DGTk: A Data Generation Toolkit

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by

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CERTIFICATE

It is certified that the work contained in this thesis, titled "DGTk: A Data Generation Toolkit" by V.Vamsi Krishna, has been carried out under my supervision and is not submitted elsewhere for a degree.

Date

Adviser: Dr. P.J. Narayanan

To Mom, Dad and Sis

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Abstract

Computer Vision (CV) mainly focuses on analyzing images or video streams to find objects or events of interest. Over the last few years very high quality algorithms have been developed in this area due to the advances in the fields of Machine Learning, Image Processing and Pattern recognition techniques. Image Based rendering (IBR) algorithms deal with rendering novel views of a scene at photo realistic quality, given few views of the scene along with some additional information about the 3D structure of the scene. There has been a dramatic increase in the quality IBR algorithms developed due to the multi fold increase in the processing power (both on CPU and GPU).

Both Image Based rendering and Computer Vision algorithms require accurate and high quality data for experimentation, tuning, and testing. Traditionally research groups created datasets for this purpose. The datasets so developed have become standard testbeds for comparing the performance of CV and IBR algorithms. As more and more high quality algorithms began to be developed, most of such datasets have become obsolete and lack the ability to differentiate the performance of these algorithms. To overcome this problem, researchers create synthetic datasets which give a good indication of the algorithm's performance on the real world images. Due to the inherent advantages of ground truth data such as repeatability and ease of creation, it has become a very important part of the CV and IBR algorithm development. Many research groups have developed special tools for generating datasets for fingerprint recognition, skeleton extraction, etc. Such tools are very successful in generating specific data but cannot be extended easily to support other data types. It would be helpful for the researchers to have a simple open source tool which is easily extend able to support various input/output formats.

In this thesis, we preset DGTk a tool for generating a variety of outputs. Our tool is versatile, supports various input/output formats, enables users to generate high quality, high resolution images and is very easy to use. Our tool supports most commonly used 3D file formats used in the research community including 3DS, MD2, AC3D and POV-ray. Unlike previous tools, our tool supports a variety of data types. These include depth maps, images at various resolutions, LDI, Object-maps and Alpha-maps. DGTk also can generate dynamic scenes with all these properties using a key frame animation paradigm. Our tool meets the high quality requirement of CV and IBR algorithms by providing support for ray tracing. Any scene setup in our tool can be exported to povray scene. This enables users to generate photo realistic images when ever required. Our tool has been carefully designed to be easily extendable to support

other representations of data. Our tool can generate Object-maps and Alpha-maps of any scene setup in our tool. For the first time, our tool provides both Object-maps and Alpha-maps as standard data. This information is very critical for testing matting algorithms.

The goal of our work is not just to create synthetic data, but to provide a platform for data set creation. We wish to make sharing of datasets possible and make data generation a lot easier than before. To meet these goals, we have released our tool in the Open Source. We also released a dataset for standard applications.

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Chapter 1

Introduction

Computer Vision (CV) is a discipline that emerged as a result of the efforts to make the computers understand the objects in the world from the images captured through cameras. In some sense CV can be considered to be an inverse problem of Computer Graphics. Computer Graphics tries to generate a 2D image from the given world description by approximating some of the physical phenomena (i.e, lighting, materials etc). CV on the other hand deals with reconstruction of the world (3D information) from 2D image(s). A few decades ago, Televisions, mechanical toys, etc which were produced on a large scale had to be checked by humans for faulty parts. This was a tedious process and generally error prone. This was due to the errors which could not be detected by the naked eye. As the fields of CV and Image Processing have advanced, such fault detection have become automated. This enabled the manufacturers to produce goods which are more reliable. There are many such fields where CV has made strenuous, repetitive work easy.

Virtual Reality (VR) has always been in demand for entertainment and scientific simulations. The relentless efforts of researchers to achieve photo realistic rendering has fueled the emergence of a new field of research called Image Based Rendering (IBR). IBR deals with algorithms which rather than reconstructing the world from 2D images, try to construct novel views of the world given some additional information about the world (besides 2D images). IBR is a combination of Computer Graphics and CV. It can be used to produce photo realistic environments without any approximations involved in the physical phenomena.

Computer Vision (CV) and Image based rendering (IBR) algorithms are used to analyze the events and structure from videos and images given some additional information like calibration of the camera. IBR algorithms use various intermediate structures computed from the images and other imaging parameters such as depth map, correspondences, etc for testing and tuning. Evaluation and tuning of CV or IBR algorithms require high quality images with accurate ground-truth information. Acquiring such high quality ground-truth information from real world scenes is highly complicated and time consuming. The equipment required for acquiring such high resolution data is very costly too. Synthetic data is an

alternative widely used for testing these algorithms in the initial phases of development.

Synthetic data is useful as, qualitative and quantitative analysis of the performance of these algorithms is possible using them. The performance of the algorithms on synthetic data is a good indicator of it's performance on real world images. The most important advantage of using synthetic data is that it would help in cross checking the information reconstructed by an algorithm. Another advantage of using synthetic data is that it is available for free. Synthetic data clearly plays a very important role in forwarding the research in the fields of CV and IBR.

1.1 Motivation

Traditionally individual research groups and researchers have been creating their own data sets for evaluating the performance of the algorithms they develop. The data sets so generated have become standard test beds for benchmarking the performance of certain class of algorithms e.g, CMU Datasets [21]. Every algorithm is based upon certain fundamental assumptions about the information available and the type of data it would encounter. For example an algorithm trying to do motion tracking would have to make certain assumptions about the type of motion and background changes. On the other hand an algorithm trying to do face detection might have different assumptions about the information available say lighting conditions or the color ranges of the skin color etc. A data set created for testing a particular algorithm may not be valid for testing the performance of a newly developed algorithm (with different set of assumptions).

Every time an algorithm to address a new problem is designed, the researchers have to go about creating a new data set which represents the actual data to train or test the algorithm. As generating real data at high resolution is a very costly affair (due to the requirement of high precision apparatus), researchers resort to developing tools for generating synthetic data for analysis. These tools are generally designed only for a specific dataset generation and cannot be used once Diversity in the data set becomes a critical issue. For creating diversity, one has to find or build another dataset, which again is a tedious process. This is because the tools developed for synthetic data generation are generally very limited and non-scalable. A lot of time and human resources are wasted in creating datasets for even prototype testing of an CV or IBR algorithm. If this time spent on dataset creation is reduced, researchers would be able to spend their valuable time in the development of algorithm rather than development of a tool for generating the dataset.

A desirable tool for any researcher would be, the one which enables him/her to create complex scenes which mimic the real world scenes both static and dynamic without much effort. As more and more algorithms are developed new input and output formats come into being, extensibility of the tool be-

comes an important factor. Clearly there is a need for a tool which would enable researchers to generate realistic and complex datasets without much effort. This was the motivation for this thesis work.

1.2 Major Approaches

The traditional methods of data generation for CV and IBR can be categorized into three major classes. These methods are listed below:

- Data acquisition by using high precision digital equipment.
- Extending standard 3D authoring tools.
- Developing a tool for synthetic data generation.

Data acquisition using very high precision digital equipment like lacer scanners, digital cameras, etc is a very effective way to generate datasets. This method of data generation enables the researchers to acquire the real world data at a very high resolution. Since the data represents the real world objects, all the difficult cases (such as fur, water, etc) for the CV and IBR algorithms could be present in the datasets. Though this method of acquisition is very useful, repetitive generation of data with some parameters modified can be a painful process. Even the slightest of errors in the acquisition equipment can result in corruption of the dataset. In addition to these, the major drawback of such equipment is that they are very costly and may not be accessible to most of the researchers.

Most of the standard 3D authoring tools provide facility to generate very high resolution synthetic data. Advanced features in rendering like bump mapping, soft shadows, motion blur, normal mapping etc which are common in such tools add to the realism of the synthetic data. Some of the sophisticated 3D authoring tools support their own scripting language which enables the users to add additional functionality by writing a few lines of code. Ray tracing softwares which are known for the high quality imagery they can produce, have their own scene description language enabling the users to generate synthetic data. Since most of these tools are focused on generating photo realistic imagery, extending them to generate datasets for testing CV and IBR algorithms may be unintuitive. The major advantage of this method over data acquisition using high precision equipment is the repeatability of the dataset generation with a few parameters modified.

As stated before, extending standard 3D authoring tools for generating required data may not always be very easy to accomplish. This is where researchers have no other option but to create their tool for generating the datasets. Such tools are very fine tuned for generating a specific dataset. Extending them to generate datasets for other algorithms may be virtually impossible. This method of dataset creation is very time consuming due to the development time involved (for developing a whole new data generation tool). The advantage of development of such a tool is that it could be used for generating datasets for

most of the algorithms that try to address the same problem as the algorithm it was originally developed for.

1.3 Objectives

Synthetic data plays an important role in testing and training of CV and IBR algorithms. This is because acquiring real world images is costly and tedious process. We believe that a generalized synthetic data generation tool kit with the following features would be a boon for many researchers working in the areas of CV and IBR. The development of such a tool would help researchers to quickly check if a certain technique is working or not, without worrying about the availability of datasets.

Our objective was to create such a generic tool kit and make it available to the research community. We have set for ourselves a set of requirements that have to be satisfied, for a data generation tool to be useful for generating datasets for any CV or IBR algorithm.

1.3.1 Versatility

CV and IBR algorithms are generally developed for solving some real world problems like Motion Tracking, Biometrics based Identification, 3D reconstruction and visualization, etc. The inputs to these algorithms range from, simple images to video sequences with depth information, etc. For this reason, the data generation tool should allow creation of complicated scenes that mimic the real world. The real world scenes are not always static. Hence such a tool should provide functionality to generate dynamic scenes. Datasets which have dynamic objects in the world are important for the analysis of Motion tracking, 3D reconstruction and other algorithms which operate on video sequences.

1.3.2 High Quality

The quality of images and ground truth are very critical for testing CV and IBR algorithms. Though synthetic data cannot be photo realistic, such a tool should strive to produce data which is comparable to the data produced using high precision data acquisition equipment. The tool should provide some control over the quality of the output generated. Such a feature would enable the user to evaluate the robustness of an algorithm. Though most of the visible colors can be represented using 32-bits per colors, some applications might require a higher quality color representation (e.g, 48-bits per color). Such high quality features are to be made easily accessible to the user.

1.3.3 Flexibility

Since the problem we are trying to address is very general covering a large spectrum of algorithms, the data generation tool kit should be flexible enough to provide the user with different choices. The choices

begin right from the format of the 3D models supported as input for creating scenes. There are hundreds of file formats for storing and sharing 3D graphics models, supporting at least a few of the most popular formats is essential for the tool to be usable. Such a data generation tool should be flexible enough to enable the user to setup very complex camera configurations (e.g, dome configuration, etc) once the scene is setup.

1.4 Contributions of the Thesis

The primary contribution of this work is in the creation of a tool useful for individual researchers to generate high quality, ground truth data and share it with others. Our tool is computer vision aware; it is not just another graphics authoring tool. It therefore generates depth maps, calibration matrices, correspondences, etc., which are valuable to computer vision researchers. Conventional graphics authoring tools focus on setting up the 3D world and generating views of it. The data generation capability can be added as additional functionality to tools like 3DStudio Max or Blender. But such extensions are generally very unintuitive and difficult because the internal implementation details are hidden from the users. In addition to this, the commercial 3D authoring tools like 3D Studio Max, Maya etc are very expensive and may not be accessible to every one. Open source 3D modeling tools (e.g Blender) are difficult to use or unstable. We chose to create a new tool of our own since the requirements are different. We may need to represent additional type of information about the environment which can require unintuitive extensions to the existing file formats. A simple, open-source tool that can import standard models but has an internal structure that suits computer vision applications is preferable. Since the users have access to the code, they would be able to extend the tool to support the required data. We designed our tool to work intuitively along side these tools rather than extend any of them.

(a) (b)

Figure 1.1 Some scenes made using our tool. (a) Rendered using our tool's internal renderer. (b) Rendered using povray from the scene description generated by our tool.

Features	3DSMax	Maya	Blender	DGTk
High-Resolution	√	√	√	√
High-Quality	√	√	√	√
Dynamic Scenes	√	√	√	√
Ray tracing	√	√	√	√
Open-Source, Free	×	×	√	√
Camera Calibration	×	×	√	√
Depth-Maps	×	×	×	√
Object-Maps	×	×	×	√
Alpha-Maps	×	×	×	√
LDI	×	×	×	√
Point Correspondence	×	×	×	√

Table 1.1 Comparison between various synthetic data generation tools and DGTk.

Our tool has a GUI similar to standard 3D authoring tools. This makes learning to use our tool a feeble task. DGTk (our tool) supports a variety of standard 3D file formats (AC3D, MD2, 3DS and povray) to be imported for creating complex 3D scenes which mimic the real world scenes (Figure 1.1). The tool presents a simple select and drag interface for moving the 3D models imported to the tool. Even the cameras and lights are abstracted as objects and can be manipulated by the user just like any other objects. There are no limitations on the number of objects, cameras or lights that can be placed in a single scene. This would be for first time where both Object maps and Alpha maps are generated as ground truth information. These representations are very useful for the algorithms which try to estimate silhouette of objects and object matting. We present the user with an interface which enables him to know the exact resolution at which the image is going to be rendered. High resolution (images larger than the frame buffer size) image rendering is supported in our tool. Our tool provides the user with the flexibility of rendering high quality images using POV-Ray (a ray-tracing software). The simple human readable scene description language used by our tool enables users to create complex camera configurations which would be very expensive to setup in the real world. Default support for intermediate representations like alpha-maps, depth-maps, object-maps, etc which are very valuable researchers, and a simple GUI for generating complex data are the key features of our tool. A comparision of different tools based on the features and representations required for CV and IBR algorithms (Table 1.1) describes clearly that our tool is a better suited for synthetic data generation.

DGTk uses a basic OpenGL based renderer for generating the required representations. The rendering algorithm used does not support features like high dynamic range rendering, normal mapping, shadows, etc. Though such complex rendering algorithms can be incorporated into our tool, we have focused on providing support for multiple representations. Real-time rendering is not a requirement in data generation. Due to our object-oriented approach in building this tool, the rendering algorithm can be

changed without effecting the other parts of teh tool. Our tool supports such high quality data by generating scene description used by POV-Ray, which can be used to generate very high quality images.

1.5 Organization of the Thesis

The thesis is organized as follows:

In Chapter 2 we give an overview of the techniques and types of data currently available. We have classified the related work into these three groups. We also provide a brief overview about the type, resolution of the data generated in their work. In Chapter 3, we describe the design requirements for a synthetic data generation tool. This requirement analysis is based on our observation of the limitations in the previous work. We then go about describing the development cycle of our tool. We describe how the tool has evolved from a simple program which takes command line arguments and renders high resolution images to a fully functional GUI based tool for data generation. We describe the objectives we have achieved through the design of our tool. Chapter 4 describes various data formats that our tool can generate. Each section describes a file format, it's uses and the implementation details for generating that format. We also discuss some of the features of our tool which make it easy to use for synthetic data generation. The representations of 3D scenes generated by our tool are showcased in Chapter 5. Chapter 6 is a summary of what we have achieved by developing such a data generation tool. We also provide some of the future possibilities to be explored. In Chapter B, we provide a detailed overview of the file format we have designed for representing a scene created using our data generation tool. We discuss the merits of such a standard representation for scene representation. We also discuss why the current scene description languages provided by most of the rendering softwares are inadequate for this purpose.

Chapter 2

Related work

The researchers all over the world have been actively creating and sharing datasets (both real and synthetic) which enabled the comparison of the performance of different algorithms which address the same problem (e.g, 3D depth map construction, Motion tracking, Object Detection, etc). We have classified the previous work done into three major sections, (1) Data Acquisition using High-Resolution Equipment, (2) Extending existing tools for Data Acquisition and (3) Data Generation Tools for generating Synthetic Data.

2.1 Data Acquisition using High-Resolution Equipment

In an attempt to provide a generic platform for comparing the performance of Stereo matching algorithms, Scharstein and Szeliski [15] have designed a collection of data sets. Their work goes beyond just creating datasets, and presents a comparison between some of the stereo algorithms along with an insight of their working. The datasets were created by acquiring images using a high-resolution camera.

The development in the stereo matching algorithms have outpaced the ability of standard datasets to discriminate among the best performing algorithms. In 2003, one year after their previous work, Szelski [16] was developed to create more challenging scenes with accurate ground truth information. In this work a method for acquiring high-complexity stereo image pairs with pixel accurate correspondence information using structured light is explained. The data acquisition equipment consisted of a pair of hight-resolution cameras and one or more projectors that cast structured light patterns. The datasets created using this method were made available for the research community to use.

In a more recent work, Steven at al [17] present a method for acquiring and calibrating multi view image datasets with high-accuracy ground truth. These high-accuracy calibrated multi-view image datasets helped in the qualitative comparison of stereo reconstruction algorithms which was not possible before. The datasets described in this work were generated using the Stanford spherical gantry, a robotic arm. Images were captured using a CCD camera with a resolution of $640x480$ pixels attached to the tip of

the gantry arm. One pixel in the image acquired roughly spanned $0.25mm$ on the object surface.

Fellenz [4] have developed a low cost vision head for enhancing the dense depth maps. CMU over the years has developed a large number of data sets which have become the standard test data sets e.g, CMU PIE database [21], etc.

In all the work referred above, the data had been acquired using a high resolution camera along with some highly calibrated apparatus. As a result, the datasets are highly accurate and very realistic. The main disadvantages of datasets generated using such equipment are:

- Advances in algorithm development may lead to datasets becoming obsolete.
- Recreation of the data at a higher resolution may be virtually impossible.
- Minute errors in the calibration of the apparatus may lead to corrupt datasets.

2.2 Extending existing Tools for Data Acquisition

Though very high quality data acquired using high precision digital devices is available for usage by other researchers, the inherent problems (described above) involved in such datasets resulted in increased use of Synthetic datasets. The synthetic data has the advantage of repeatability of the datasets with some modified parameters. Standard Computer Graphics (CG) tools like Ray tracing softwares and 3D authoring tools have been traditionally modified or extended to generate synthetic data.

Ray tracing softwares which are very popular in the CG community, are capable of producing very high quality images of 3D scenes. Over the past decade, ray tracing softwares have evolved into complex software systems. These softwares now have their own scene description language which are powerful tools for creating complex scenes. Some of the ray tracing softwares support animation scripts for the objects in the scenes. While some of the ray tracers have tried to simulate various types of lens effects, particle effects and projection types, others have tried to achieve realistic light simulation. A more comprehensive comparison among some of the free ray tracing softwares is presented in Haynes [6]. The power of ray tracing softwares to create and render realistic scenes that mimic the real world scenes, makes them a good option for creating datasets. Since these softwares are designed only to generate images, it is not feasible to extend these to generate intermediate representations like object maps, corresponding points, etc.

Standard 3D authoring tools take the data generation to next level by providing flexible User Interfaces (UI) for setting up complex 3D scenes. This makes the scene setup a lot easier compared to writing the scenes in text. The 3D authoring tools (both commercial and free) such as 3DSMax, Maya, blender etc are capable of rendering high resolution images using ray tracing, But they do not generate depth maps,

Calibration data, Corresponding points, Layer depth images etc by default, which are typically required for testing CV and IBR algorithms. Fortunately these 3D authoring tools provide the flexibility to the user to extend the functionality by writing simple scripts. For example 3DSMax supports MAX scripts, Maya has it's own scripting engine which supports MEL scripts, Blender (an open source 3D authoring tool) allows users to write python scripts for extending its functionality.

The commercial products like 3DSMax, Maya are very costly and hence may not be accessible to everyone. Though blender is a free software and has many features for animation and rendering, it's UI is considered unintuitive. Once the users become familiar with it's interface, it is a very good tool to use for data generation. Some of the researchers [9, 11, 13] have tried to extend blender to produce computer vision data like depth maps, camera calibration information, etc.

Figure 2.1 A frame from the first ever open movie "Elephant's Dream". This movie was created from scratch using blender for modeling and rendering. The project proved that such cinematic quality rendering can be achieved through open source tools. The creation of this movie has fueled the development of blender. Many tools which make animation easier have been added based on the feed back from the developers of this movie. (Courtesy Orange the open movie project.)

2.2.1 Blender review

Blender is an Open source multi-platform 3D modeling and animation suite. It has support for Windows 98+, Mac OS 10.2+, Linux (i386 and PPC), Solaris (Sparc), FreeBSD, and even Irix (mips3). It has grown into a complex tool since it has been licensed under the GNU GPL in 2002. The movie "Elephant's Dream", the first ever open movie was made using blender. The current version 2.42 has enhanced character animation tools. It's development has been boosted since the release of the "Ele-

phant's Dream" movie. Many enhancements to the animation tools were a result of the feedback from the blender community. Blender has one of the fastest ray tracing engines for rendering the scenes. The rendering pipeline till recently did not have tiling support and hence the images rendered were limited by the frame buffer size. The current version (blender 2.42) has tiling support where each tile is rendered in a separate thread. Blender provides an excellent interface for creating organic models (e.g, models like monsters, humans, plants, trees, terrains etc). Blender supports bone animation through objects called armatures which provide both forward and inverse kinematics. Though these features enable for very complex animations, they are daunting to use, even for intermediate users.

Since the early versions, this tool has relied greatly on keyboard shortcuts. This makes the tool hard to learn. In the more recent versions, the development team has tried to over come this problem by providing most of the operations as menu items and buttons. Though this helps intermediate users, novice users still find it difficult to use the tool because of too many menus and shortcut keys. The reference of shortcuts provided by the developers runs to nearly nine pages. Such complex systems are hard to use for novice users. On the other side, once the tool is mastered, it is the best tool available. In addition to modeling, rigging and animating, blender's users can develop small games by making use of game engine provided in it. This game engine features collision detection, physics simulation and many more. Blender has several areas where it can improve. Lack of simple interface is one of the most important drawbacks. The UI provided is very flexible and can be changed to imitate any of the standard UIs. But the scope of functionalities provided by blender is so broad that one can easily become lost in all of the options. Even a simple task like changing the material property of a surface requires clicking and selecting multiple options. One of the best things about blender is it's support for plug-ins in the form of python scripts. This enables users to write scripts to export as well as import models in their own file format. Unfortunately the python api of blender is very huge. It may be difficult to find the right classes for implementing an extension. On the brighter side, it has a great support; For example, the Blender Web site features a bug tracker any user can post in. Most of the submitted bugs usually fixed within days, and new testing builds are available almost every week. In addition to these, there are many on-line tutorials available on the Internet which are specifically designed for novice users.

On the whole blender is a great 3D suite for modeling and animation. Due to it's complexity, it may be difficult for new users to adopt this tool. This is the main reason why most researchers tend to develop their own tools for data generation rather than extending blender using it's scripting capability.

2.2.2 3DSMax review

3DSMax is a commercial 3D authoring tool popular among the game development and other industries based on computer generated imagery (CGI). It was one of the softwares which pioneered in providing UI for character animation. This tool has been up to date with the current state of the art interfaces

available for various modeling and animation requirements.

3DSMax has a very powerful network based rendering system which makes use of all the nodes connected in the network for rendering a scene at very high resolution. This tool has a plug-in system which enables the users to change the rendering algorithms, export new representations of a scene or even import a new file format. The scripting provided by these tools enables artists to create animations with very high precision. AutoDesk the developers of 3DSMax have designed their own proprietary scene description for 3DSMax which has evolved into a powerful representation which allows users to store animation information as well. 3DSMax 8 (the latest version of 3DSMax) has a very unique easy to use UI for adding hair to a model. The user can groom the hair of the character using a comb control provided as a part of styling interface. This interface a short learning curve compared to Maya's hair modeling system. In addition to this, Max has support for cloth simulation. Once a mesh is specified as a cloth, the internal simulation engine manages the movement of the cloth in the scene. All these features in such tool are focused on making the UI better for artists. The character studio which is provided as a part of 3DS Max is perhaps one of the best systems available for creating character animations. Such complex features like Inverse Kinematics, Quaternions, Curve-editing etc are used for provide maximum control of the animations. These tools are better suited for artists and are really an overkill for data generation for CV and IBR. To obtain the best performance, these tools try to optimize the rendering algorithms so as to generate images of scenes quickly and provide the artists with more time to create and modify the animations.

The number tools provided in this software is enormous. Users can write scripts for camera motion in the scene or even develop plug-ins for supporting different file formats. This is not generally enough for the data generation requirements. For generating different representations of a scene (i.e, depth maps, alpha maps, ldi, etc), the user requires a through insight of the internal data structures used in the tool. This is clearly not possible in closed source, commercial softwares like 3DSMax.

2.3 Data Generation Tools for Specific Data

Due to the increased adoption of finger print based authentication systems, methodical and accurate performance evaluation of finger print recognition algorithms is required. Since collecting large finger print databases is expensive and problematic due to the privacy legislation, a method for generating synthetic finger prints had to be constructed [2]. In Capelli [2] the author presents a method for generating synthetic finger print data based on few parameters. When extending existing tools to generate the required datasets is not possible, researchers have no other option but to develop their own tool for the data generation. For example, representations like Layer Depth Images (Shade et al [18]) cannot be generated by extending the existing tools. In their work the authors describe a few methods for acquiring the datasets for the algorithm.

2.4 Summary

The increase in the pace of development of CV and IBR algorithms led to a situation where the current datasets have become inadequate and can no longer be used for qualitative comparison of new high quality algorithms. All the time and revenue spent in gathering such datasets could become wasted. Researchers have tried to over come this problem by providing data generation tools for some specific problems. Though such tools help in generation of datasets, they are generally very limited in terms of extendability and type of data generated. Some of the commercial authoring tools like 3DSMax, Maya, etc are either very costly or cannot be extended due to lack of information about the internal representation of data in these tools. Open source tools like blender have a very complex ui which is difficult to use. Due to constant change in the architecture of the system, it may be difficult to update the data generation scripts. In addition to these, since such tools are specifically designed for modeling and animation, it may require un-intuitive extensions to the current file formats. A single versatile, extendable, flexible tool for generating data for CV and IBR algorithms would help in improving the pace of algorithm development by reducing the time spent in data acquisition.

Chapter 3

DGTk: Design

3.1 Design Details

The data generation tools available are generally developed for generation of a specific type of data sets only. For example data generation for finger print identification, Corresponding Points, etc. Though such tools are capable of generating high quality data, they may become unusable due to their limited extendability. A tool kit which can generate more than one type of datasets and is extend able would be very useful for CV and IBR research community. Based on our analysis of the tools available for data generation, (Chapter 2), we have come up with a design for a generic data generation tool.

In this chapter, we present the design details of DGTk a toolkit to generate data for computer vision and image-based rendering algorithms. The goal of such a toolkit is to enable individual researchers to generate high quality synthetic data and to help them share the datasets with others in the community. DGTk is designed to be a standalone toolkit using which one can create a scene consisting of cameras, lights, geometric objects, etc. For versatility, the tool allows the user to import 3D models in standard

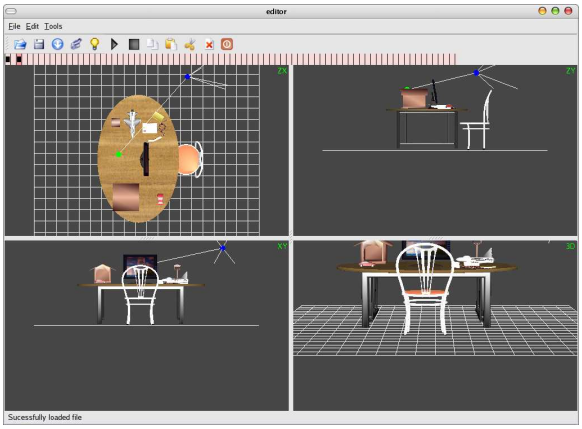


Figure 3.1 Screen Shot of the Tool

formats like blender, ac3d, 3DStudio, etc. Several objects, lights, and cameras can be placed in the scene. Each of the objects placed in a scene can be moved for creating dynamic scenes. Their positions can be specified at key frames and interpolated for the intermediate time steps. The scene description can be saved and shared with others. Several representations at many resolutions can be generated for each camera in the scene including images, depth maps, object maps, calibration matrices, pairwise correspondence, etc.

The image generation is done using OpenGL API for the sake of speed. The whole tool relies on OpenGL and Qt for rendering and UI handling. We have developed a basic OpenGL based renderer which is used for displaying the 3D scenes made by the user. The tool has four views of the scene (Figure 3.1). Each view in the tool is actually the same basic renderer, with the camera parameters modified. Our primary design goal was to make the tool as flexible as possible so as to appeal to many researchers. Very high-quality imaging can be achieved through support for generating scene descriptions which can be used in ray tracers. Our tool outputs files for the open-source ray tracing tool POV-Ray for this purpose. The tool is designed to be extensible. Users can write their own code to handle other 3D model formats or to generate novel representations. Though generating and sharing datasets is very important, it would be useful if the researchers could share the actual scenes that were used for generating the dataset. This enables the researchers to generate datasets using same scenes at higher resolutions or with some camera parameters modified. To support such sharing of data scenes, we have developed a high level ASCII file format for the scene description. This file stores the information about objects in the scene (i.e, different 3D model files), their positions, rotation and scale factors. Since our file format is very simple, users can write their own scripts to generate scenes with complex camera configurations. This would be very useful because data generation with such complex configurations in real world is very expensive.

3.2 Class Hierarchy for Input Objects

To enable easy extendability, we have designed a class hierarchy in the tool (Figure 3.2). This class hierarchy, makes adding support for a new 3D input model or generation of new file format very easy. Each object (including lights and cameras) in the tool inherit the class $glObject$ which stores the details like rotation, scale and position. All the inputs provided by the user are stored internally and used to calculate the required data from a scene. Care has been taken so as to enable the toolkit would be as scalable as possible in terms of the range of system configurations on which it can be run. When ever we had to choose between features supported in high-end graphics hardware and those that are supported in almost all graphics hardwares, we have invariable chosen the features which are supported in all graphics hardware. For example, the generation of matting information which describes the area of pixel (at the borders) covered by a primitive can be found on some of the high-end graphics hardware by enabling

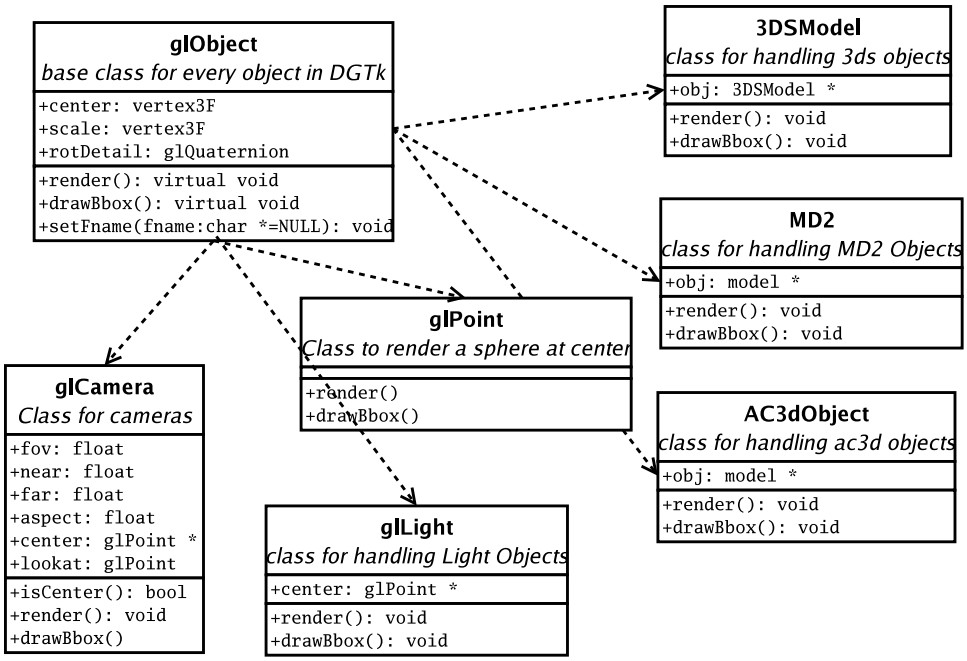


Figure 3.2 Class diagram of the toolkit

some OpenGL features like multi-sampling etc. But such features are not available on low-end graphics hardware. We tweaked the $SuperSampling$ algorithm which is used for full scene Anti Aliasing and implemented it so as to make our tool scalable. Similar decision was made while deciding about the method for rendering high resolution images.

As stated before, our tool enables users to import 3D models and setup complex scenes. Our tool does not provide any interface to the user which enables him/her to add or edit points, triangles, etc of the models imported into the tool. Though such features can be added into the tool, that is not the focus or purpose of our tool. The user is provided interface for moving, rotating and scaling selected objects. Though our tool provides an interface for creating dynamic scenes, it does not meet the animation requirements completely. Complex animations like walking, face expressions etc are very difficult to be setup in our tool. Since providing complex animation tools in a data generation toolkit is an over kill, we have ignored such features. Instead, we support MD2 file format. This file format is an simple open animation format which is based on key frame systems. If the user desires to make a scene which has complex scenes like people walking around on the ground, all the user need to do is import MD2 objects with required animation and translate, rotate or scale them as required. All the file formats supported by our tool (AC3D, 3DSMax, POV-Ray and MD2) are very popular and large databases of 3D models in these formats are freely available on the Internet. The advantage of supporting open formats like AC3D, MD2 and POV-Ray is that users can generate these models using any open source 3D authoring tool

like blender and use them for data generation, all at free of cost.

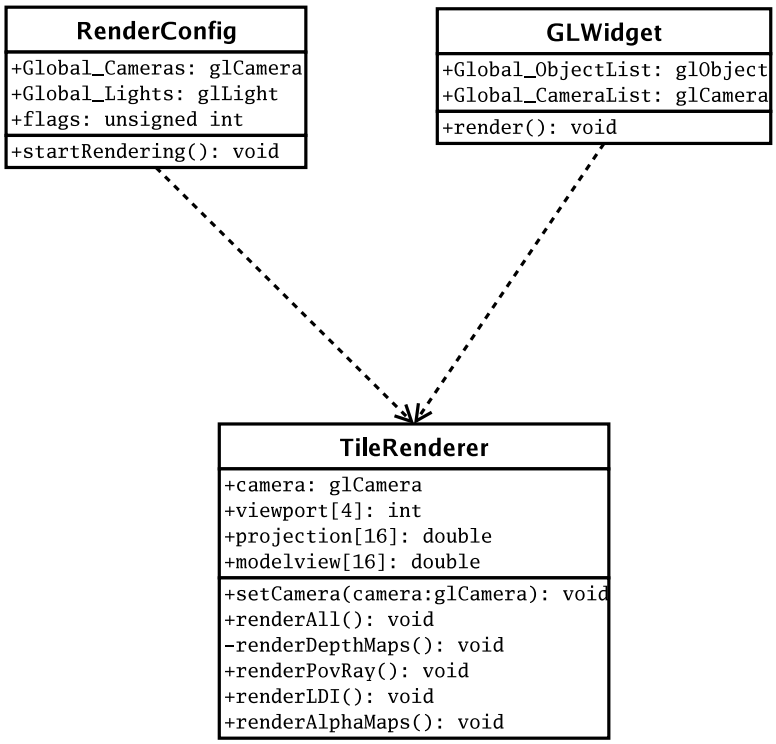


Figure 3.3 The class diagram of the output representations. Tiled renderer is the class responsible for generating the final output representations. The input to this renderer is the $glCamera$. This object provides the parameters set by the user in the $RenderConfig$ class (i.e, the image dimensions, tile dimensions, etc). The $GLWidget$ class is the class used for setting up the scene. This class handles the object movement etc and hence provides the object positions, camera positions.

3.3 Output Class Hierarchy

We have developed a c++ class for rendering the scene. This class has different methods each for rendering a separate representation of the scene. The class provides a single method for rendering all the frames of a single camera. This is done because, the user may require the tool to render different camera views at different resolutions. Once the user starts the rendering process, these parameters are used to calculate the image resolution and the number of tiles to be rendered. These parameters are passed to the tile renderer as function arguments in the form of the camera class. Tile renderer uses this camera information to render the final output (Figure 3.2). If the user needs to generate a new representation, he/she needs to add another method to the tile render class and invoke it for every tile render. The advantage of this method of implementation is that the user is completely abstracted from the tiling process and hence very high resolution representations can be generated without any difficulty. The renderer is

built using OpenGL with support for texturing, lighting and materials. This means that every rendering operation in our tool has to be done using OpenGL. Since OpenGL is the industry standard for rendering operations, we have decided to use it for our rendering purposes.

$RenderConfig$ is a class which provides the user with GUI for setting up the camera resolution for each camera in the scene. It also provides a number of check boxes each for rendering a different representation. Based on the user's selection of these check boxes, a flag variable is set and passed to the tiled renderer where it will be used for generating different representations of the scene. The $RenderConfig$ class also sets some of the attributes like image dimensions, tile dimensions for each camera object which is passed to the tiled renderer. The tiled renderer uses this information for calculating the number of tiles, view frustum for each of the tiles and generates the output. These representations include the depth maps, tiled images, full high resolution images, POV-Ray scene description for high quality rendering, Object maps, matting information in terms of alpha maps, point correspondence and layer depth images. Each of these representations is implemented as a separate method in the $TiledRenderer$.

3.4 GUI Class Hierarchy

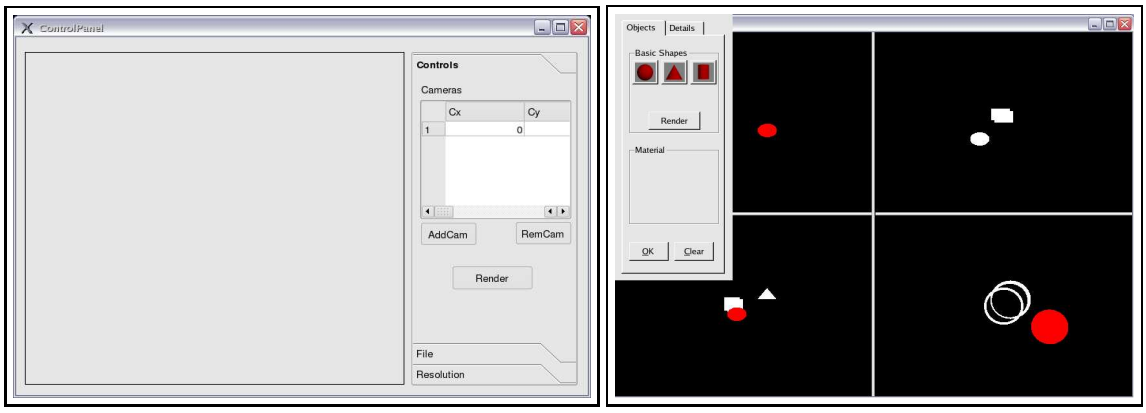
Many 3D authoring tools have strive to achieve perfection in their user interfaces. These tools have GUIs that have been rigorously tested so as to make sure that the learning curve for the users is as minimal as possible. We tried to achieve the same perfection in the GUI of our tool. The time line feature in our tool, which is useful for creating dynamic scenes, is an inspiration from a popular 2D animation software called Macromedia Flash. There were many iterations in the development cycle, where we constantly changed the UI before achieving the current UI. We considered implementing innovative sketch based modeling interface for creating models described in [8] for our tool. This idea was later discarded since creating 3D models is not the focus or purpose of our tool. Our tool evolved from a simple command line rendering tool to a fully featured tool with very easy to use UI which mimics standard 3D authoring tools (Table 3.1).

3.4.1 The Main Window

The GUI of our tool is composed of six major components. The $MainWindow$ class is used for creating the main GUI window with four frames, each for a different view of the scene in the tool. This class contains instances of the GUI for configuring cameras, lights, rendering parameters etc. This class is responsible for providing the menu interface along with the tool bar buttons for performing basic operations like opening a file or saving a file. These also include editing operations like cut, copy and paste. Since interfaces for specifying the render parameters for the cameras, lights, different representations and the dynamic scenes are part of the whole tool, we have put instances of GUI for

Version	UI	Input	Output
V 0.1	command line	AC3D	High Resolution Images
V 0.2	GUI (Figure 3.4(a))	AC3D	High Resolution Images
V 0.8	GUI (Figure 3.4(b))	AC3D, Standard Shapes	High Resolution Images, Povray Files, Depth Maps
V 1.0	GUI (Figure 3.1)	AC3D, MD2, 3DS, POV-Ray	High Resolution Images, Depth Maps, Object Maps, LDI, Matting Images, LDI

Table 3.1 Overview of Previous Versions of our tool.



(a) (b)

Figure 3.4 Screen Shots of GUIs of Previous versions of DGTk.

these configurations as part of the $MainWindow$ class (Figure 3.4.1). This enables easy access to the render parameters for the final tile renderer. For example, the main interface has a play button which can be used to preview the animations in the main window itself. This is possible due to the interaction between the $GLWidget$, $TimeLineWidget$ and the $MainWindow$. Once the play button is clicked in the main window it sets the animation variable in the $GLWidget$ and the $GLWidget$ window starts taking the interpolated values of the object's properties from the $TimeLineWidget$. This is possible because we maintain a global variable for the time line and the objects as well. The following sections describe in detail each of the GUI classes.

3.4.2 The TimeLineWidget

This is a custom made widget which looks like a modified version of the Macromedia flash's time line GUI. This widget is a Qt class for handling the creation of dynamic scenes. This class is the responsible for providing the user with the interface for providing information about the key frames for the dynamic scene. This class has it's own popup menu to support the basic functionalities required like making

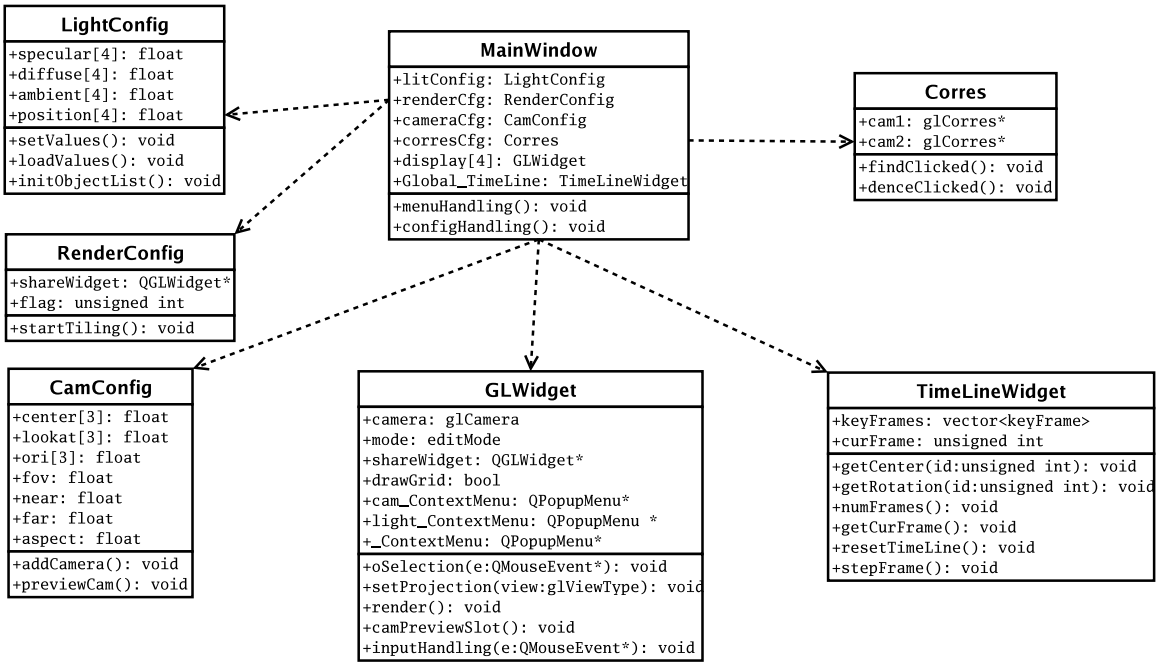


Figure 3.5 Class diagram for the interaction between the GUI classes. The $MainWindow$ class contains instances of the other GUI classes providing a single point access for the tiled renderer. This separates different tasks which are to be handled by the whole GUI. For example, the dynamic scenes are completely handled by the $TimeLineWidget$ and the $MainWindow$ class does not have to do anything at all. Similarly the rendering and object movement in the scene is handled by the $GLWidget$ itself and $MainWindow$ class deals only with displaying these widgets.

a key frame. The interpolation algorithm is implemented in this class itself. Methods for retrieving the position and orientation of an object are provided in this class. This is essential for abstracting the rendering algorithms from the interpolation algorithms. The only difference in the rendering widgets is that they retrieve each object's parameters from the $TimeLineWidget$ instead of specifying them in line. Even though a new method of interpolation between key frames is implemented, the other rendering algorithms need not be changed. Currently we use temporal key frames based animation system with simple linear interpolation of positions of the objects in the intermediate frames. More complex algorithms for key frame animations are described in [5]. Researchers are actively exploring other means of specifying the key frame information, like spatial key frames [7]. Such interfaces and algorithms can be easily adopted by our system.

3.4.3 The GLWidget

The $GLWidget$ is a class which handles displaying the scene in the GUI. This class handles the user input (i.e, the mouse clicks and drags for object placement in a scene). This class inherits $QGLWidget$ which handles the event generation part of the UI. When ever the user clicks or drags, a message is received by this class and the corresponding action is taken. We required the final GUI to have four different views of the same scene, each displaying front, top, side and the 3D views of it. To support this we made this class as generic as possible. The panning and zooming of camera is also implemented in this class itself. Our GUI uses four instances of this same class with view parameter changed. If some changes in the rendering algorithm occur, the changes are to be made only in this class and they would be reflected in all the four views. The problem with creating four different OpenGL windows is the context of rendering, the textures that were loaded would not be accessible in other contexts. To over come this problem, we use the sharing of the context which is provided by the Qt's $QGLWidget$ class.

3.4.4 The Configuration Widgets

The GUI provided by our tool enables the user to drag and place objects at desired positions in the scene. But for some of the objects like cameras and lights, the user may require to know the exact locations of these objects. For this reason, our tool provides special configuration GUI for these objects. The camera widget provides the user with a simple interface with text boxes. These are used for creating a camera object which can then be used to generate the required representations. Lights are undoubtedly the most important objects for most of the CV algorithms. Knowing the exact properties of lights is more important than anything else for some of these algorithms. It is for this precise reason, we provide a configuration tool for specifying the properties of lights in the scene. The other way for specifying exact values for these objects or any other objects in the scene is to set these values in the scene description file itself.

3.4.5 The RenderConfig Widget

One of the major goals of our work was to make the data generation process as simple as possible. Providing a good easy to use GUI for setting up the scene is just half way to our goal. We had to provide a good easy to use UI for the user to select different representations that he/she can generate. The $RenderConfig$ class is the widget class we developed to handle this part of our tool. This widget provides the user with an interface which enables the user to know the exact resolution at which the image would be rendered. i.e, for the given image dimensions and the camera parameters, the tool would display the worst case resolution of the image in terms of pixel distance to world distance ratio. In addition to displaying such information, this class is responsible for passing the information about the required render parameters from the GUI to the data generation algorithm. This widget presents the user with a set of check boxes, each for a different representation of the scene and hence making the data generation very easy.

3.4.6 The Tiled Renderer

High resolution data is very useful for qualitative and quantitative analysis of CV and IBR algorithms. Tiled Rendering is a standard method used for rendering very high resolution images which are larger than the frame buffer size. To match this requirement we designed a module called $TiledRenderer$. This module takes the parameters required for rendering in the form of a camera object. Each camera object can describe it's own image dimensions and tile dimensions, based on these parameters, the final representations are rendered. First the number of tiles to be rendered in horizontal and the vertical direction are calculated. Each tile is rendered by changing the view frustum and using the same camera parameters. Once each tile is rendered, it is placed at it's corresponding position in the full image buffer. This tiled renderer abstracts the tiling procedure from the data generation algorithms. The data generation algorithm is applied on to each tile in this module. If the user desires to add support a new representation to be generated by our tool, he/she needs to add a method in this class which renders the required representation without bothering about the tiling process.

3.5 Extensibility

One of the main goals for developing a data generation tool for CV and IBR algorithms is to provide the research community with a unique tool which is easy to extend to support generation of new representations of data. To meet this goal we have made DGTk completely extensible by following an object oriented design. Any desired input format can be imported into our tool by implementing a special class for reading and rendering that particular file format. The only requirement is that this class has to inherit from the $glObject$ class implemented in our tool. Similarly any new representation of a scene imported into the tool can be made by implementing a subroutine as a part of $TiledRenderer$ class. We used a

different strategy for extending the representations so as to enable users to be abstracted from the tiling process.

3.6 Discussion

Many research groups have developed synthetic data generation tools [2, 11, 13] for various CV and IBR algorithms. But they have always been limited to a particular representation of data, since they were not developed to be generic data set generation tools. For example, tools like SFinGe were created to generate finger print data alone. It was not designed to be a generic synthetic data generation tool for all the authentication algorithms. The design philosophy behind creation of our tool is to have a generic tool which would be easy to use and easy to extend for data set generation for various CV and IBR algorithms. Through our design described above we believe we have reached that goal. The GUI provided by our tool is one of the easiest to use and can be learnt easily without much effort. This makes it attractive for time bound research experiments to be conducted on synthetic data.

Chapter 4

DGTk: Different Formats and Implementation

Our tool currently provides the user with the flexibility to import many standard 3D file formats to create complex scenes. To achieve our goal of creating a generic data generation tool for CV and IBR algorithms, we designed our tool to be easily extendable to support many representations that may be required for these kind of algorithms. Our tool currently supports six different types of data for the user to generate. In addition to these representations, our tool can also generate very high resolution and high quality images. We support high quality data generation through generation of POV-Ray scene description. Our tool unlike the standard 3D authoring tools is vision aware; it generates depth maps, objects maps, point correspondence information which are very valuable for vision researchers. The following sections describe implementation details of the data that can be generated by our tool.

4.1 Arbitrarily High Resolution

Very high resolution data can be acquired from the real world scenes using expensive high resolution image acquisition equipment. If synthetic data has to be comparable to the real images, datasets have to be generated at a very high resolution. High resolution images are important because they can be used to test the difficult cases of the algorithms. High resolution can be defined in two terms, firstly by the number of bits used for representing a color and secondly the distance represented in the real world corresponding to one pixel span in the image. Hence forth, any reference to the term resolution refers to the later definition. Ray tracing softwares provide facility to generate images at very high resolution. The image resolution is limited only by the memory available in the system. Researchers have been making use of ray tracing softwares for generating such high resolution datasets. Though the ray tracers provide an option to change the resolution, it is generally in terms of image width and height. There is no direct method for the user to find out the resolution (pixel distance to world distance ratio). Control over the resolution at which images are rendered helps in the qualitative analysis of CV and IBR algorithms [15–17]. 3D authoring tools like 3DSMax, Blender, etc provide functionality to export the scenes to scene description of many ray tracing softwares. These tools typically make use of some standard graphics api like OpenGL or DirectX for rendering the scenes and limit the maximum

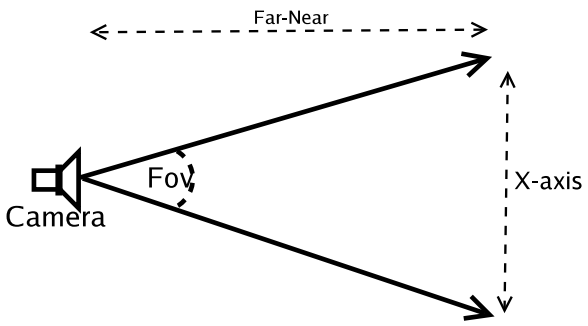


Figure 4.1 Camera Parameters

resolution of the image that can be rendered on a single system to the size of the frame buffer supported in the graphics hardware. To over come these limitations, these softwares have support for render farms (specialized clusters for rendering large images). This still does not solve the problem of control over the resolution. In DGTk the user can select each camera placed in the scene and specify the resolution at which each view has to be rendered. The user is provided the information about the worst case ratio between the pixel distance and the world distance.

The resolution of the image is dependent on the parameters (like fov, aspect ratio, near and far) of the camera. Simple trigonometry helps in finding the resolution of the rendered image from these parameters. Figure 4.1 shows some of the parameters that are important in calculating the resolution of the final image generated. The distance along world X_{axis} that will be imaged by the camera with field of view fov can be calculated using Equation 4.1. Once we have found the distance along X_{axis} covered by the camera, we can find out the distance along Y_{axis} by multiplying the X_{dist} with the aspect ratio of the camera. Resolution of the camera along X_{axis} can be calculated based on the image width and distance along X_{axis} covered by the camera using Equation 4.2. Similar process can be used to find the resolution of the image along the Y_{axis}.

$$X_{dist} = 2 \times (far - near) \times \tan(\frac{fov}{2}) \tag{4.1}$$

$$X_{resol} = \frac{X_{dist}}{ImageWidth} \tag{4.2}$$

4.1.1 Implementation

OpenGL and/or window systems limit the size of rendered imagery in several ways [5]:

- The window system may not allow one to create windows or pbuffers which larger than the screen's size. Typical limits are 1280 by 1024 pixels.
- glViewport's width and height parameters are silently clamped to an implementation-dependent limit. These limits can be queried via glGetIntegerv with the argument GL_MAX_VIEWPORT_DIMS. Typical limits are 2048 by 2048 pixels.

Interactive applications do not require higher resolutions, hence it is not a limitation for such applications. Rendering scenes at high resolution is inevitable in case of data generation tools. The standard method for generating such high resolution images is to divide the high resolution image into tiles that can be rendered in the frame buffer and then combining them to get the full image. This method can also be used for scene anti aliasing by down-sampling the high resolution image.

Tiling involves dividing the original camera frustum into number of smaller frustums which will be used to rendering each tile. The size of each tile decides the number of tiles required for rendering the high resolution image. Looping through all the tiles in horizontal and vertical directions, the scene is rendered using the same camera parameters (i.e, position, direction and orientation) and each tile's frustum. Once each tile is rendered, the high resolution image is made by combining these tiled images. Below is the detailed step-by-step description of how tiling can be achieved [22].

1. Allocate memory for the final image.
2. Create tile rendering context.
3. Set the camera parameters and tile's frustum.
4. Render the scene.
5. copy the tile to it's location in the final image.
6. if this is the last tile exit else go to step 3.

While specifying the parameters of the camera, we assume that the camera's frustum is symmetric about the coordinate axis. Since the $glFrustum$ (OpenGL function for specifying the camera frustum) parameters can be non-symmetric, we have to calculate the parameters of $glFrustum$ to make it symmetric about the coordinate axis. The parameters of a symmetric frustum can be calculated using the camera parameters (fov, near, far and aspect) using Equation 4.3.

$$\begin{aligned} top &= \tan(fov \times \frac{\pi}{180 \times 2}) \times near \\ bottom &= -top \\ left &= aspect \times bottom \\ right &= aspect \times top \end{aligned} \tag{4.3}$$

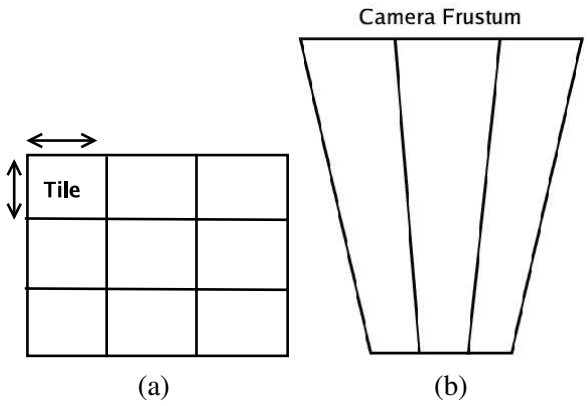


Figure 4.2 Frontal view of the frustum divided into a number of tiles (a). Top view of the same (b).

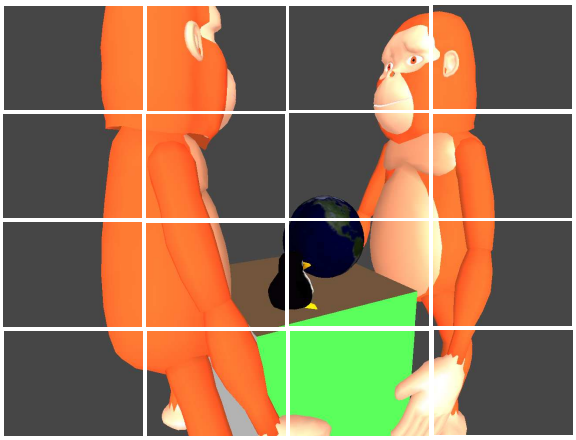
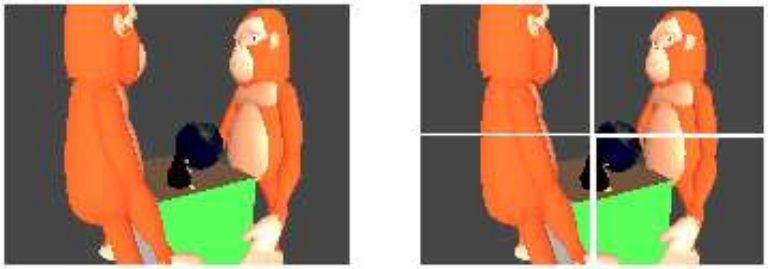


Figure 4.3 High resolution image with its' tiles. The final image is 1280x960 with each tile rendered at 320x240 resolution.



(a) (b)

Figure 4.4 (a) shows a 640x480 image created with same tile size, (b) is an image of 640x480 rendered using tiles of 320x240. If we perform image subtraction between these two images, the resulting image is completly black. This shows that the tiled images generated by our tool are accurate to the pixel level.

Once the symmetric frustum is created, the frustum is divided into parts based on the tile size specified by the user (Figure 4.2). These tiles which are created by dividing the large frustum may be non-symmetric. We assume that the tile size is uniform over all the tiles used to render the final image (Figure 4.3). Our system uses a small tile size (640×480) when tiling is necessary, as it is the minimum supported resolution on any kinda of hardware.

4.1.2 Validation

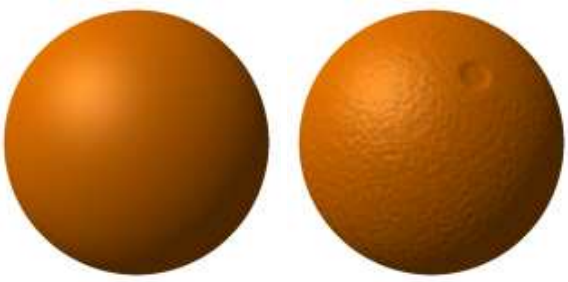
In the process of tiling, the same scene is rendered using the same camera with frustum parameters modified. These frustum parameters are calculated based on the tile position and the tile size. Due to the process of rasterization involved in rendering pipeline, the pixels on the boundaries may be rendered more than once in different tiles. Since we have based a constraint on the tile size across the full image, we made sure that there are no such repetitions of pixels at the boundaries. We formulated the following simple test to validate our high resolution data:

- Generate 640x480 image using tile size of 320x240 (640x480 image using 4 tiles).
- Generate 640x480 image using tile size of 640x480 (640x480 image using single tile).
- Perform Image Subtraction of the above images.
- If the final image is all black the tiling did not produce any artifacts.

Figure 4.4 shows an example of our validation process. Note that the tiled image shown in the figure is just to demonstrate that it is a tiled image. It is actually similar to the original image. We have checked these results for various resolutions with varying tile sizes.

4.2 High Quality

The distinct features that separate real world images from the CG imagery are shadows, illumination etc. DGTk's in-built renderer supports the default OpenGL features like texture maps, lights and materials. Though these are good enough for generating quite realistic images, the user may have a requirement of even better quality images. Such high quality rendering can be achieved by generating images with bump maps, shadows (soft and hard), Motion blur, etc. Just applying Bump Mapping on a simple sphere (Figure 4.5) can change it's look drastically. Such advanced features can be supported through ray tracing. For this reason we provide an interface in our tool which enables the user to generate the scene description for POV-Ray [10].



(a) (b)

Figure 4.5 (a) A Smooth sphere. (b) A Bump Mapped sphere

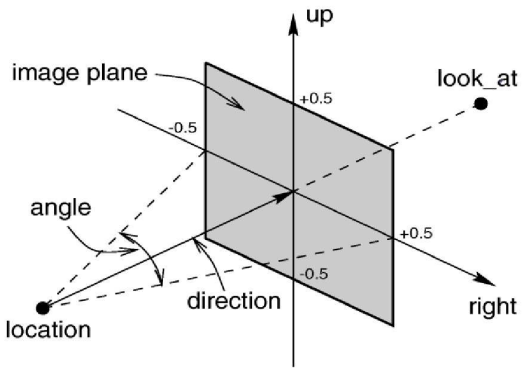
(a) (b)

Figure 4.6 (a) A simple scene imaged using our OpenGL renderer. (b) Ray Traced image of the same scene.

Persistence of Vison Ray tracer (POV-Ray) is a very popular, free, platform independent ray tracing software which supports all advanced features described above. POV-Ray can generate very high quality images with a color resolution up to 48-bits per pixel. It supports many atmospheric effects like ground-fog, rainbow, etc. Finally the most important feature, it has an easy to use scene description language. Very stunning three-dimensional graphics images can be created by writing just a few lines of text. We exploited this feature for incorporating such high quality rendering into our tool.

The user can select to generate POV-Ray scene description files for a scene setup in our tool, and the tool would automatically generate the scene description files for all the views that match those generated using the in-built renderer (Figure 4.6). Once the scene description files (with .pov extension) are generated, the user can generate high quality images at arbitrarily high resolution using POV-Ray software.

4.2.1 Implementation



POV-Ray's scene description language has the $mesh2$ and $smooth\_triangle$ objects to efficiently represent arbitrary 3D models. We use $smooth\_triangle$ keyword for representing non-textured objects and $mesh2$ object for representing textured objects. The $mesh2$ syntax was designed for use in conversion from other file formats. Using this keyword, we can specify the normal vectors, UV vectors and the texture list of a 3D object. Once the user starts the process of generating the scene description, each object in the scene, including lights, cameras etc are written into a file. All the transformations on the objects (translation, rotation and scaling) are applied to the objects using the $matrix$ keyword, which allows us to specify any 4×4 transformation matrix to be applied to an object.

The POV-Ray camera has ten different models, each of which uses a different projection method to project the scene onto the screen. All cameras have common parameters location, right, up, direction, and keywords to determine its location and orientation (Figure 4.2.1). Based on the type of projection, the interpretation of these parameters differs. POV-Ray supports different projection types like perspective, orthographic, fish-eye, ultra wide angle, omnimax, paranomic and cylinder. Since CV and IBR techniques are mostly based on perspective projection, our tool supports only this projection type. Below is the pseudo code of the camera generated by our tool. cx, cy and cz are the camera location parameters, $aspect$ the aspect ratio, $fovX$ is the field of view of the camera along X_{axis} and lx, ly, lz is the location at which the camera is looking. This defines a perspective camera with the given parameters. This camera exactly matches the camera specified in the OpenGL system.

```
camera {
    location < cx, cy, cz >
    up < 0, 1, 0>
    right < -aspect, 0, 0 >
    angle fovX
    look_at < lx, ly, lz >
}
```

While specifying the camera parameters for OpenGL api, we use $gluPerspective$. This takes six parameters as input namely, field of view along Y_{axis} ($fovY$), aspect ratio ($aspect$), near plane distance ($near$) and far plane distance (far). Given these parameters, we calculate the parameters required for the povray camera (i.e, $fovX, aspect$) using Equation 4.4. Once these values are computed, we substitute the value of $fovX$ in camera definition shown above.

$$\begin{aligned} height &= 2 \times (far - near) \times \tan(\frac{\pi}{180} \times \frac{fovY}{2}) \\ width &= aspect \times height \\ fovX &= 2 \times \frac{180}{\pi} \times \arctan(\frac{width}{(2 \times (far - near))}) \end{aligned} \tag{4.4}$$

In our tool we have a default head light (light on the Y_{axis}). This is also exported into the povray file along with any additional lights that the user adds to the scene. All the properties (Diffuse, Specular, etc) of the light source are exported to the povray file.

4.3 Camera Calibration

Calibration information of a camera is very vital for many of the CV algorithms which try to estimate the 3D structure of an object from it's images. There are algorithms which try to estimate the camera parameters from the images. Qualitative analysis of such algorithms would be possible if the datasets have both the images and the calibration information of the camera used for imaging it. In CV literature, the camera is treated as a 3×4 matrix transformation which transforms the homogeneous 3D world coordinates ($P_{4\times1}$ Matrix) to image coordinates ($P'_{3\times1}$). The image of a scene can be calculated using Equation 4.5.

$$P'_{3\times1} = M_{3\times4} \times P_{4\times1} \tag{4.5}$$

The camera matrix $M_{3\times4}$ consists of two parts, external parameters (position and orientation relative to the world coordinate system) represented by $[R|t]_{3\times4}$ and the internal parameters (principal point or image center, focal length and distortion coefficients) represented by $K_{3\times3}$. There are many toolkits [1, 9, 20, 24] that can provide the camera calibration given some images and the corresponding points

in the images. Such toolkits try to estimate the camera parameters based on the corresponding points provided. The calibration information generated by these toolkits is highly dependent on the input corresponding points provided. If the corresponding points are not accurate, the error may effect the calibration parameters. Such limitations can be overcome while using synthetic data. Since the camera information is already known, the calibration information is perfectly obtained.

4.3.1 Implementation

Our tool can generate the camera calibration information for each camera placed in a scene. OpenGL has a state machine architecture. If we set some values for color, depth test, etc all the subsequent calls will be effected by it. OpenGL provides a method called $glGet$. This method can be used to retrieve the current state of the OpenGL system. We can retrieve even the projection and model view matrices. These matrices are used to transform the points in world coordinate system to the camera coordinate system (Equation 4.6). If a world point in homogeneous coordinate system is $Wp_{4\times1}$, $Mv_{4\times4}$ the model view matrix representing the position and orientation of the camera, $Pm_{4\times4}$ the projection matrix, then the coordinate of the same point in normalized unit cube is given by Equation 4.6. The projection matrix $Pm_{4\times4}$ is responsible for handling the type of projection of the camera (i.e, perspective or orthographic). The model view matrix $Mv_{4\times4}$ is for specifying the external parameters of the camera.

$$Pm_{4\times4} \times Mv_{4\times4} \times Wp_{4\times1} = Np_{4\times1} \tag{4.6}$$

The projection matrix is retrieved from OpenGL using $glGetDoublev()$ with $GL\_PROJECTION$ as the first parameter and a pointer to an array of sixteen $double$ elements as the second argument. Similarly the model view matrix is retrieved. These matrices are then transformed into the form $K[R|t]$, Where K is a 3×3 matrix which refers to the internal parameters of the camera. R and t ($[R|t]$ a 3×4 matrix) give its external parameters. The matrix $K_{3\times3}$ is obtained from the homogeneous projective matrix by removing the third row and fourth column and the multiplying it with view port matrix used in OpenGL. The matrix $[R|t]_{3\times4}$ of the camera can be obtained by removing the last row of the homogeneous viewing matrix used in OpenGL. The 3×4 matrix obtained by multiplying K and $[R|t]$ is the camera matrix in the world coordinate system.

The calibration information so obtained is stored in a simple text file format. First the name of the data that is going to follow and then the data are stored. The names are K, $R|t$, and $Viewport$ these represent a 3×3 matrix, a 3×4 matrix and four integer values $(x, y, width, height)$ respectively. The actual K matrix which represents the internal parameters of the camera is formed by multiplying the K matrix in the file with the view port matrix formed using the four integer values.

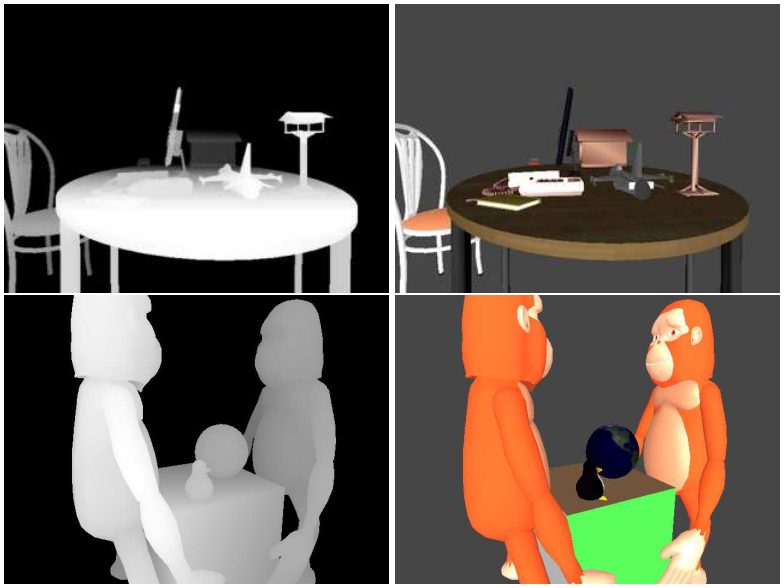


Figure 4.7 Depth and Texture maps of different scenes. In Depth maps, brighter means closer to the camera.

4.4 Depth Maps

Many CV algorithms (stereo algorithms for 3D reconstruction) try to estimate the 3D structure of the objects given different views of it. There are many IBR algorithms which make use of the depth maps along with their images to construct novel views of a scene. A depth map represents the distance of the point corresponding to each pixel in the image from the camera center (Figure 4.7). This would essentially give the shape of the object in the 3D space. Hence the 3D structure is equivalent to the depth map of a scene. Many algorithms trying to retrieve 3D information from a scene essentially try to estimate this depth map and there by construct the 3D model. Because of the numerous applications of the depth maps in CV and IBR literatures, we have provided an option for the user to generate depth maps.

In OpenGL, the 3D points specified are multiplied by the modelview matrix to transform them to camera coordinate system. This is followed by multiplication with projection matrix which transforms the world coordinates to unit-cube coordinates (Equation 4.6). The z-buffer in this unit-cube coordinate system represents a scaled version of the depth map of a scene. The default values of the depth buffer range from 0 to 1, which represent closest and farthest points to the camera respectively.

In real world, motion toward or away from the eye has less effect on the objects that are already at a long distance. For example, if you we move six inches closer to the computer screen in front of our face, it's apparent size increases dramatically. On the other hand, if the computer screen were at a large distance say 40 feet away, then moving six inches closer would have little noticeable effect on its size.

This effect is due to the perspective projection. OpenGL simulates a perspective view by dividing the coordinates by the clip coordinate value W which represents distance from the eye. As the distance from the eye increases, $\frac{1}{W}$ goes to 0. Therefore, $\frac{X}{W}$ and $\frac{Y}{W}$ also approach zero, causing the rendered primitives to occupy less screen space and appear smaller. Similarly the Z is also divided by W with the same results. Hence, perspective divide causes Z precision to be more near the front plane of the view volume than at the far plane. A more detailed overview about the precision of depth buffer is available in [23].

To avoid such inconsistencies in the precision due to perspective divide, We estimate the 3D world coordinates of each pixel in the image by back projecting them into the world coordinate system using the camera calibration data. This is a problem that most CV and IBR algorithms strive to solve. When the world points are multiplied by the model view matrix (Equation 4.7), the resulting coordinates are in camera's coordinate system. We can find the depth map of each of the points by just taking the Z_c value. Since we have only the 3D coordinates of the triangle points. we can retrieve the 3D world coordinate corresponding to each pixel in the image using the functions like $glReadPixels$ and $gluUnProject$ which OpenGL provides.

$$Mv_{4\times4} \times Wp_{4\times1} = Cp_{4\times1} \tag{4.7}$$

The function $glReadPixels$ when used with a parameter $GL\_DEPTH\_COMPONENT$, gives access to the depth buffer. This buffer may contain floating point number or unsigned byte values based on the format parameter passed to $glReadPixels$. We use GL_FLOAT for retrieving the floating point depth buffer values in the range 0 to 1. Since values closer to 0 are closer to the camera, we save one minus the depth value at each x, y location and normalize the image to generate visually appealing depth map images. The images so created represent a scaled version (depth values range from 0 to 255) of the actual depth map. To find the actual depth map, we make use of the $gluUnProject$ function. This function takes in the window coordinates of the image generated along with projection matrix, model view matrix and the view port matrix to generate the 3D world coordinate of the point. But depth map is to be specified in terms of camera coordinates not the world coordinates. This can be acquired by sending the identity matrix to the $gluUnProject$ instead of the actual model view matrix which represents the camera's external parameters (position, orientation, etc). This essentially removes the perspective projection transform and not the model view transform, hence the values acquired are now in camera coordinate system.

We save the depth maps in a binary format along with the camera calibration data (both at double precision). First we write the projection matrix, then the model view matrix, followed by two integers specifying width and height of the depth map. This is followed by the depth of each pixel of the image in the camera coordinate system. Depth maps are generally used by the algorithms which require

additional structural information about the 3D scene. They can also be used as high quality ground truth by structure recovery algorithms.

4.5 Layer Depth Images

LDIs were first introduced in J.Shade et al [18] and is a special data structure for IBR. This is a more general alternative to sprites and sprites with depth. Unlike the general Depth Maps which just store the depth value of the first hit object in the view direction, an LDI stores multiple depth and color values (depth pixel) per pixel in the view. This method of storing multiple depth values helps in storing the information about the occluded portions of objects as well. As a result of such extensive information, the novel view synthesis would not have the problem of holes (i.e, occlusions).

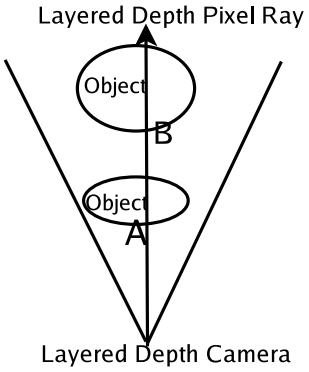


Figure 4.8 A and B are stored in the same depth pixel

We iterate through each triangle of each object in the scene and using a simple line triangle intersection method, we find the point of intersection between the rays emitting from center of the camera to the end of the frustum with these triangles. Since we know the camera center's coordinates, and the end point of the line can be found using the $gluUnproject$ function. Once we find these two points for each ray, we represent the line using the parametric Equation 4.8, where P is any arbitrary point on the line, P_0 is the starting point of the line, P_1 is the end point of our line segment, t is the parameters value between 0 and 1. The plane formed by the triangle points is represented by using Equation 4.9, where N represents the normal to the plane, P and P_0 represent points on the plane. By substituting the P from 4.8 in 4.9, we can calculate the value of the parameter t for the point of intersection 4.10. Once the parameter is found, we can find the point using Equation 4.8. This point lies on the plane containing the triangle. But to ensure that this point is inside the triangle, we find the cross product of any of the two sides of the triangle and see if the cross product of one of the sides and the line joining the point of intersection point in the same direction. If the two cross products are in the same direction, the point of intersection

lies inside the triangle, else it is outside the triangle.

$$P = P_0 + t \times (P_1 - P_0) \tag{4.8}$$

$$N.(P - P2) = 0 \tag{4.9}$$

$$t = \frac{N.(P_2 - P_0)}{N.N} \tag{4.10}$$

We store all the depth and color values that the ray comes across before reaching the end of the frustum (Figure 4.8). Each triangle of the objects is rendered using the camera information, the texture information and the material information. Once rendered, the color (i.e, material, texture etc) information can be retrieved using the $glReadPixels$ function provided by OpenGL. The points of intersection and depth information are calculated at double precision. The LDI's are stored in a binary format. First two integers width and height. This is followed by $width \times height$ number of Layered Depth pixels. Since each Layered depth pixel consists of the R, G, B, A and Z and spatial index, The number of depth pixels (an unsigned int) at each layered depth pixel followed by the depth pixels are written.

4.6 Object Maps

Silhouette is the simplest representation used in cartoons, technical illustrations, architectural design and medical atlases. Complex models can be rendered as silhouette edges for generating non-photo realistic images. Silhouettes are useful in applications such as virtual reality and visual hull construction. Many silhouette extraction algorithms try to separate an object from others using segmentation (when the background color is not assumed). Silhouette of a model can be either computed in object space or in image space. Object space algorithms involve computation of list of silhouette edges for every given viewpoint. Screen space or image space algorithms usually involve image processing techniques. Image segmentation is a very important part of solving CV problems like object detection, recognition and tracking. Real world images are formed by various features like texture, light and other object properties. The CV algorithms would ideally want the parsed image (image decomposed into it's constituent objects), but this is a very difficult problem to solve. This is due to the inherent ambiguity in the perception of a 3D scene. If researchers develop a vision algorithm assuming that un-ambiguous segmentation of a scene is available, there is no way to provide real world inputs for testing such algorithms. We provide ground truth for this in the form of an object map. Since our tool can generate the object maps from any camera point, it can be used for both object space and image space silhouette extraction.

The object map is defined as an image where each pixel is labeled with a unique id corresponding to the object that projects to it. i.e, the R, G, B value assigned to each pixel is actually the object id of the object the pixel belongs to. Our tool generates the Object Maps as PPM images (Figure 4.9). Each object is given a unique object id in terms of R, G, B values. This information can be used for testing the accuracy of image segmentation algorithms.

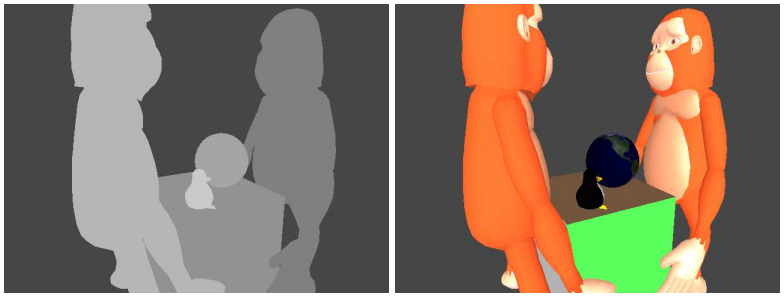


Figure 4.9 Object map and Texture map of a scene

OpenGL has a state machine architecture i.e, if a particular feature is enabled or changed, all the subsequent OpenGL calls will be effected by it. For example if the color is set to white using the function $glColor3f(1,1,1)$, all the subsequent primitives will be drawn using white color. For achieving realistic rendering, we enable the lighting and texturing features of OpenGL using $glEnable$ function with $GL\_TEXTURE\_2D$ and $GL\_LIGHTING$ respectively. While generating object maps, we procedurally calculate the object's id using it's location in the memory as index. The textures, lights and material properties are disabled using $glDisable$ function. Once these are disabled, we specify the color of each object (R, G, B values for $glColor3f$) based on the object id calculated. Since the other features effecting the color (lights, textures and materials) are disabled, the images rendered have unique color for each object i.e, the object maps. While generating these images, we do not enable any kind of anti-aliasing. As a result, the images generated have very perfect boundaries i.e, at each pixel location, we can clearly state that it belongs to a particular object, there is no partial presence of objects.

4.7 Alpha Maps

Matting algorithms deal with extraction of a foreground object from the background by estimating the color and opacity of the foreground object at each pixel location. Hence these algorithms unlike segmentation or silhouette extraction algorithms, require data which has higher precision near the object boundaries. The image along with this opacity information is typically called a alpha matte or key. Generating alpha matte for foreground objects with thin whisps of fur or hair is a very difficult problem. Fractional opacity values (values between 0 and 1) of the foreground object's boundaries are to be produced in these cases. Matting is useful for compositing foreground objects into a new scene. This technique is particularly useful in film and video production for creating special effects. A common method used for extracting the matte is to use a background of known color and make certain assumptions about the colors present in the foreground object. Other approaches attempt to estimate the foreground and background using some standard distributions like Bayesian, Poisson, etc [3, 12, 14].

Our tool provides an option of generating such intermediate values of object's presence (i.e, a value between 0 and 1). The matting images generated by our tool have R, G, B and A channels unlike the

Object maps. The alpha Chanel of a matting image represents the blending parameter for the objects. If we assume that the alpha value of the foreground object at a pixel is α then the alpha value of the background object is $1 - \alpha$. Hence the alpha value of the object closer to the camera at a pixel location can be stored in the alpha Chanel instead of storing both values. This can be considered as a problem similar to anti-aliasing an image.

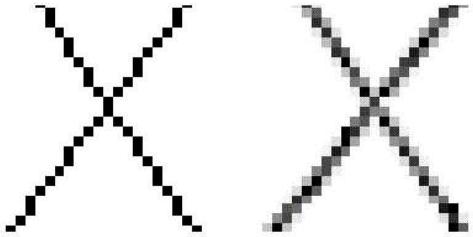


Figure 4.10 Aliased and Anti Aliased Lines

Aliasing is a problem related to the digital displays in today's computers due to sampling. The current consumer technology have a finite memory and processing power. As a result it is not possible to render enough samples for an acceptable representation of reality. Due to this lack of samples artifacts like jagged, crawling edges and flickering objects are common in current 3D accelerators. These artifacts hamper the immersiveness that computer games and 3D applications strive to deliver. To over come the artifacts caused due to aliasing, anti-aliasing algorithms have been developed. Anti-aliasing is basically the process of removing the unwanted artifacts like jagged triangle edges. The method commonly used for anti-aliasing is to average the color at the borders for smoothening the jaggies caused due to aliasing (Figure 4.10). The color assigned to a boundary pixel during anti aliasing is based on the area of the pixel that a primitive covers(known as coverage). Figure 4.11 shows the partially covered pixels (with different proportions occupied by the polygon). We modified a standard technique called super-sampling used for anti-aliasing, to find the coverage of the pixels at the boundaries of rendered objects. Super sampling involves

- Rendering the whole scene at a larger resolution than the required final output resolution
- Down-sampling the high resolution image to the required resolution.

During down-sampling of the high resolution image, the color of the output pixel in the down-sampled image is calculated based on the weighted sum of the colors in the corresponding pixels in the high resolution image. Each $N \times N$ matrix in the super-sampled image corresponds to a single pixel in the down-sampled image. For example, if we render the high resolution image at four samples per pixel (i.e, the high resolution image is twice as large as the original image), then the color ($C_{x,y}$) of a pixel at x, y in the down sampled image can be calculated by using Equation 4.11 where, c_i refers to a unique

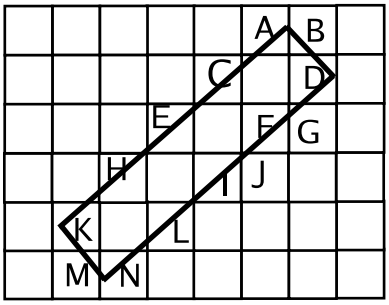


Figure 4.11 Partially Covered Pixels

color of a pixel in the $N \times N$ matrix. N is the number of samples per pixel in x and y direction, n_{c_i} is number of pixels in the $N \times N$ matrix with color c_i.

$$C_{x,y} = \sum_{c_i} \frac{n_{c_i}}{N^2} \tag{4.11}$$

4.7.1 Implementation

The ratio $\frac{n_{c_i}}{N^2}$ described above gives the coverage of a primitive with color c_i in the down-sampled image. Instead of using this ratio for averaging the color for the pixel in down-sampled image, it is used for finding the alpha value at that pixel location. The id of the object closest to the camera at that pixel is assigned as the color at that pixel. Since object id is required and not the texture information, we render a super-sampled object map of the scene along with it's depth map. The dimensions of the super-sampled image are dependent on the number of samples per pixel and required final image dimensions, it may not be feasible to render the whole image at once. Hence we use the tiling technique described in section 4.1 for rendering the super sampled image. We apply the $N \times N$ matrix used for down-sampling the super-sampled image on the depth map as well (i.e, for every $N \times N$ matrix in object map, a matrix of same dimensions and location is considered from the super-sampled depth map). We find the id of the object closest to the camera based on the depth values obtained from the depth map. Since objects closer to the camera have a lower depth value, we find the location in the matrix with the lowest depth value. Since object maps specify the segmentation of objects perfectly, we use the pixel location corresponding to the lowest depth value in the matrix to find the id of the object closest to the camera (from the object map matrix). Once the id of closest object is found, we assign this object id as R, G, B value to the pixel in down-sampled image. The coverage value (i.e, $\frac{n_{c_i}}{N^2}$) is assigned to the alpha channel of the same pixel. The following is the modified super sampling algorithm for obtaining the alpha maps with the help of object maps.

- Render super-sampled image of the scene based on the number of samples per pixel.
- Read the depth buffer of the super sampled image.

- for each $N \times N$ matrix in super sampled depth buffer.
  - Find the minimum depth value in the matrix.
  - From the corresponding matrix in object map, find the object id at the pixel location with minimum depth value.
  - Find the coverage value of the object with the above id in the matrix using the ratio $\frac{n_{c_i}}{N^2}$. Where n_{c_i} is the number of pixels in the $N \times N$ matrix with id c_i.
  - Assign the object id c_i as R, G, B values and the coverage value as the A value of the pixel corresponding to this matrix.
- store the image with R, G, B, A values. The alpha channel contains the information about blend between the foreground and the background objects.

4.7.2 Example

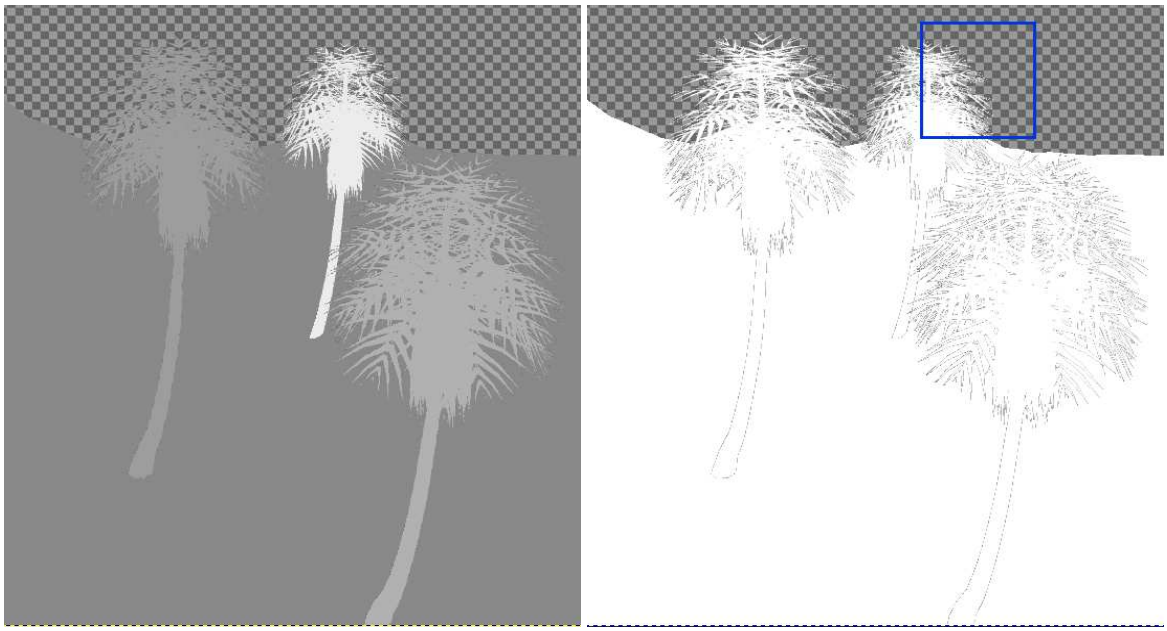
Let us consider a situation where the super sampled image is four times the size of the actual image (i.e, sixteen samples per pixel). Then each pixel in the actual image corresponds to a 4×4 matrix in the super sampled image. From the depth image (depth map) in the super sampled image, we consider the 4×4 matrix corresponding to the 4×4 color matrix which represent one pixel in the down sampled image. The object id (color value in 4×4 color matrix) at the closest point in the depth map's 4×4 matrix is the id of the object closest to the camera. The alpha value is calculated based on the number of pixels with that color (object id) to the total number of pixels ratio.

$$color = \begin{bmatrix} 9 & 10 & 10 & 10 \\ 9 & 10 & 10 & 10 \\ 9 & 9 & 10 & 10 \\ 9 & 10 & 10 & 10 \end{bmatrix}; depth = \begin{bmatrix} 1 & 1 & 0.8 & 1 \\ 0.8 & 1 & 0.8 & 1 \\ 1 & 0.5 & 0.8 & 1 \\ 0.5 & 1 & 0.8 & 1 \end{bmatrix} \tag{4.12}$$

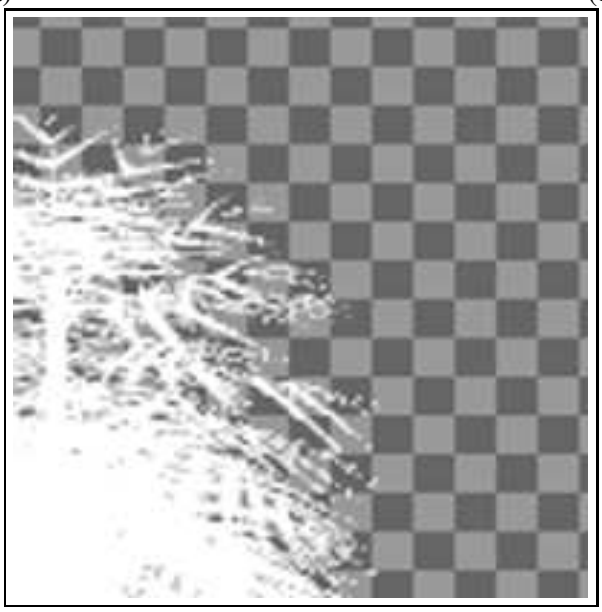
Suppose the color (object map colors) and depth matrices are as shown above, then the pixel corresponding to this 4×4 matrix in the actual image will have color as 9 and the alpha value as $\frac{5}{4 \times 4}$. Color 9 is selected because the depth value corresponding to this color is the minimum in the depth map matrix.

4.8 Pixel Correspondence

Some CV and IBR algorithms require correspondence information between two input images, i.e, which pixel does a particular pixel in first image correspond to in the second image. Human beings and other animals are able perceive depth by finding points in the two views (one through the left eye and the other through right eye) that are images of the same point in the scene (Figure 4.13). For a computer to perceive depth, a stereo vision (setup of two cameras separated by a small angle) has to be setup



(a) (b)



(c)

Figure 4.12 (a) The alpha map generated by our tool with object id as the color. (b) The alpha matte of the same image. The grey values at the boundaries represent the fractional opacity of the foreground object. (c) Shows the marked area in (b) at a higher scale. It clearly shows the partial opacity at the boundaries of the tree.

and the corresponding points are to be found. Unfortunately the reliable identification of corresponding points is a very difficult problem. This problem is complex because a point visible in one view may be occluded in the other or vice versa. For this reason selecting the right points for correspondence is also important.

The advantage of using the synthetic data is that we have the 3D model of the scene. This information about the model can be used to find the points of the 3D point in different views because the camera calibration information is known. For each view, the 3D point is multiplied by the camera matrix to retrieve the 2D point in the image.

Figure 4.13 The white dots show the corresponding points between the two views.

Our tool can generate both dense correspondences (i.e, for each and every pixel in the first image, we find the corresponding pixel in the second image) between pairs of images, and sparse correspondences (corresponding points for the selected pixel locations in the first image). The correspondences are stored as floating point disparity to have sub pixel precision. For generating the sparse correspondences, the user has to select few points in the left (reference) image and our tool generates the corresponding points to those points in the right image. We also handle the occlusion based on the camera view. For each point selected in the reference image, the 3D point is found using the $gluUnProject$ function. Once the 3D point is found, we use the camera matrix of the destination (right) view to calculate the window coordinates of the point using $gluProject$ function. If the z coordinate of the selected point in the destination view is smaller than or equal to the value in that view's depth buffer, we have found the corresponding point. Else the point has been occluded in the new view. Using this method, we can find the dense correspondences as well.

4.9 Dynamic Scenes

With the increase in the availability of cheap hardware for video acquisition, the last few years have seen a boom in the amount of video content available. Hence the demand for video analysis and summarization algorithms has increased multi fold. Many motion tracking and activity detection algorithms have been developed in the recent years for enhancing the security and search capabilities in videos. Videos are nothing but a sequence of images which capture a real world scene across time. It would be a boon to the researchers in these fields if synthetic videos can be generated for testing their algorithms. Many 3D authoring tools enable users to create complex character, fluid and fur simulations and render them as video streams. The major limitation to such tool is the lack of ability to generate the data that provides additional information about the structure of the objects in the scene e.g, depth maps, Object maps, matting information etc. In some of these tools, the dynamic scenes which require motion of the camera can only be generated by writing our own scripts. Due to the requirement of such dynamic, and realistic data, we have added support in our tool for generating Dynamic scenes.

Our tool has the ability to generate dynamic scenes using the information specified by the user in the form of key frames. The user can with ease setup the scene for every key frame and generate the animated sequence of interpolated images. Each key frame specifies the position of all the objects at that particular time instant. We have designed a simple structure for saving the details of each key frame. It contains the frame number, and each objects rotation, translation and scale properties. These properties are interpolated for the (time) frames between the specified key frames. The interpolation of the key frames is done based on the (time) difference between two consecutive key frames. So if the user wants some animation to be faster he/she just has to make sure that the difference between two key frames is low.

The position vector of the objects in the scene is interpolated using linear interpolation between the initial and final positions in the two consecutive key frames. The position of the object in the current frame is calculated based on the ratio of distances between the current frame to initial key frame and that between initial key frame to the consecutive key frame. If P_{cur} is the position of the object in the current frame (K_{cur}), the object's position in the initial key frame K_{init} is P_{init}, position in the consecutive key frame K_{final} be P_{final}. Equation 4.13 gives the relation between them.

$$P_{cur} = P_{init} + \frac{P_{final} - P_{init}}{K_{final} - K_{init}} \times (K_{cur} - K_{init}) \tag{4.13}$$

Suppose P_0 and P_{10} are positions of an object in frame 0 and frame 10 respectively, the position of the same object in frame 5 is found using Equation 4.13.

$$P_5 = P_0 + \frac{P_{10} - P_0}{10 - 0} \times (5 - 0)$$

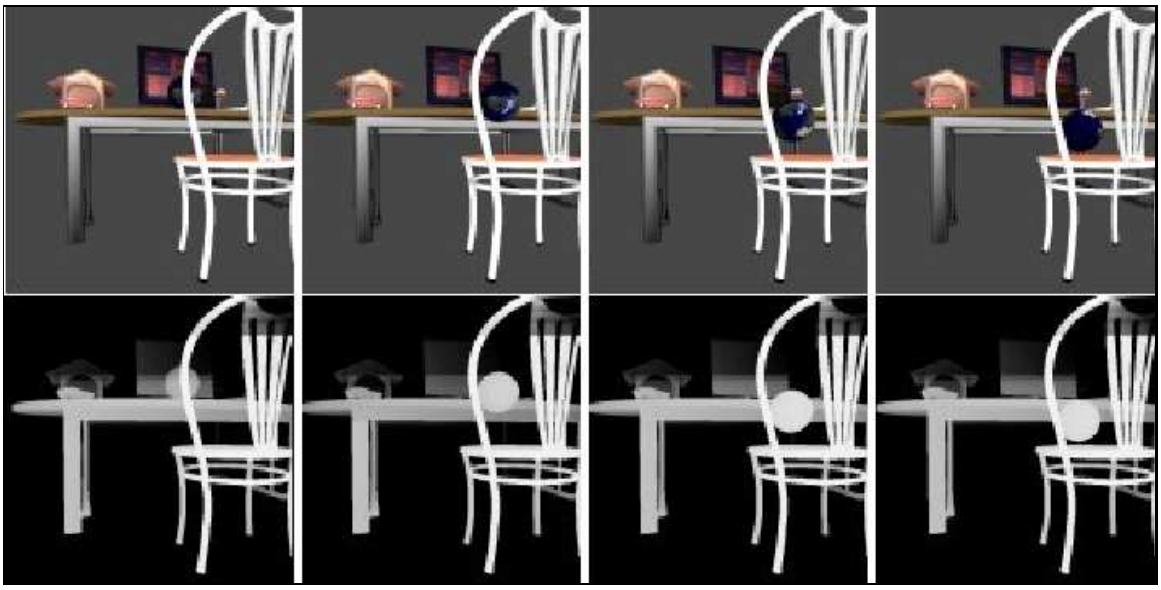
Where as we use spherical linear interpolation of quaternions for the smooth interpolation of rotations [19]. Quaternions are four dimensional vectors which can be use to represent the angle of rotation and the axis about which the rotation is to be applied.
The advantage of using our tool for generating dynamic data over the other 3D authoring tools is the ability to generate additional information for each frame along with the texture map. Very complex scenes with multiple objects crossing each other, scenes with camera motion can be generated along with the object maps, depth maps, matting etc (Figure 4.14). Though our tool supports translation, rotation and scaling, it would be hard for a user to create complex animations like people walking etc. For such scenarios, we provide the user with the facility to use the models in formats like MD2, etc which store the animation details in the model file.

4.10 Ease of Use

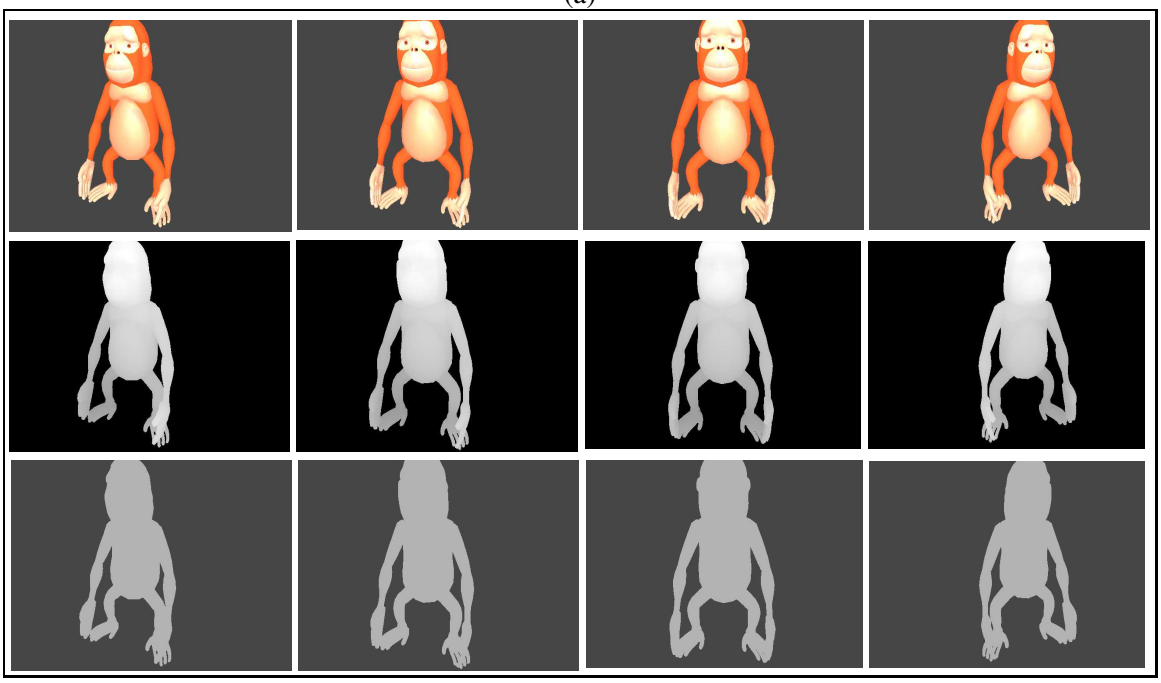
We have designed the graphical user interface for our tool so as to make it easy for the researchers to setup complex scenes and generate very high quality data. We implemented the GUI using QT. Since our target audience are researchers in the fields of CV and IBR, we adopted the graphical user interface used by most of the 3D authoring tools (Figure 3.1). Setting up complex scenes that mimic the real world is possible because the user can import any of the large number of 3D models available on the Internet and place them in appropriate positions by just clicking and dragging the objects to move, rotate or scale them in the 3D space.

The tool currently has support for loading AC3D, 3DS, Md2, and a limited polygonal models of Povray scene format. We have support for exporting the 3D scene to povray files (.pov) which can be rendered using a ray tracer like povray. Generating different output formats is as simple as selecting the options in check boxes and starting the rendering process (Figure A.1.3). For example, the user can generate images of arbitrary large resolution (in terms of height and width) by just adjusting the parameters using a pair of scroll bars (Figure 4.15). The resolution of the image generated in terms of pixel distance to world distance ratio is displayed in the resolution control interface to enable the user to find the appropriate resolution for his/her experiment.

Dynamic scenes can be created with ease. The user specifies the position, orientation and scale of the objects in the world at some key frames (key frames in time domain). These key frames represent the every object's parameters at that particular time instant. When the user imports 3D models into the tool, they are by default placed at the origin in the world coordinates. Once the user has imported and positioned all the objects (including cameras)in the world scene, the user has to specify the first key frame (frame 0 is to be the first key frame). Subsequently, the user can move, rotate or scale these objects and specify key frames at any frame (Figure 4.16). A minimum of two key frames with at least one frame gap in between them and at least one camera in the world are required for the tool to be able to generate



(a)



(b)

Figure 4.14 (a) A dynamic scene with a ball bouncing off the table along with depth maps. (b) Texture maps, Depth maps and Object maps of a scene with camera motion. The second strip of images in both (a) and (b) represent the depth maps of the corresponding scenes. These are grey scale images where the brightest pixels correspond to the points in 3D world closest to the camera. The third strip of images in (b) represent the object maps of the same scene. Each object in the scene has a unique R,G,B value.

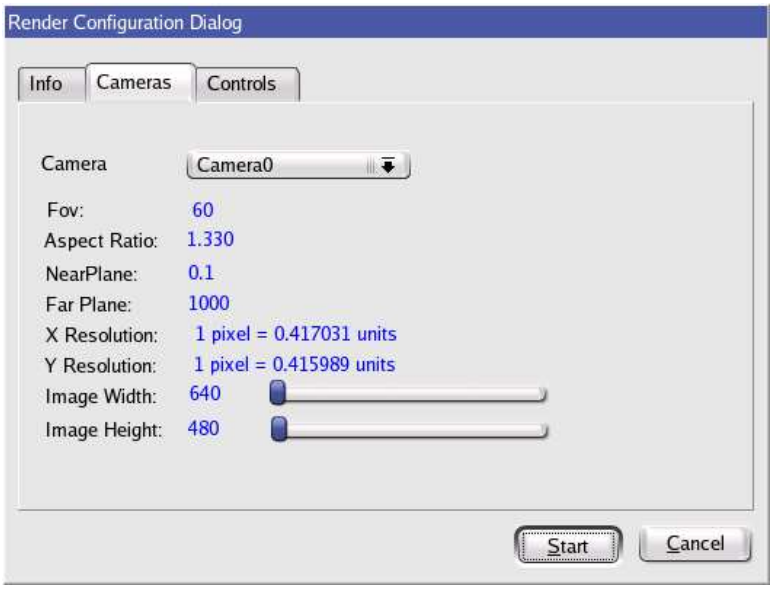


Figure 4.15 The camera configuration panel for setting up the resolution of the image to be rendered as viewed by the camera.

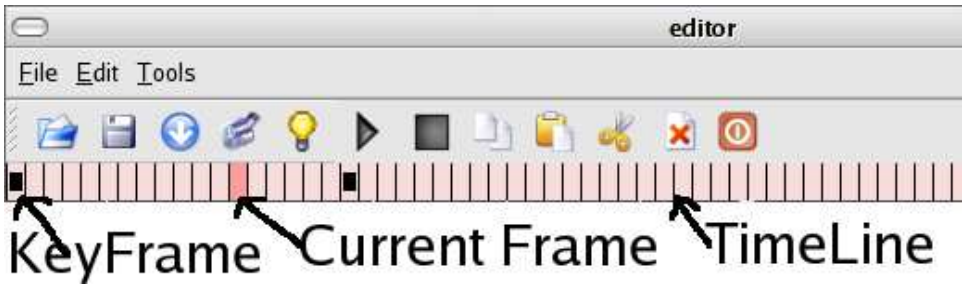


Figure 4.16 GUI for the dynamic scenes

required output(s).

The user can place as many cameras as required. The position and orientation of the cameras placed in the world can be specified manually or the user can change these by clicking and dragging the camera objects in the world. The user can add lights and cameras, move them like any other 3D objects. Provision for preview of the scene from a particular camera's point of view is given, to help the user know exactly how the scene would look in the final images. Our tool provides GUI for specifying parameters of cameras and lights (Figure A.3, Figure A.4). This helps the user in placing these objects at precise positions.

Each object in the tool has its' own context menu. Some of the options like preview are only available for cameras and others like move, rotate and scale are available only for normal 3D models and not the

cameras. The user can cut, copy and paste the models imported into the tool. This helps in creating scenes which require multiple instances of the same 3D model.

Chapter 5

Results

DGTk is developed using Qt and OpenGL libraries. We chose to develop our tool using Qt since it can easily be ported to run on multiple platforms. The library itself is built using a c++ hierarchy and hence enabled us to develop a complete object oriented tool. When ever we were faced with a choice of using features offered on high end graphics cards and the features supported on most of the graphics cards, we have invariably chosen to use the features supported on most of the graphics hardware. As a result our tool can run on a vast range of system configurations. The default tile dimensions used in our tiled renderer is 640×480, this resolution is generally supported on almost every system. Our tool gives a better performance if there is a provision for hardware acceleration in the system. DGTk requires Qt3.3 or above and OpenGL libraries to be available on the target system. The goal of developing this tool was to make synthetic data generation easy, this tool is made available as an Open Source tool. It can be downloaded from "http://research.iiit.ac.in/~vkrishna/editor.tar.gz".

The highlights of our tool would be the ability to generate data sets with ease and be able to share the data as well as the means of creating the data. The file format we designed as a part of DGTk can be used to share complex camera configurations which may be required for some of the CV and IBR algorithms. Our tool provides flexibility to the user in terms of the types of 3D models that can be imported, to create the scenes. DGTk is a vision aware tool; It can generate various representations of a 3D scene like depth maps, object maps, point correspondences etc which are very valuable for CV and IBR researchers. It would be the first time where the object segmentation and the matte information are provided as ground truth data in the form of alpha maps. Our tool presents the user with one of the easiest interfaces for creating dynamic scenes. This helps in creating large amounts of different representations of dynamic data along with the actual images. Another important feature of our tool would be it's object oriented frame of design. The over all UI of our tool is similar to that of some of the standard 3D authoring tools. This makes our tool easy to master. We have taken care to make sure that the tool is easy to extend for supporting new representations and file formats.

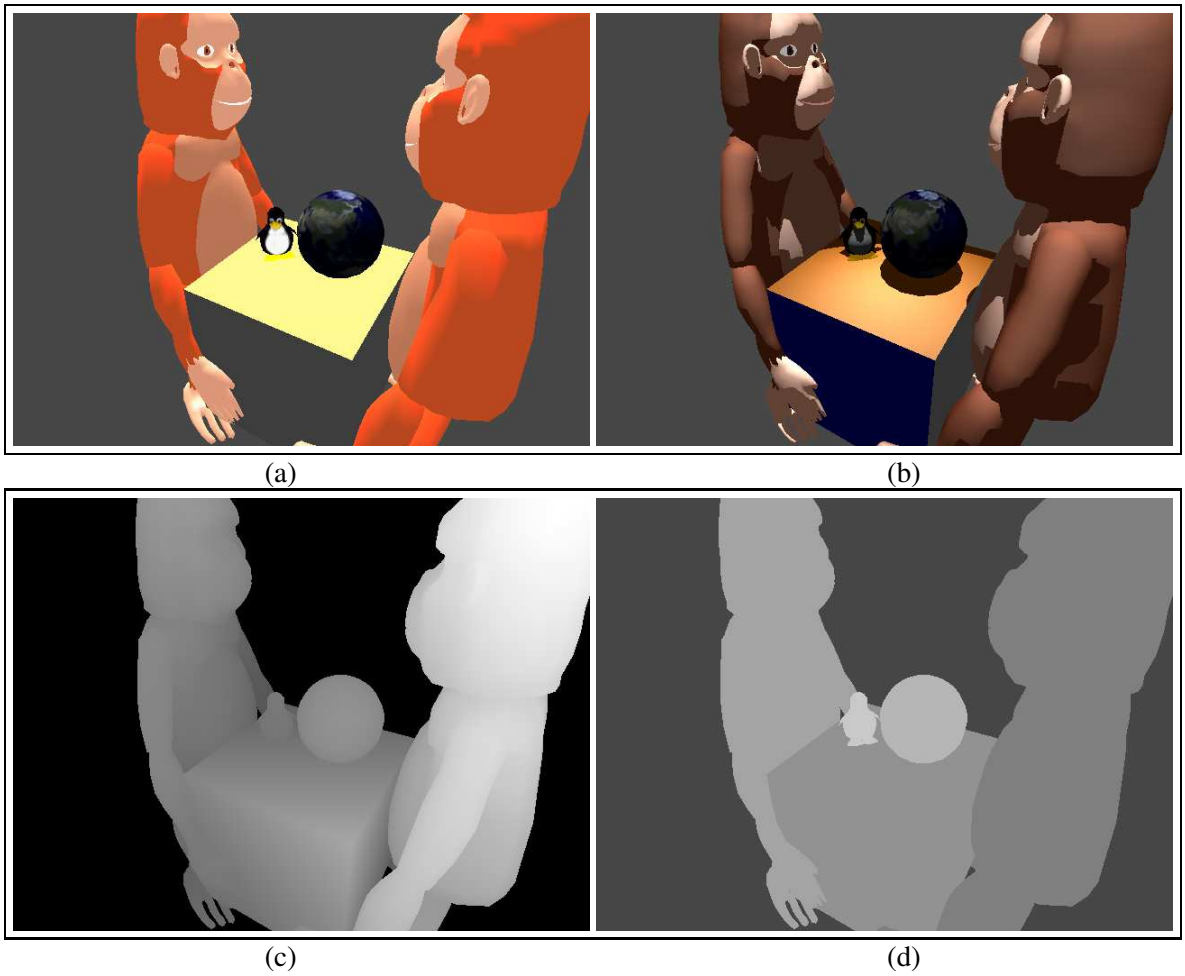


Figure 5.1 (a) The image generated by using our tool. (b) The same scene rendered using POV-Ray from the scene description language generated by our tool. (c) The depth map of the scene. (d) The Object map of the same scene.

DGTk makes use of texturing, lighting and materials provided by OpenGL to create the final images. This enables users to create complex scenes which match those in the real world. Our tool provides it's users to render the images of the scenes using POV-Ray in case the default rendering does not meet the requirements. OpenGL is a graphics package mainly used for real time rendering. To achieve speed some of the material and light properties are approximated rather than exact values. But in the case of ray tracing softwares, they are mainly developed for offline rendering and hence manage to implement the complex lighting and material properties.

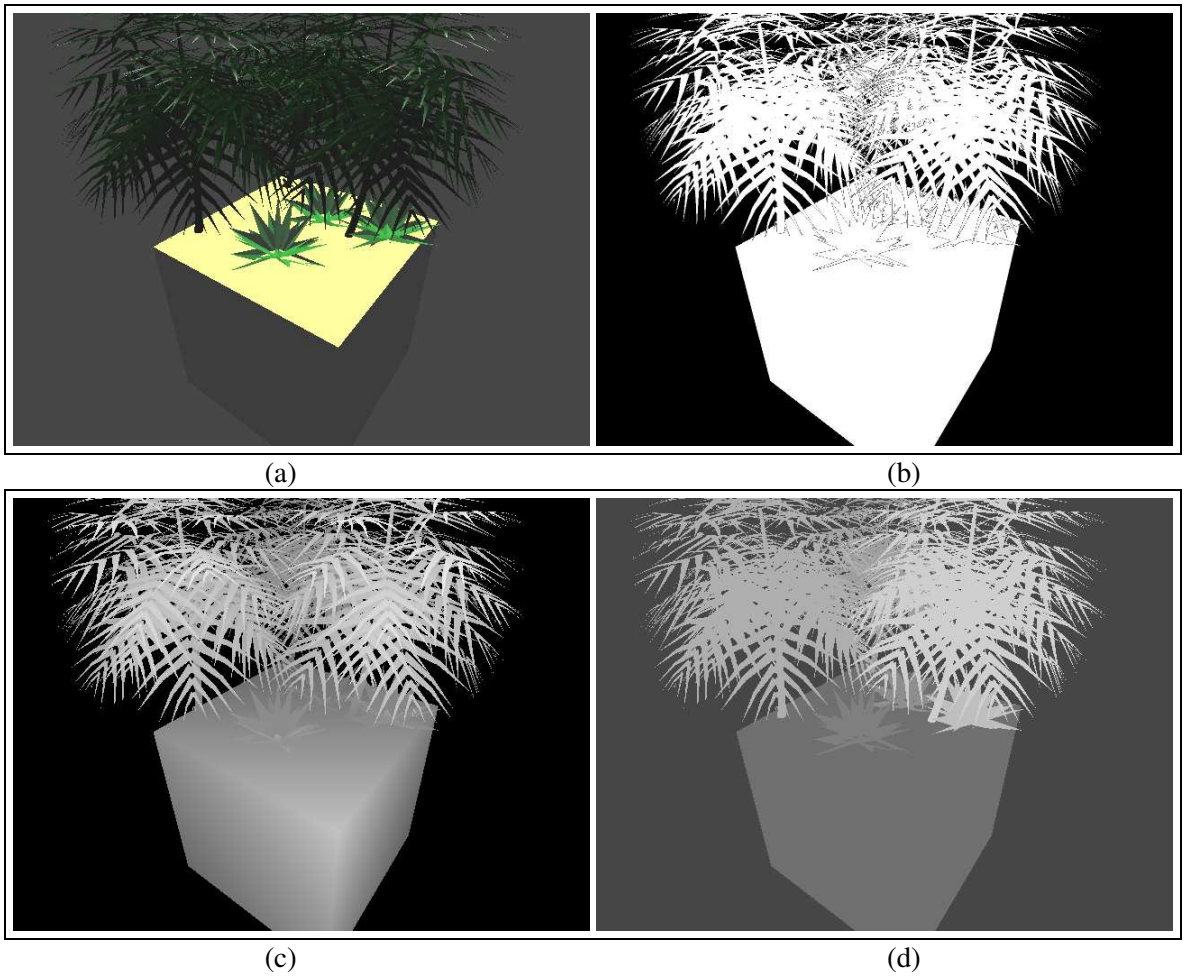


Figure 5.2 (a) A scene with trees and grass which have thin polygons. This scene is an ideal case for testing the alpha maps generated by our tool. (b) Alpha matte corresponding to the scene. The alpha map shows the partial opacity of the object at the boundaries. This is essential for testing some of the matting algorithms. (c) Depth maps describe the distance of each pixel in the image from the camera in the camera coordinates. We have inverted the actual depth map values to generate visually appealing images. The brighter pixels correspond to the pixels closer to the camera. (d) The Object map of such complex scenes are very useful for testing segmentation algorithms. Each object in the 3D scene is given a unique object id. Every pixel in the image is assigned a R,G,B value corresponding to the id of the Object which projects to it.

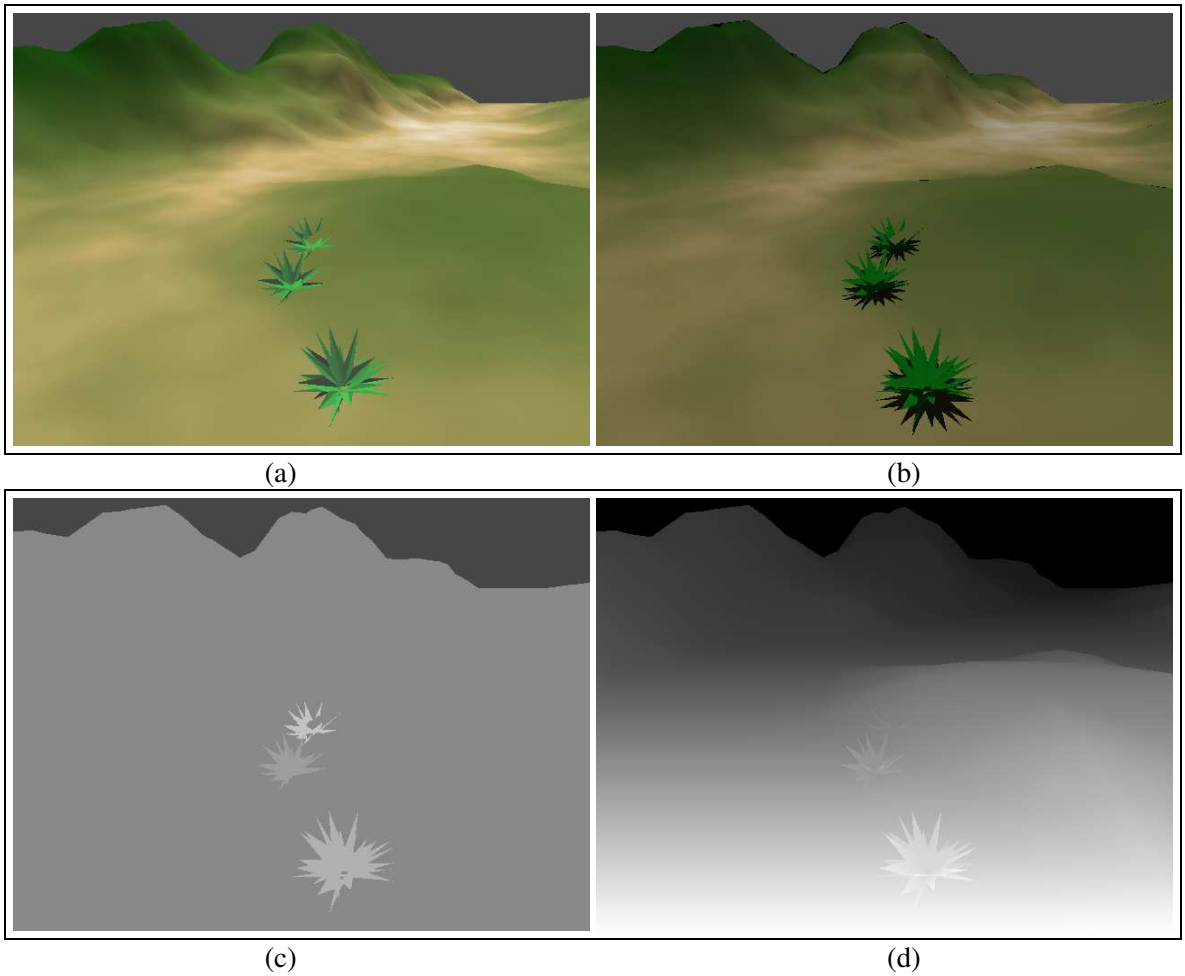


Figure 5.3 A simple scene with a terrain model and grass model. (a) Scene rendered using the in-built rendering algorithm which is based on OpenGL. (b) The same scene rendered using POV-Ray. The ray tracer generated high quality images with shadows, bump maps, etc. (c) Object map corresponding to the scene. Each object is perfectly segmented in the image with a unique color assigned to the pixels which are project by the object. Such accurate data can be generated by our tool since the 3D information is available.

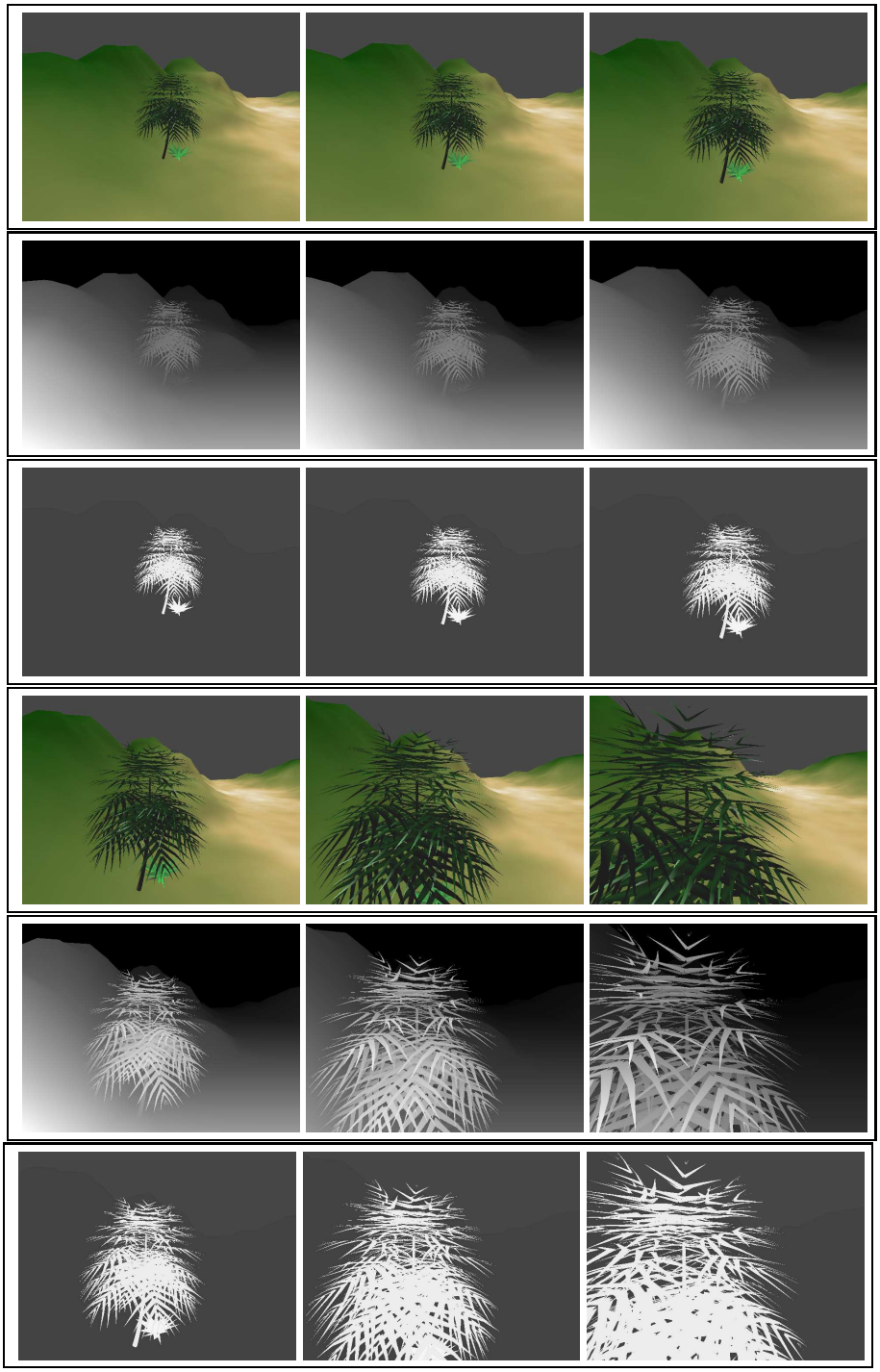


Figure 5.4 This figure shows six frames of a dynamic scene created using our tool. The actual sequence has fifty four frames. The major advantage of our tool is that all the representations can be generated for every frame of the dynamic scene. This is not possible in most of the available systems. The first strip of images shows the texture (actual image) of the scene through a camera. The second strip of images are the depth maps of the corresponding scenes. The third strip of images are the object map representation of the scene. This is the first time where users can generate different representations of complex scenes with ease.

Chapter 6

Conclusions and Future Work

In this thesis, we have presented a versatile toolkit to produce high quality synthetic data for testing Computer Vision and Image Based Rendering Algorithms. We have described why such a tool is necessary for improving the research in these areas. Various formats commonly used as datasets for testing CV and IBR algorithms have been implemented in our tool. The major contribution of our work is in the creation of a tool which enables the researchers to create their own datasets with ease. We have designed the tool so as to enable sharing of datasets among the researchers. Our tool has been successfully used for testing some of the algorithms developed at our lab. The idea behind development of such a tool goes beyond just creating datasets for CV and IBR algorithms. The major impact of this tool is on the time spent on creating the datasets for testing such algorithms. The tool itself is not limited to generating only data which can be used in CV and IBR algorithms. Our tool can easily be extended to support more input formats or output formats. It is intended to make our tool available freely along with some datasets for the community to use.

6.1 Future Work

As the developments in the areas of CV and IBR are at a high pace, the tool has to be up-to date to be able to generate high resolution data which can be used to compare state of the art algorithms. There are a lot of aspects in our tool that require attention in the future. With the increase in the power of the graphics hardware, the point based representations have gained popularity in the fields of IBR. Support for these representations would be a critical development for our tool.

DGTk currently supports generating images at various resolutions. The idea behind supporting such functionality was to enable users to test the robustness of their algorithms to changes in resolutions. Though this is enough under the current scenario, it may be useful to be able to add procedural or random noise to the data generated. Support for noise models in the data generated is another critical feature to be added in future.

6.2 Conclusions

We created a tool which solves the problem of lack of good tools for generating synthetic data sets for testing CV and IBR algorithms. The tool not only reduces the time spent by researchers in creating data sets, but also enables them to share the data in a standard format. The problem with using data created years ago is the that it may be inadequate to test the current state of the art high quality algorithms. Our tool enables researchers to over come this problem by providing a scene description format which can be used to render data again at any required resolution or quality. This tool has proved to be helpful for testing algorithms which are in development stage. Since it can generate any required ground truth data. For example, if a motion tracking algorithm or alpha matte algorithm assumes it has a perfectly segmented image, the user can use the object maps generated by our tool as the segmentation. The segmentation provided by our tool is perfect and can hence be used as a benchmark for comparision of new algorithms.

6.3 Summary

Due to increasing demand for high quality CV and IBR algorithms, high quality data sets which can differenciate among the best performing algorithms is very desirable. Such data is very difficult and time consuming in real world. The performance of these algorithms on synthetic data is a good indicator of their performance on the real world data. Hence high resolution synthetic data is required. Researchers and research labs spend a lot of resources in the creation of data sets and data generation tools for testing their algorithms. It may not be feasible to extend such tools, since they are generally developed for generating a single data representation. We tried to address this problem by creating a data generation tool which is easily extendable and is easy to use for generating standard data like depth maps, alpha maps, object maps, etc. This tool makes sharing of data possible in the research community.

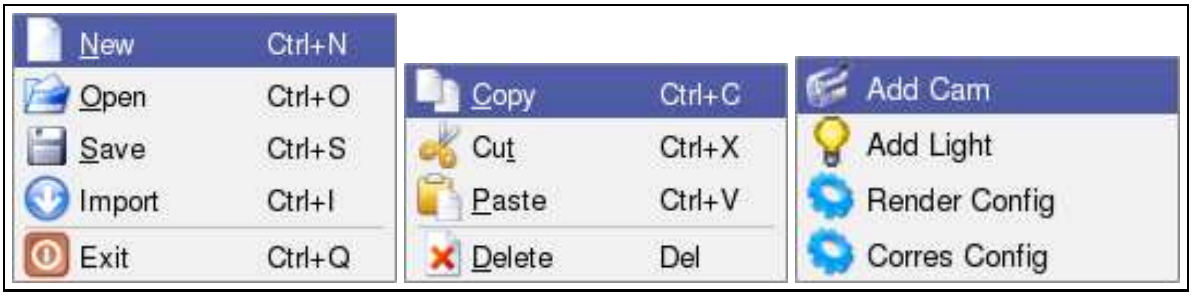
Appendix A

User Manual

DGTk is a vison aware tool which can generate depth maps, object maps, point correspondences, etc which are very valuable for CV and IBR researchers. We have designed the tool to be very flexible, versatile and easy to extend. The reasons for developing a separate tool for data generation rather than extending already available tools include, (1) Lack of availability of information about internal representation of data in such tools, (2) Very complex and difficult to learn interfaces, (3) Require unintuitive extensions to tools due to their internal architectures. (4) Lack of good documentation for extending such tools. In this chapter we intend to introduce various features of our tool to the users.

A.1 Main Window

The GUI of our tool is similar to that of a standard 3D authoring tool. The main window that appears once the application launches, contains a menu bar and a tool bar. The menu has the standard elements like $File, Edit$ and $Tools$. These three menus provide all the functionality that is needed for the user in terms of data generation. This is another major advantage of using our tool. The user does not have to spend hours trying to figure out which item performs what function. The menu items contain the standard images depicting the operation to be performed by that particular menu item (Figure A.1).



(a) (b) (c)

Figure A.1 (a) File menu, (b) Edit menu and (c) Tools menu. Each operation has it's own standard icon beside the operation.

A.1.1 File Menu

The standard operations like opening an already saved scene, creating a new scene, saving the current scene, importing 3D models in known formats like 3DS, AC3D and MD2 and finally an item to quit the tool. While designing our tool we have designed a simple ASCII file format for saving the scene description. These files generally have an extension ".scene". The user can generate any data he/she requires by opening these scene files.

A.1.2 Edit Menu

The major use of our tool would be for creating complex synthetic scenes which mimic those in the real world. The user may want to place hundreds and hundreds of trees in a scene which are actually a single 3D model file. To make such operations easy, we provide simple editing operations (cut, copy and paste). The user can cut, copy or paste any object that has been imported into the scene. Even the cameras can be deleted or copied. This is particularly useful for creating complex outdoor scenes.

A.1.3 Tools Menu

The tools menu is the most important for the users. Users can add a camera to the scene using $Tools->$ $addCam$ menu item (The menu item with a camera beside it). Adding light is done using $Tools->$ $addLight$ menu item (The item with a bulb icon next to it). $Tools->RenderConfig$ is the menu item that is useful for setting the data to be generated. This menu item brings up a dialog box which looks like Figure A.1.3. The user can generate different outputs by checking against the required outputs. For example, if the user wants to generate depth maps for the scene setup in the tool, the user should open the render configuration dialog by using $Tools->renderConfig$, then in the controls tab of this dialog box the user has to check against the depth maps option and click on the $Start$ button. This will generate the depth map for the scene. Any number of formats can be generated at a time.
The user can change the tile dimensions by specifying the dimensions in the text boxes provided in the interface. These are then used to render the final image. The default values are set to 640 and 480 which are minimum values supported by most of the graphics cards. The resolution of the image to be rendered can be changed by dragging the scroll bars presented in the render configuration dialog box. The user is provided with vital information like the worst case resolution that would be achieved by rendering the image with current dimensions.

The $Tools->addLight$ brings up a popup window which looks like Figure A.3. The user can specify the exact values required in the text boxes provided in the UI. Once the values are filled, the user has to click on the $SetValues$ button. The user can enable or disable any light by selecting the light from the combobox and checking/un-checking the check box provided. All three color properties of the light Ambient, Specular and the Diffuse can also be specified in this dialog box. Once a particular light is enabled, the user will be able to see a colored sphere in the four views of the tool. This is the graphical

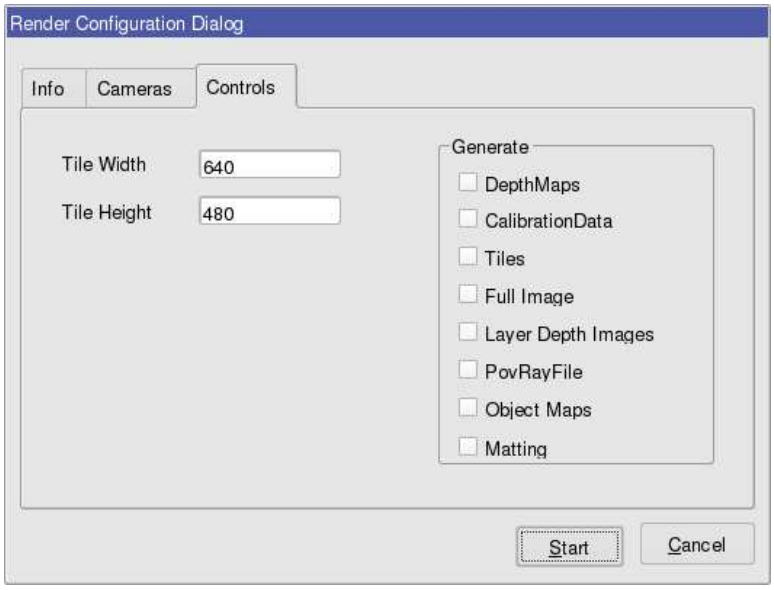


Figure A.2 The render configuration panel. This is where the user selects what outputs are to be generated by the tool.

representation of the light and can be moved and placed at any desired location just like any other object imported into the tool.

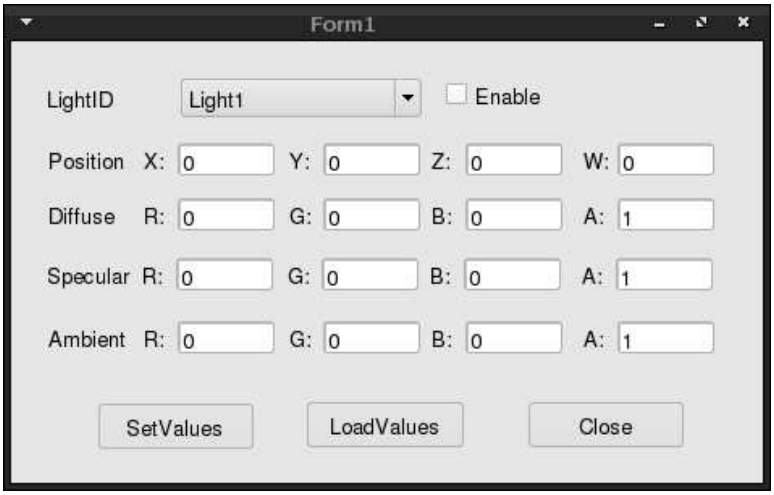


Figure A.3 The configuration dialogs for placing lights at specific locations

The camera dialog (Figure A.4) can be accessed by using $Tools- > AddCam$ item in the menu. The camera center can be specified in the 3D world cordinates using the text boxes in the UI. Simillarly the look at and orientation of the camera can also be specified. The field of view, aspect ratio, near plane and far plane are also specified using the same UI. The user can directly preview the camera's view by

clicking the $Preview$ button. Clicking on the Add button adds the camera with specified parameters to the current scene.

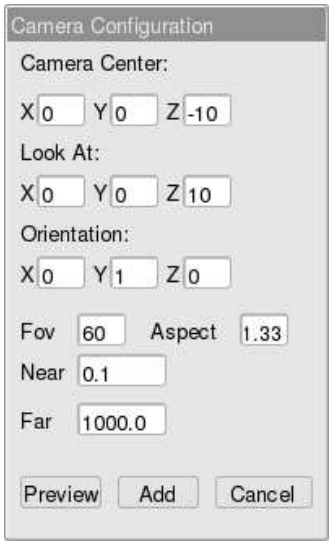


Figure A.4 The GUI for specifying the exact values for the cameras

A.1.4 Tool Bar

The tool bar in the main window uses the same icons to represent the operations that are presented in the menus. The only operations missing in the tool box are the render configuration and correspondence. The user can access these dialogs only through the menus.

A.2 Creating a Static Scene

For creating a new scene in DGTk, first invoke $File- > New$. This clears all the objects in the scene and resets all the four views. Now the user can start importing new objects into the scene using $File- > import$. Currently the tool allows the user to import AC3D, MD2, 3DS and some simple povray models. If there were no errors while loading the model into the tool, the object appears in all the four views of the tool. The user can now click and drag the object to place it at a desired location. The user can identify which object is currently selected with the help of a green bounding box which appears around it after selection. Once all the objects required in the scene are imported to the tool, the user must add at least one camera in the scene to be able to generate data. There may be more than one cameras in a scene. The user can preview the scene from the camera's point of view using the camera's context menu which pops up when the user right clicks on it. A final check to see if every required object has been added would be helpful before making any further progress. The user must now right click on the first frame in the time line widget and select $MakeKeyFrame$ item. This creates the first

key frame of our scene. For creating a static scene the user should now left click on the third frame in the time line widget, then right click and make it a key frame. If the user desires, he/she can save it using $File- > Save$. Now that the scene is setup, the user can launch the render configuration dialog using $Tools- > RenderConfig$ and start rendering the required representations of the scene.

A.3 Creating a Dynamic Scene

Once the first key frame is created after a scene is set (i.e, the first frame in the time line widget is made as a key frame), The user can create a dynamic scene quite easily. We shall show how to create a dynamic scene which has simple linear motion of one or more objects. Now that the first key frame is set, left click on a frame some ten frames away from the first frame. Move the objects in the scene by clicking and dragging them to a new position. Right click on the same frame again and make it a key frame. This results in a scene which is nine frames long and has moving objects. The user can also create dynamic scenes with rotating objects. For this, instead of dragging the objects, right click on the objects, select the $rotate$ item in the context menu and move the move a little to see the rotation of the object. Once the object reaches the desired orientation, make the second key frame. This process can be used to create as many key frames as required. The important point to note while creating a scene is to import all the required objects before making the first key frame.

Appendix B

Scene File Format

B.1 Introduction

The major hurdle for most of the researchers while using synthetic data is that the tools developed for data generation are not scalable. Such tools cannot be used by other researchers to generate data with some other scene setup. This limits the data that can be shared among the researchers. The datasets cannot be changed very easily. Some researchers have tried to over come this hurdle by specifying the constraints and methods to be used for acquiring the datasets [17]. A lot of time goes into configuring these tools to generate the data which is acceptable for testing the algorithms. If such data generation tools provide some method of sharing the scene created for generating the datasets, the users would be able to make minor modifications like changing the objects in the scene and use the same configuration of cameras, lights etc to generate new datasets.

Many ray tracing softwares support very powerful high level scene description languages. Users can represent complex scenes which mimic the real world with ease. These scene description languages are generally in ASCII format (human readable format), but they are very complex to understand at the first look. Since complex mesh objects require a large number of vertexes and texture coordinates, the amount of data that is present in these scene description files cannot be understood without the help of some kind of scene graph editor. Many 3D authoring tools have the capability to generate the scene description of the scenes setup using them. As stated in the earlier chapters, Though such tools have been very effective in generating high resolution images with photo realistic quality, It is very unintuitive to extend these softwares to generate any other representation which may be useful for creating datasets, crucial for testing CV and IBR algorithms.

A data generation tool would require a more robust and abstract representation of the world. A representation that can be extended to incorporate any new extensions made to the tool. Care has to be taken not to make such scene files human readable and at the same time extend-able. Human readability of the files is an important since it enables the user to make modifications to the scene file to match his/her

requirements. The scene files have to be independent of the data they have been created to generate. Such abstraction would enable generating different kinds of data using the same scene file. Due to the lack of such standard scene format which supports both dynamic and static objects, we have formulated our own new file format for such scene description.

B.2 Design

Based on our analysis of the requirements of the scene description format, we have designed an ASCII file format for storing the scene that the users setup using our tool. The properties of the objects such as their positions, name of the 3D model file are to be stored in the scene file. The information about the data generated or that can be generated should not be stored in this file. We have designed the file format so that it is very simple to parse. It's also very easy to generate scene files using the models that are already available with the user. The scene files used by our tool have a ".scene" suffix.

The over all structure of a scene file is of the structure:

```
(Object Type) (Object Details)
```

The scene file always starts with a number describing the total number of objects that are in the scene. The whole scene file is divided into two blocks. The first block describes the information about the models, lights and cameras that are present in the scene. The second block again contains two or more blocks (each representing a key frame) based on the number of key frames. By default the user has to mark a minimum of two key frames. This constraint has been imposed so as to make use of the same rendering pipeline in our tool for both dynamic and static scenes. The key frame block has the following structure:

```
(Frame Number)
(Details of all objects, one in each line)
```

The order in which the object details are specified in the key frames have to be in the same order as they have been specified in the first block of the file. This is important so as to maintain consistency across different key frames. The following is the basic structure of the whole scene file. $\%f$ indicates floating point value, $\%d$ indicates an integer value and $\%s$ indicates a string value.

```
%d (num objects)
Object Type: <object parameters>
...
...
%d (num key frames)
```

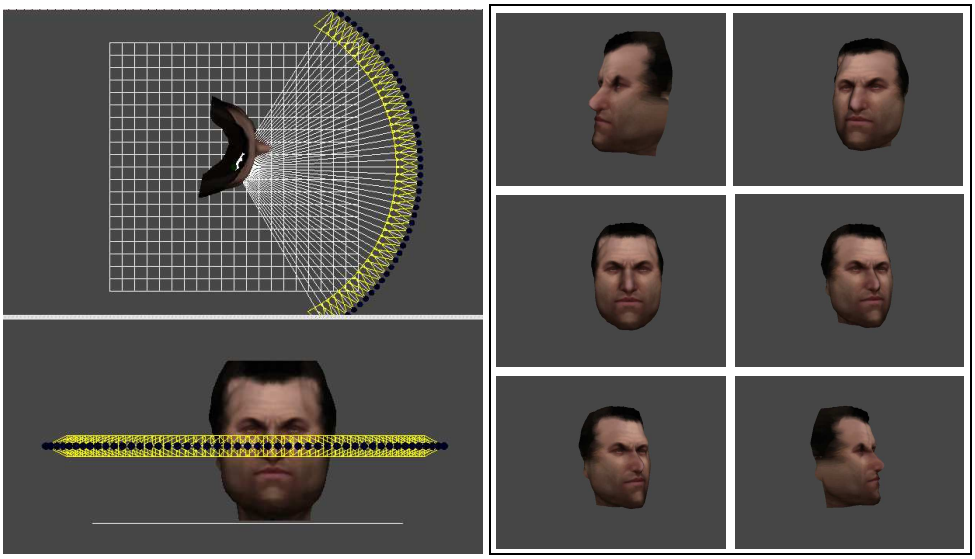
```
%d (frame number)
<object parameters>
...
...
%d (frame number)
...
...
```

The first line in the file describes the number of objects present in the scene. The lines following this number are the details about each object. We have defined special tags for each object type describing the kind of object that follows, to make the file more readable and to perform extra operations on the scene file. For example, the camera object has the location and the look at values. These values are represented by two objects and hence require the tool to read another object in the file when it finds a camera object. This is a simple strategy we have adopted to ensure easy extendability of the tool to support different input formats. There are some predefined object types that are currently supported in our file format. $glObject\_Light$ refers to light objects, $glObject\_AC$ to represent an AC3D file or a povray scene file, $glObject\_Camera$ for specifying the camera details, $glObject\_3DS$ for 3ds objects and $glObject\_Md2$ for md2 objects. Following this information is the number of key frames in the scene. This gives the total number of key frames that have been setup by the user in the scene. What follows is a sequence of frame number and object details blocks. Each of these are important building blocks of the dynamic scene to be generated using the tool. Each key frame represents a time instant. For all the time instances in between these key frames, the tool has to interpolate the object properties based on their values at the key frames.

The file format does not have any limitation on the number of objects of any type that can be placed in the scene file. Many objects, cameras, light sources can be present in a single scene file. Due to the freedom over the number of objects (cameras especially) users will be able to create complex camera configurations like hemisphere or circular etc. Figure B.2 is an example of complex camera setups possible using our tool by specifying the cameras externally in the scene file. This is an important feature because specifying parameters of each camera in the GUI can be inconvenient. Since we are using OpenGL for rendering purposes, the common number of lights supported on most of the graphics hardware is eight. This is the current limitation on the number of lights that can be put in a scene.

B.3 Implementation

We have implemented a simple parser for parsing the input scene files and setting up the scenes in the tool. The integer value in the first line is read and based on this number, the rest of the data is loaded. As



(a) (b)

Figure B.1 (a) A semi circular setup of 48 cameras for acquiring the images around the face model. The cameras in this scene were added not using the tool but through another program which generated the center and look at points of all the 48 cameras. Such large number of cameras cannot be added manually into a scene as it is very time consuming process. (b) Images of some of the views of the camera setup.

Figure B.2 An outdoor scene created and rendered using our data generation tool. This scene has multiple objects and a single camera unlike the above figure.

stated before every line describes an object type followed by the details about that particular object. The tokens describing the object id are used for creating an instance of the corresponding class implemented for loading that object type. For example, we have implemented a class called $acObject$ which inherits a base class called $glObject$, for loading the ac3d models. Similarly we have implemented $md2Object$, $Model\_3DS$ for loading MD2 and 3DS models respectively. While loading the scene files, the tool loads all the key frames in the scene. These key frames are shown in the time line just like they were when the actual scene was created. While loading the information about the key frames we assume that the order in which the object details appear is same as the order in which the object model details appear in the first block of the scene file.

The following is an example scene file:

```
3
glObject_AC: tuxedo.ac
glObject_AC: world.ac
glObject_Camera: ( 60, 0.1, 1000, 1.33 )
[ 2.45 0 -7.24999, -4.5 0 4.09998, 0 1 0 ]
2
0
< 0 0 0 > { 1.00 , < 0, 0, 0 > }
< 0 0 0 > { 1.00 ,< 0, 0, 0 > }
< 2.45 0 -7.24999 > { 1.0000 ,< 0, 0, 0 > }
< -4.5 0 4.09998 > { 1.00000 ,< 0, 0, 0 > }
2
< 0 0 0 > { 1.00 , < 0, 0, 0 > }
< 0 0 0 > { 1.00 ,< 0, 0, 0 > }
< 2.45 0 -7.24999 > { 1.0000 ,< 0, 0, 0 > }
< -4.5 0 4.09998 > { 1.00000 ,< 0, 0, 0 > }
```

The scene file shown above describes a scene with two 3d models (ac3d files tuxedo.ac and world.ac) along with a camera. During design of our tool, we have combined the rendering pipeline for both static and dynamic scenes. Due to this design methodology, every scene file should have two key frames even though there is no motion in the scene. The above scene file has two key frames one at frame 0 and another at frame 2. You will observe that there is no change in the position of the objects in the two frames.

Publications

Our paper describing this work got accepted in International Conference on Visual Information Engineering (VIE 2006). We plan to update the tool and present it as a journal at Journal of Graphics Tools (jgt).

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