIP_port 4243
      }
      pipe
      {
         window
         {

            attributes
            {
               hint_drawable     pbuffer
            }
            channel
            {
               name     "channel2"
            }
         }
      }
   }
   compound
   {
      channel   "channel0"
      wall
      {
         bottom_left  [ -.32 -.20 -.75 ]
         bottom_right [  .32 -.20 -.75 ]
         top_left     [ -.32  .20 -.75 ]
      }
      load_equalizer { mode 2D }
      task      [ CLEAR ASSEMBLE ]
      compound
      {
         channel   "channel1"
         outputframe{ }
      }
      inputframe{ name "frame.channel1" }

      compound
      {
         channel   "channel2"
         outputframe{ }
      }
```

```
            inputframe{ name "frame.channel2" }

         }
      }
   }
```

A configuration for two rendering nodes, at resolution 640*480 pixels, using DB mode without load balancing may be generated using the following command:

configtool –c 2 –n nodes –x 640 –z 480 -m DB –a –o config.eq

The execution result, i.e. the config.eq contains:

```
global
{
   EQ_WINDOW_IATTR_HINT_FULLSCREEN    OFF
   EQ_WINDOW_IATTR_PLANES_STENCIL     ON
}
server
{
   config
   {
      appNode
      {
        pipe
       {
                 window
                 {
                     viewport [ 10 10 640 480 ]
                     attributes{ hint_fullscreen OFF }
                     attributes { planes_stencil ON }
                     channel { name "channel0"}
                 }
         }
     }
     node
     {
         connection
         {
                 hostname "hostname1"
                 TCPIP_port 4243
         }
         pipe
         {
            window
            {
               attributes
               {
                  hint_drawable     pbuffer
               }
            attributes
            {
               planes_stencil ON
            }
            channel
            {
               name     "channel1"
            }
         }
      }
   }
node
{
   connection
   {
               hostname "hostname2"
               TCPIP_port 4243
   }
   pipe
   {
      window
      {
         attributes
         {
            hint_drawable     pbuffer
         }
         attributes
         {
            planes_stencil ON
         }

         channel
         {
            name     "channel2"
         }
      }
   }
}
compound
{
   channel   "channel0"
   buffer    [ COLOR DEPTH ]
   wall
   {
      bottom_left  [ -.32 -.20 -.75 ]
      bottom_right [  .32 -.20 -.75 ]
      top_left     [ -.32  .20 -.75 ]
   }
   task      [ CLEAR ASSEMBLE ]
   compound
```

```
        {
           channel   "channel1"
           range     [ 0.00000 0.50000 ]
           outputframe{ name "frame.channel1"}
        }
        inputframe{ name "frame.channel1" }

        compound
        {
           channel   "channel2"
           range     [ 0.50000 1 ]
           outputframe{ name "frame.channel2"}
        }
        inputframe{ name "frame.channel2" }

      }
   }
}
```

The nodes file contains the name or the Ips of the rendering nodes:

```
hostname1
hostname2
```

- **SSH Configuration**

  Before adding a new node in the system, a passwordless SSH connection must be configured from the rendering server system to the new node. In this project, the OpenSSH implementation for Windows was used.

  Steps:
  - Download OpenSSH for Windows (www.openssh.com)
  - The OpenSSH client and server is installed
  - The following commands are executed in the folder <OpenSSH Dir>\bin:
    - mkgroup -l >> ..\etc\group
    - mkpasswd -l [-u <username>] >> ..\etc\passwd
    - net start opensshd
  - The file <OpenSSH Dir>\etc\sshd_config is modified as follows:
    - Strictmode no
    - PasswordAuthentication yes
    - RSAAuthentication yes
    - AuthorizedKeysFile   ~/.ssh/authorized_keys
  - The public key of the server is added in the file: ~\.ssh\ authorized_keys

- **FileZilla Configuration**

  Steps:
  - Download FileZilla from server: http://filezilla-project.org/
  - Install FileZilla server
  - Create directory: C:/SavedSessions
  - Configure user Anonymous:
    - FileZilla->Edit->Users->Add
    - Shared Folders: select previously created folder
  - The correct functioning is tested by accessing: ftp://<hostname>/