Intelligent Camera Control for Graphical Environments

by
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Submitted to the Program in Media Arts and Sciences,
School of Architecture and Planning,
in partial fulfullment of the requirements for the degree of
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Abstract:

Too often in the field of computer graphics, practitioners have been more concerned with the question of *how* to move a camera rather than *why* to move it. This thesis addresses the core question of *why* the camera is being placed and moved and uses answers to that question to provide a more convenient, more intelligent method for controlling virtual cameras in computer graphics. After discussing the general sorts of activities to be performed in graphical environments, this thesis then contains a derivation of some camera primitives that are required, and examines how they can be incorporated into different interfaces. A single, consistent, underlying framework for camera control across many different domains has been posited and formulated in terms of constrained optimization. Examples from different application domains demonstrate a variety of interface styles that have all been implemented on top of the underlying framework. Evaluations for each application are also given.

Thesis Supervisor: Dr. David Zeltzer, Principle Research Scientist at the Research Laboratory in Electronics.

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CHAPTER 1. INTRODUCTION

Too often in the field of computer graphics, practitioners have been more concerned with the question of *how* to move a camera rather than *why* to move it. There is a great deal of research devoted to proper representations for interpolating camera motion conveniently or in what sequence transformations should be performed in order to provide efficient culling of objects outside of the field of view of the camera. However, very few researchers have looked at the basic reasons for which cameras are used in computer graphics. This thesis addresses the core question of *why* the camera is being placed and moved and uses answers to that question to provide a more convenient, more intelligent method for controlling virtual cameras in computer graphics.

Once we know why to change the camera's view of the world, we can then start addressing how to change it. In this thesis, I examine similarities across many different activities that can be described in terms of camera *primitives*. These primitives can be conveniently and powerfully described as constraints that must be satisfied to achieve the designated tasks. A single, consistent, underlying framework for camera control across many different domains has been posited and formulated in terms of constrained optimization. After discussing the general sorts of activities to be performed in graphical environments, this thesis then contains a derivation of some of the primitives that are required, and examines how they can be incorporated into different interfaces.

The primitives can be viewed as behaviors for *software agents* of varying levels of sophistication. The agents might simply provide specific interfaces to a variety of camera primitives, or the agents might combine primitives, sequence them, connect the primitives to devices, or use the primitives as behaviors for autonomous action.

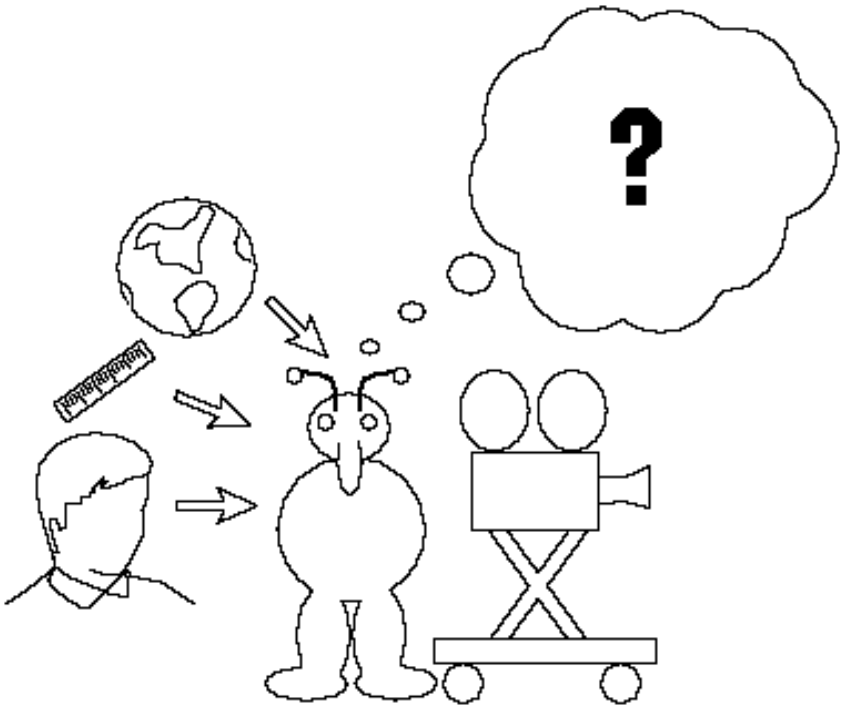


Figure 1: The camera agent

Figure 1 is a representation for the motivating concept of this thesis. The intelligent camera agent positions the camera by finding the bottom of a complicated, multidimensional terrain. That terrain is constantly changing, new mountains erupting, or new valleys and ridges appearing. The terrain changes in order to follow our intentions, because of movements of objects in the world, or because of some internal rule base for the agent. It is the goal of this thesis to look at how our intentions, and how knowledge about the world, and other rules, can help shape that terrain, and show how from this basis, we end with a powerful, flexible, underlying framework for interfaces into new worlds of camera control.

The skeptical reader may wonder why we need this intermediate step between our intentions and movements of the camera. There are several reasons that will be justified in this thesis:

- There is often no convenient way to find out where to place the camera to sat-

isfy our intentions, but there is often a convenient mapping between our intentions and a “constraint” terrain.

- That mapping can be described in formal, mathematical terms that can be used to generalize knowledge across many different domains, rather than only in the domain for which an intention was originally derived.
- The terrain represents a convenient way of combining several intentions at the same time.
- The terrain responds to an ever changing world, making the camera, which follows that terrain, respond automatically to changes in the environment.
- The agent’s own internal knowledge can change the terrain, providing a means of combining the autonomous action of the agent with the changing environment, and our own changing intentions.

The new and original knowledge that is contributed by this thesis is a more thorough understanding of how and why humans control their view within computer graphic environments. A single, unifying structure for controlling the camera is proposed and a variety of camera primitives (or behaviors) are examined in several different application domains. The utility of the underlying framework is shown by the wide-reaching application domains for which the framework is applicable.

1.1 Reader’s Guide

In Chapter 2, I describe the graphical environment and the virtual camera and then set forth the basic problem and the solution scheme proposed.

In Chapter 3, I discuss related areas of research in computer graphics, constrained optimization, robotics, user interface design, and film theory.

In Chapter 4, I set forth a taxonomy to describe the different kinds of graphical environments and the visual requirements necessary to achieve goals in each domain.

In Chapter 5, camera primitives and constraints are derived and discussed formally.

In Chapter 6, I look at the different ways that interfaces can be built using the proposed framework in five different applications; a mission planning system, a virtual museum, filming a conversation, a virtual football game, and a visibility assistant.

Chapter 7 contains an evaluation of the applications described in the previous chapter.

Chapter 8 presents conclusions and future work.

Appendix 1 presents the details of the path planning algorithm that was developed for the virtual museum.

Appendix 2 presents the details of the visibility algorithm that was developed for the camera framework.

Appendix 3 discusses the graphical prototyping environment in which all the examples have been implemented.

Appendix 4 discusses the optimization software that was used for solving the constrained optimization problem at the core of the camera primitives. It also gives code examples of how to combine a number of camera primitives.

CHAPTER 2. INTELLIGENT CAMERA CONTROL

2.1 General Problem

Current interest in so-called immersive interfaces and large-scale virtual worlds serves to highlight the difficulties of orientation and navigation in synthetic environments, including abstract “data-spaces” and “hypermedia” as well as more familiar modeled exterior and interior spaces. As Ware and Osborne [Ware90] point out, this is equivalent to manipulating a viewpoint – a synthetic camera – in and through the environment, and a number of recent articles have discussed the camera control problem in detail.

Nearly all of this work, however, has focused on techniques for directly manipulating the camera. In my view, this is the source of much of the difficulty. Direct control of several degrees of freedom of the camera is often problematic and forces the human participant to attend to the interfaces and its “control knobs” in addition to – or instead of – the goals and constraints of the task at hand. If the intention of the user of the system is, for example, to observe some object X, then allowing him or her to simply tell the system, “Show me object X” is a more direct and productive interface. This thesis will explore ways in which we can generalize instances of this form of “task level interaction” for synthetic cameras across a wide variety of tasks.

Before the statement of the general problem, it is first necessary to define two essential terms: Computer Mediated Graphical Environment (or just graphical environment), and the synthetic or virtual camera. By graphical environment, I mean any interactive, graphically rendered computer display which is intimately associated with a geometric model. Graphical environments are usually a spatial representation of an information space or a

representation of an actual environment. Types of graphical environments, and the visual tasks that are associated with them will be discussed in chapter 4.

By virtual camera, I mean the method of specifying the parameters which control the view within the graphical environment. Virtual cameras are, by definition, a crucial part of any graphical environment because the camera's view is a primary means by which information about the graphical environment is transferred to the user. Other interface modalities, such as aural and haptic exist, but by and large, most of the information currently comes through the visual system and this thesis is devoted to examining only the visual modality. Without being able to control the virtual camera, the user is left with a single view of only a small portion of a potentially infinite environment. It is important that the user be able to affect what s/he is seeing either by changing parameters that control what is occurring in the graphical envrironment directly, or by changing the view through manipulating parameters of the virtual camera within the graphical environment.

In general, I will consider seven degrees of freedom that must be controlled: three for the cartesian position of the virtual camera in space, three for the orientation of the camera, and a final one for controlling the field of view for the camera (see figure 2). There are several other parameters of a camera that can be controlled but will not be considered in this thesis. Some of those are: the aspect ratio of the resultant frame, the depth of field for the camera, the "shutter speed", and lighting of the environment. These additional parameters are not considered because most computer graphic systems model an idealized "pin-hole" camera where there can be infinite depth of field (everything is in view at once), infinitesimal shutter speed (no motion blur), and direct control over the lighting within a GE. Controlling these other parameters can often greatly enhance the look of the resulting image, but these tend to be extremely subjective and stylistic changes [Potmesil81]. For the purposes of this thesis, the idealized model for the virtual camera is used.

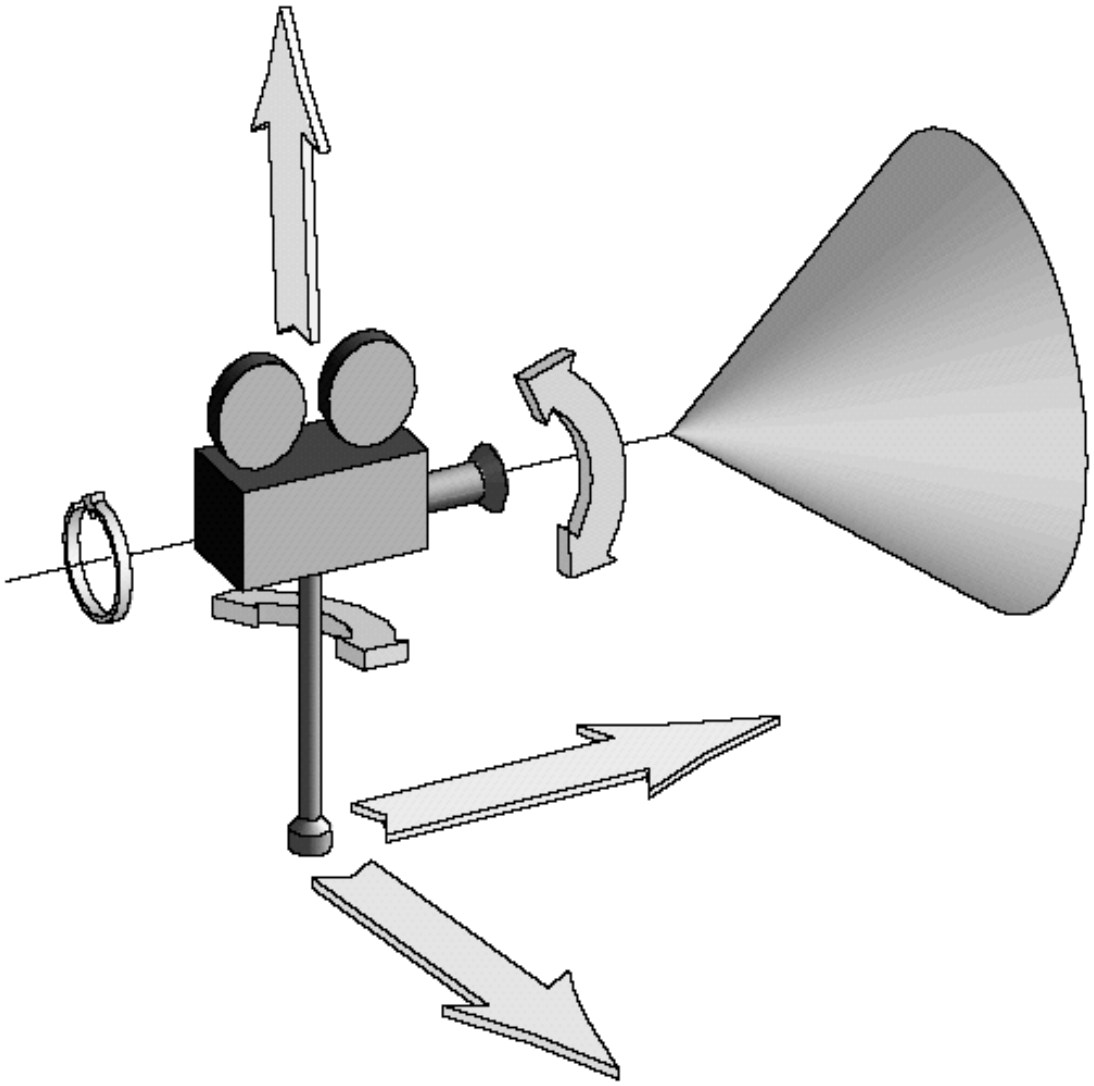


Figure 2: The Virtual Camera with its 7 degrees of freedom.

It is important to examine some distinction between a virtual camera in a graphical environment and a real camera in a real environment. Real environments offer many constraints and affordances which are not available in graphical environments. For instance, in a real environment, the camera can not move through physical objects. There is no such distinction for virtual cameras, however movement through objects can often be extremely confusing to viewers. Also, different mountings can be used for the real camera that help

control the way the camera can move. For instance, a fluid head may be used, which produces viscous damping which resists sudden changes of position for the camera head (rotation and tilt). Also, it is inconvenient to rotate the camera about its direction of gaze (roll) which is rarely done in filming real scenes. There are, however, some inherent advantages that virtual cameras have over real cameras. Because there are no built in constraints on the virtual camera's degrees of freedom, the virtual camera can move to any place within the graphical environment, even if that would be physically unfeasible for a real camera. This might mean flying along with a ball as it is thrown in midair, or moving through a window without any means of support. Also, when controlling virtual cameras, one does not need to worry about velocity limitations or torque constraints of motors that might be needed to control real cameras. In addition, in graphical environments, the assumption is made that the position of objects in the environment can be easly recovered, something which is still in general an unsolved problem for real environments.

Table 1 represents the basic camera movements in more familiar cinematic terms to give some notion of the effects of changing various camera parameters.

Table 1: Common Cinematic Terms

Cinematic Term	Definition
pan	Rotation of the camera about the vertical axis.
tilt	Rotation of the camera about the lateral axis (axis formed by the cross product of the view normal and the view up)
roll	Rotation of the camera about the view normal
dolly	Translation of the viewpoint along the lateral axis.
truck	Translation of the viewpoint along the view normal.
crane	Translation of the viewpoint along the up vector.
zoom	Changing field of view of the camera.

Even though control of the view within graphical environments is crucial, to date only the crudest methods for specifying the view have been included in most graphic systems. One common method is to directly control the degrees of freedom of the camera through the use of dials or sliders. This at least lets the user change the view but is rarely convenient for achieving any tasks that needs to be performed in a graphical environment. It is especially difficult to produce any sort of satisfactory presentations because of the difficulty in specifying a desired motion accurately and continuously.

Another method, perhaps the most common, is to somehow specify the position and orientation of the camera at certain *key* points in time. Motion between those key points is then described by using an interpolating curve [Barsky83, Gomez84, Kochanek84, Shoemake85, Stern83]. A variety of different interpolating curves have been used to produce different motions. Linear interpolation, with sharp first order discontinuities at the key points tends to look unrealistic. Cubic spline interpolating functions permit the camera to ease in and ease out of a motion. This kind of motion looks slightly better than linearly interpolated motion, but is still too regular and contributes to the synthetic, unnatural look often attributed to computer graphics. However when the key points are interpolated, there still exists the problem of how the key points are specified in the first place. These methods are sufficient for only the simplest of camera specifications and movements.

Other methods for moving the camera can include scripting or programming the camera, for example, to maintain a certain distance from an object as it moves through a scene, or to move along a complicated path while maintaining the center of interest at a certain object. These methods can be powerful, but often require programming knowledge and specific effort for any particular situation [Reynolds88, Drucker92].

Physically based methods try to generate motions for objects based on certain physical parameters such as mass, inertia, and minimum control effort, and these methods can also be applied to the camera [Armstrong86, Badler86, Brotman88, Bruderlin89, Girard87, Isaacs87, Isaacs88, McKenna90, Raibert84, Sturman89, Schröder90, Wilhems87, Witkin90]. Closely related to these methods are forward simulation systems which model the effects of a user applied control force and frictional forces to derive the motion of the

camera [Turner91]. This can achieve extremely realistic looking results in terms of what a real physical camera might do but can be extremely difficult to control to obtain a desired behavior.

This thesis addresses the creation of a single, common, framework in which to talk about forms of virtual camera specification within graphical environments based on the task level concerns of the user. Although I concentrate completely on purely computer mediated environments, the general framework can be applicable to the control of real cameras, either in motion control systems or for teleoperation systems.

There are a variety of basic reasons for camera movement and placement that will be elaborated in this thesis. One reason is for *exploration*; we might wish to discover what's in a space, or find out what objects might be nearby. Another reason might be to *perform* some activity in the space. A camera might show us what it looks like to do that action from multiple points of view, or the camera can be situated in a way in order to best perform the activity, or the camera might be able to provide useful, adjunct information. If we're not sure exactly what we want to do, another reason to move the camera might be to help *plan* our activity. Planning might involve specifying motion of the camera to present the environment to a non-interacting observer or it might involve changing the environment itself. Planning might necessitate more and different kinds of views of the environment. Finally, before actually performing the activity, it might be necessary to *rehearse* that activity, again observing from different points of view in order to better familiarize ourselves with the process.

The constraint framework that I envision can be embodied as the controlling behavior for a *software agent* which is aware of the environment and the user's intentions, and has internal knowledge applicable for controlling a camera. The agent makes decisions based on a multidimensional terrain, where the goal of the agent at any time is to find the lowest point of the terrain. If there are several low points on the terrain, techniques are suggested to bring the system to the lowest point. Barriers exist in this terrain where the camera should not go. "Mountains" are places where the camera may go, but it is "preferable" to be elsewhere. This terrain is constantly evolving over time. The environment changes, thus

changing the underlying terrain. Our goals change from time to time, which also changes the terrain. The agent may have its own goals which also change the terrain. It is the object of this thesis to discover how changes in our intentions, changes in the environment, and external knowledge can be unified into a single underlying framework. In chapter 5 we talk about a formal mathematical description of camera primitives which can be combined to form the constraint terrain that determines the agent's behavior.

The new and original knowledge that is contributed by this thesis is a more thorough understanding of how humans can control their view *in* computer graphic environments. A taxonomy of several different application domains is proposed and analyzed to extract visual tasks to be performed in each domain. Camera primitives are described which can assist in the performance of those tasks and a framework which allows for the combining and reusing the camera primitives is presented. The framework is validated through examining a variety of example application domains.

This problem is of interest to an increasingly large audience since it touches on issues of research in computer graphics, virtual environments, human machine interfaces, and software agents.

2.1.1 Virtual Environments

As described above, graphical environments are essentially a superset of virtual environments. Virtual environments commonly refer to a graphical environment in which a user is immersed in the environment, typically by tieing the control of the virtual camera to the motions of the operator's head and body through the use of a head mounted display. Navigation through a virtual environment (or in another words, controlling the motion and placement of the virtual camera) is still a very open issue [Brooks88]. Users often become lost in virtual environments and may become disoriented or even ill if an interface is not satisfactory. If virtual environments are to be used to represent or manipulate information, there must be good ways in which to explore the information space, locate specific information, present that information to others, and perform tasks within the environment.

2.1.2 User interface design

User interface design has received a great deal of attention in the research community, since it is clear that when interacting with a complicated system, a well-designed interface can greatly affect the ease of use and the effectiveness of the system. In addition to designing an appropriate interface for navigating and exploring a graphical environment, it is often important to be able to present the information to a non-interactive observer. Interfaces, therefore, must be designed with this purpose in mind. This has typically been the domain of special purpose computer animation systems, with notoriously difficult-to-use interfaces. The methodology for doing interface design has heavily influenced the structuring of this thesis. By breaking domains down into tasks, and analyzing those tasks, I have attempted to show that the results in this thesis are generally applicable across a wide range of domains.

2.1.3 Software agents

A software agent is a method of building an interface which can assist the user in performing tasks. The software agent may learn by observing a user's actions, or may encapsulate knowledge on how to perform a task conveniently. The general area of virtual camera control is a fine example of how software agents might be used to assist the user in interacting with a complicated task. The agent can either act autonomously or closely assist a user in achieving the desired task (these tasks will be defined in chapter 4 of this document). The actions that a camera agent is capable of are clearly defined in the framework for camera control.

Don Norman describes several ways in which human reasoning and planning can run into problems [Norman93].

1. Lack of completeness: In most real tasks, it simply isn't possible to know everything that is relevant.
2. Lack of precision: There is no way that we can have precise accurate information about every single relevant variable.
3. Inability to keep up with change: What holds at one moment may not apply at another. The real world is dynamic, and even if precise, complete information were available at one point in time, by the time the action is required, things will have changed.
4. A heavy memory load: To know all that is relevant in a complex situation

requires large amounts of information. Even if you could imagine learning everything, imagine the difficulty you'd have finding the relevant material just when it is needed. Timely access to the information becomes the bottleneck.

5. A heavy cognitive/computational load. Even if all the relevant variables were known with adequate precision, the computational burden required to take them all properly into account would be onerous.

The intelligent camera framework that I am describing in this thesis can assist in all of these areas.

1. Lack of completeness: in an exploratory domain, the system can maintain information about the position of all the objects of interest, obstacles, and accessways. It can give assistance in a variety of forms, from giving a guide in the form of a highlighted path, to moving the user along a path, to immediately transporting the user to the proper place within the database. The museum application described in section 6.1 shows an example of this style of assistance.
2. Lack of precision: the system can place the user at the exact point that meets the conditions specified by the user. The visibility assistant described in section 6.5 demonstrates an example of this style of assistance.
3. The assistant is ideal for dynamic environments. If the user can express intentions (often best as constraints), the system can maintain those constraints as the environment changes. The mission planner (section 6.2) and the football game (section 6.4) are both examples of camera assistance for dynamic environments.
4. Heavy memory load: The assistant can encode not only information about the environment, but rules for presenting the environment. The conversation filming agent, described in section 6.3, shows one way of encoding those rules.
5. Heavy cognitive/computational load: Not only can the assistant perform difficult computation tasks to achieve the intentions of the user, but it can automate repetitive tasks, thus freeing the user to perform other actions. This is demonstrated in nearly all the examples for chapter 6.

2.2 Overview of the solution proposed

The general strategy taken in this thesis will be the following:

- A taxonomy of interactive graphical domains is presented and a list of the requisite visual tasks associated with them.
- Camera primitives are derived to assist the user in performing the visual tasks described in the previous step.
- A framework which can combine the camera primitives is presented and discussed. It is important to note that this framework is intended to be general and extensible.
- Interfaces are built on top of the framework for a set of representative domains. This will provide an opportunity to explore some extremely different kinds of user interfaces that can be developed on top of the underlying framework and demonstrate the general utility of the framework.
- Evaluations of the resultant applications will be discussed to indicate the effectiveness of the proposed camera framework.

2.2.1 Framework

The essential idea is that the intentions of a human user with respect to a given task can be formulated in terms of mathematical constraints. By providing a framework of constraints for camera specification I have created a domain independent language for building visual interfaces. It needs to be shown that this “language” is general, efficient, and robust.

2.2.2 Generality

Generality will be shown by looking at the virtual domains in which a camera needs to be applied. We need to show that the domains we investigate are a sufficiently representational subset of all possible domains. Obviously there is no way of enumerating all possible domains, but at least a sufficiently large set can be spanned. Within each domain, a number of representational tasks that would naturally be performed within the domain are described. For each of those tasks, it is shown how they can be conveniently expressed in the form of the constraint language that I am suggesting.

2.2.3 Efficiency

Efficiency issues must be explored from two sides: implementation/algorithmic concerns and appropriateness concerns. To address the algorithmic issues, it needs to be shown that the kinds of constraints are algorithmically sound. Problems and methods of dealing with local minima must be explored, computational efficiency and scalability must be discussed, and trade offs between expressing constraints in different ways should be identified. The appropriateness issue is more closely related to whether choosing constraints in general (and the specific constraints that are chosen) can adequately express the kinds of tasks that need to be performed. The classic example here is the Etch-a-Sketch problem. In the toy Etch-A-Sketch, the knobs let you move horizontally and vertically which are all right for certain tasks, but completely inappropriate for trying to draw a diagonal line. In this instance, a better solution might be one that controls the angle of a line and one that actually draws the line. How can we show that the constraints that we have picked are appropriate for expressing the tasks that we need to do? That question is answered by looking at the wide range of interfaces that has been generated and showing the different styles of interaction that can be supported.

2.2.4 Robustness

From an algorithmic standpoint, we need to examine when the system breaks or produces results that are not satisfactory. How much special purpose coding needs to be done in order to achieve more correct results. How easy is it to produce conflicting constraints and what can be done when this happens? These issues are examined in chapter 7.

The five applications that are examined in this thesis are the following: a virtual museum, a mission planning system, a conversation filming agent, a visibility assistant, and a virtual football game. These tasks represent a wide sampling of different styles of interaction which have different visual task requirements. They are described in detail in chapter 6.

CHAPTER 3. BACKGROUND AND RELATED WORK

This chapter will discuss relevant background from the areas of computer graphics, constraint based systems, optimal control, robotics, teleoperation, human factors, user interface design, human perceptual capabilities, and cinematic style . Some general references that have been extremely useful are as follows: [Foley82, Foley90] for a general introduction to computer graphics; [Carroll91, Laurel90, Baecker87] for some essays in human computer interaction; [Ellis91] for studies of camera control in virual environments and teleoperator; [Fletcher80, Gill81, Press88, Rogers76] for numerical algorithms and optimization techniques; [Arijon76, Katz88] for film directing techniques.

3.1 Computer Graphics

Camera movements have long been studied in many different contexts within the field of computer graphics; for animation; for exploration/manipulation, or for presentation. I will briefly discuss work in each area, and touch upon how this work contrasts to the existing body of literature.

3.1.1 Interpolation

Early work in animation is devoted to making the movement of the camera continuous and developing the proper representation for camera movements along a path [Barr92, Barsky83, Bartels87, Gomez84, Kochanek84, Shoemake85, Stern83]. These works are all devoted to giving the animator greater control in creating smooth movements and finding ways to interpolate between user specified keyframes. Although generating spline curves for camera movement can produce smooth paths, it can be difficult to relate the movements of the camera to objects in the environment, or even to find appropriate keyframes

in the first place. Also, such kinematic specifications for paths tend to produce movements that are physically impossible and unsettling to a viewer. It has also produced an unmistakable style for computer animations that is not necessarily attractive. In cinematography, a much higher emphasis is given to the composition of a single frame rather than moving the camera through the environment. Both [Barr92, Shoemake85] discuss the benefits of representing object orientation (including cameras) as quaternions. Quaternions have the advantage of having the same local topology and geometry as the set of rotations (untrue for euler angles). They are a compact representation (only 4 numbers), and only have one constraint (unit-length). There is the problem of dual-representation in that any rotation is represented by two quaternions, one on either side of the hypersphere.

Brotman and Netravali [Brotman88] introduced a method for using optimal control to interpolate between keyframes in a dynamically realizable method while trying to minimize control effort. Their work produced subjectively more appealing interpolations. The previously mentioned discussion in [Barr92] extends interpolation of orientations into including velocity constraints through basic optimization methods. They advocate the use of packaged optimization routines because of their robust stopping conditions on an optimal solution.

3.1.2 Physical Simulation

Physical simulation can produce far more natural looking movements than keyframe specification. It has been used in a variety of systems for animating the motion of characters [Armstrong86, Badler86, Bruderlin89, Girard87, Isaacs87, Isaacs88, McKenna90, Raibert84, Sturman89, Schröder90, Wilhems87,Witkin90]. It has even been used for the simulation of camera motion by using forward simulation of a camera with mass, friction, and viscosity [Turner91]. One problem with all dynamic simulation systems is that it is difficult to get the system to behave in a desired manner.

3.1.3 Optimization

One solution to such a problem is to use optimization techniques. There is a large history of constraint techniques for computer graphics starting with diagramming and 2D simulation systems. Sutherland’s pioneering Sketchpad paper [Sutherland63] allowed users to

specify constraints between objects and the system propagated and relaxed constraints until a solution was found. The ThingLab system [Borning79] was designed as a simulation laboratory for experiments in physics and mechanics. Thinglab had built in rules for quickly satisfying constraints procedurally if possible and by relaxation if the other approach was not successful. Several attempts to aid in drawing and manipulation have used constraint based systems including Juno [Nelson85], Snapdragging [Bier90], Briar [Gleicher92], Figuremaker [Kalra90].

Constrained optimization techniques have been used extensively for three-dimensional animation systems too.Witkin and Kass [Witkin88] use optimization over both space and time to find optimal paths between initial and final conditions for rigid bodies. They use a similar optimization procedure (Sequential Quadratic Programming) to explore the space of solutions iteratively. One limitation of this work is that the complexity growth of the problem limits the length of time over which it is useful. In addition, because of the highly non-linear nature of the constraints and objectives, many numerical routines do not converge. Cohen [1992] extended this work to allow for greater user interaction during the solver stage. He also represents the contraints and objective functions in compact form (splines) which allow for greater robustness in the solver. The work in this thesis is in some ways very similar to these approaches. I use Sequential Quadratic Programming to explore space for an optimal position of the camera subject to user specified constraints. The user can assist the optimization by halting it, and restarting it with different initial conditions.

to make physically realizable systems with constraints [Witkin87, Terzopoulos87, Platt88, Kalra90, Pentland90].

Kass [Kass91, Kass92] proposes a general system for graphically combining functions in a dataflow paradigm and then using interval arithmetic or optimization methods to come up with a solution to the problem. Kass's system includes a number of well thought out features for dealing with this type of problem including computing the derivatives symbolically and then compiling the derivatives for efficient evaluation during the optimization process.The advantages of his system are that the system is extremely general and can be applied to a wide variety of problems in graphical systems. His system does not perform any global optimization (since it is nearly impossible to do so on general problems). He shows one example with his system which derives the camera parameters based on the known position of 4 projected points. His system is not designed to specifically deal with camera placement problems though certain modules can be built based on combining the functions he provides. Some work in this thesis has origins in the same notions as Kass's work. Convenient specification of an optimization problem in terms of a graphical programming environment is shown in the section about the virtual football game (see section 6.4).

The system proposed in this thesis relies on constrained optimization techniques to achieve the specified goals for a static position or for limited dynamic movement of the camera. The optimization conditions can be defined as energy constraints, or as strict boundary constraints. In general, however, the camera is not treated as a physical object and not dynamically simulated, since a more general optimizer is being used.

3.1.4 Virtual Environments & Scientific Visualization

With the advent of virtual environments and related 3D interactive worlds [Adam93, Bishop92, Blanchard90, Blau92, Earnshaw91, Earnshaw93, Esposito93, Fisher86, Greeenberg74, Zyda92], a great deal of effort has been spent on presenting convenient methods through which users can change their view of an object or the world. Metaphors, as discussed in [Ware90] provide the user with a model that enables the prediction of system behavior given different kinds of input actions. A good metaphor is both appropriate

and easy to learn. Some examples of metaphors are the “eyeball in hand” metaphor, the “scene in hand” or “dollhouse” metaphor, and flying vehicle control.

In the “eyeball in hand” metaphor, the user can use a six DOF device to position and orient a camera by directly translating and rotating the input device. Ware found this method somewhat awkward to use but easy for users to learn. The “scene in hand” metaphor lets the user rotate and translate the scene based on the position of the input device. This was found to be very convenient for hand sized objects, but nearly impossible to use for navigating inside closed spaces. Another scheme discussed by [Ware90] was to simulate control of a flying vehicle. The user’s position and orientation affected the velocity and angular velocity of the camera viewpoint and direction of gaze. This metaphor was quite appropriate for navigating through space, but difficult to examine all the sides of a single object since it was difficult to maintain the gaze on a particular object while moving. 3D input devices such as a Polhemus isotrack system or a spatial systems Spaceball enable the user to specify 6 degrees of freedom simultaneously, and simulations of these devices can be done using only 2D devices [Chen88, Evans81]. Some of the problems inherent in using these devices are the noise which is inherent in user movements and the number of degrees of freedom which must be simultaneously controlled.

Mackinlay et al [Mackinlay90] discuss the problem of scaling the camera movements appropriately. They developed methods to include both the ability to select an object of interest and to move exponentially towards or away from the object. By selecting ‘point of interest’, the authors can reorient the camera to present a maximal view of the desired object. In this way, the degrees of freedom are restricted and the user can concentrate more on the task of navigating through the environment based on what is in the environment.

Brooks et al [Brooks86, Brooks88] and Airey [Airey90] develop several different methods for moving around architectural simulations including steerable treadmills or shopping carts with devices to measure the direction and speed of movement.

Blinn [Blin88] suggested alternate modes of camera specification for planetary flybys based on four separate requirements. In general, the goal is to place an object in the fore-

ground (the spaceship) and an object in the background (the planet), and have the system interpolate interesting views while the spaceship moves. One mode is the standard view formulation achieved by specifying the view point of the camera, the view normal (gaze) of the camera, and the view up vector. Another mode is to find a position based on the current gaze (I'm looking here, where should I stand?). Another is to find a gaze based on the current position, (I'm standing here, where should I look?). Finally, the last mode attempts to find both the view position and the normal based on the task specification. The approach that Blinn uses involves representing the unknown vectors in terms of vectors that are known. The idea for Blinn's work is in some ways a basis for this thesis since his concept of camera placement is based on achieving a particular goal, however, his solution is rather specific to the situations that he describes. His work can be expressed within the framework of this thesis in a clear, succinct fashion (see chapter 5).

The above works all show that different interfaces are appropriate for different user requirements. No one interface is ideally suited for all tasks, and a common underlying structure on top of which several different metaphors can be implemented would give the user a powerful tool to interact with 3D environments. Another important point emphasizes the ability to select object of interest within the environment. I have expanded on this by allowing the user to specify constraints on the camera according to general properties of the environment.This lets the user manipulate the camera motion based on the actions within the environment, which is, after all, the goal in the first place.

Furthermore, while direct manipulation has certain advantages in interactive systems, there are several deficiencies. It is not necessarily good for repetitive actions, and any action that requires a great deal of accuracy, such as smooth movement for cameras, is not necessarily suited to input using one of the metaphors suggested in the preceding paragraphs. There obviously need to be ways to manipulate the environment that is uncoupled with direct control of the degrees of freedom of the camera.

3.1.5 Automatic Camera Control

One method of automatically controlling the camera was suggested in [Philips92] for use in manipulations in the Jack system. The camera was positioned at a visible location at an

appropriate angle for manipulation using specific kinds of controllers.

Karp and Feiner [Karp90] describe a system which automates the creation of presentation based on a heuristic reasoning process. They use certain user specified goals along with a rule base to decompose the problem first into a series of sequences, and then into a series of shots. Finally, they compose each shot and then patch up the resultant sequence using other rules. They do not specify how they deal with any camera specification at the shot level other than fairly straightforward lookat types of constraints, or specific solutions to a number of issues that they have enumerated. Their system could be used on top of a more sophisticated shot creation mechanism such as the one described in this thesis. This thesis uses a more straightforward user specified template approach with a sophisticated constraint mechanism to attempt to capture cinematic rules as opposed to a complicated rule base. Each approach has distinct advantages, one being essentially top down, while the other being bottom up. My focus (so to speak) is on the composition of the image rather than an automatic composition of an entire narrative.This work expands on their notion of incorporating cinematic rules for automatic presentation, but can be considered an underlying framework for a system such as theirs. Although I make extensive use of cinematic rules for designing the constraints themselves, these rules are not used for any actual automatic presentation. Automatic presentation in this thesis is limited to prototypes or templates that are designed by the user to accomplish certain tasks. The user of the system or the system can autonomously use these prespecified templates for controlling the camera. Seligman and Feiner [Seligman91] use visibility constraints not to control camera placement, but to affect the rendering style (cut-aways, transparency) of the resultant image.

The CINEMA system [Drucker92] was an initial attempt at unifying these disparate notions of camera control under one system. It was a method of procedurally specifying the movement of a camera based on objects in the environment.It shared the notion of easily writing scripts for the control of animations with [Reynolds82]. Problems of the CINEMA system are in part what drives the primary thrust of this thesis – the system was not sufficiently reusable or generalizable. Also, there was too much of an emphasis on programming the motion of the camera when it is clear that the average user does want to program to interact with a graphical environment.

After experiencing some of the problems with camera control in the CINEMA system, it was decided that a solution to all of the problems was to formulate camera control in terms of constraint satisfaction. Gleicher and Witkin describe constraint satisfaction for camera control in their paper Through the Lens Camera Control [Gleicher92]. However, they do not attempt to generalize their work to any context outside of directly manipulating the camera. In addition, their system has a number of limitations. Their system works purely in a differential fashion for camera parameters which makes it only appropriate for local movement. They state that they feel that local movement is appropriate for camera control in a computer graphic system which may be true for certain manipulation examples but is generally untrue in most cinematic operations. In fact, it has been stated, that nearly 70% of all shots in most films involve no camera movement whatsoever. Their method, which they call Through the Lens Camera Control (TTL camera control) is based on the notion that the change in the projection of a world space point can be based on changes in the camera parameters. Thus by calculating a Jacobian matrix which relates these two changes, a desired local change in the projected point can be achieved. Care must be taken when computing the pseudoinverse of the Jacobian to guarantee stable control of the camera through singularities in the camera parameters (i.e. points where small changes in the camera parameters will have an enormouse affect on the resultant change of the image space position of a point).

3.2 Robotics

3.2.1 Pathplanning

A camera can be considered as a simple robot. Thus many techniques developed for the robot motion planning field may be adapted for planning the movement of the camera. Some basic differences include the nature of the camera gaze which can be considered as an infinitely long upper manipulator. The motion planning problem can become arbitrarily more difficult as true three dimensional path planning can be incorporated. This thesis builds upon conventional robot path planning methodologies for the development of the constrained optimization path planning algorithm [Arkin89, Asseo88, Barraquand89, Braitenberg84, Brooks82, Hopcroft94. Kant86, Schwarz83, Thalmann88, Lozano-Perez70]. An extensive discussion of robotic motion planning algorithms is available in

[Latombe90] and has been of great use in the algorithms used for this thesis. Some of this work is discussed in greater detail in appendix 1.

3.2.2 Sensor Positioning

Robotics literature is also a source for approaches to camera positioning for robot vision tasks. Tarabanis and Tsai [Tarabanis92] review several systems for sensor planning for robotic vision. In general the requirements involve placing a camera and an illuminator in order to recognize or detect features of an object. The systems they describe often need to concern themselves with issues not present in the system presented in this thesis including depth of field, resolution of image, and illuminator placement. They state that an automatically planned system allows for the following: a robust solution satisfying the task requirements even in the presence of uncertainty; parameters can optimize the sensor output with respect to a given task criterion; and that a sensor-based system can become adaptive automatically reconfiguring itself to accommodate variations in the workspace. In general, the types of constraints considered in these systems are visibility constraints, field of view constraints (making sure the object is not clipped by the field of view of the camera), depth of field constraints (object is in focus), and pixel resolution of the object. They also look at radiometric constraints such as illuminability, dynamic range, and contrast. Since one of the primary concerns of automatic vision systems is to recognize an object or features of an object, a great deal of the work to date involves determining what are salient features of an object, and what views are appropriate to highlight those features (make sure they are illuminated properly or shown to the camera in silhouette). They describe 5 main systems: work done at SRI [Cowan87]; the VIO system [Niepold80]; the HEAVEN system [Sakane81]; the ICE system [Yi84]; and the MVP system [Tarabanis85]. Some methods use the calculus of variations to derive the camera position from images [Horn86]. Other methods have been used to position objects themselves for display [Kamada88]. In general, most of the systems formulate the problem in terms of constraints that need to be satisfied and finding solutions which satisfy those constraints. Several of the systems use a generate and test approach to the problem, while the MVP system using a global optimization solution. In addition, when the constraints are expressed analytically, a more efficient solution process can be used. The work presented here is on a similar level to the system presented in this thesis, yet the types of constraints required are somewhat

different and more limited.

In addition, reactive planning in robotics as explored by [Brooks86], and [Maes90, Maes91] can be exploited in complicated domains with moving objects where traditional path planning methods are not applicable. Reactive agents were a motivating force behind the development of the camera framework presented in this thesis. By allowing certain difficult parts of interaction to be supported by an agent style interface, the user is able to concentrate more on the task at hand.

3.3 Teleoperation

Closely related to robotics is teleoperation and supervisory control [Sheridan87, Sheridan88, Sheridan92]. Visual displays are of overriding importance in teleoperation and supervisory control because, “A fundamental issue in the design of the man-machine interface is the use of visual feedback. Visual feedback is normally the primary source of feedback information” [McKinnon91].Das [Das89] systematically compared some automatic view selection techniques in the context of a control a redundant telemanipulator. Four different sets of trials were performed to assess user performance. In the first, the user was allowed to select different views by flying the virtual camera around the workspace. In the second set, the virtual camera was fixed to the based of the telemanipulator, somewhat like viewing out of the cockpit of a plane to which the manipulator was attached. A third set fixed the virtual camera location to the side of the task. The fourth set of trials automatically selected a “best” view that found a viewpoint for the camera that provided an orthogonal projection of all the distances between the telemanipulator, two obstacles, and a goal. The “best” view place the camera at a point which was the intersection of 3 planes, each of which was a bisector of the line connecting the end-effector of the manipulator with the obstacles or the goal respectively. Performance was best when the user was allow to select between multiple views. Next base was the automatically selected view. The worst performance was using the out of the cockpit view. The best view algorithm can be thought of in the context of this thesis as optimizing the camera position subject to three constraints, maximize the angle of projection for each of the goal and obstacle objects. An important lesson taken from Das however, is that users need to have some sort of control over the selection of views to perform well.

3.4 Human factors & Human Computer Interaction

Extensive human factors testing has been done to determine the effects of different forms of visual displays on human perception and task performance. The view that a systematic approach begins with a task analysis [Brooks91, Berlyne67, Fleishman84, Miller63, McCormick76, Newell78, Whiteside85] is supported in this thesis. In fact, Brooks goes so far as to say the following:

> ...from the perspective taken here, developing good descriptions, particularly good taxonomy that adequately differentiates artifacts, is important in its own right because it is a useful, possibly necessary, precursor to appropriate formalism and, in turn, to technical theory [Brooks91].

Chapter 4 details the tasks analysis that led to the basic structure of the thesis and chapter 6 describes the way we can go from a basic task analysis to a prototype of an interface. Current theories in human computer interaction support the iterative nature of design for interfaces. If the interfaces are built on top of a consistent cognitive structure, they can be made to greatly enhance user understanding and facility [Bass92, Baeker87, Carroll87, Carroll88, Cotterman89, Landauer87, Norman87, Norman88, Norman90, Norman93, Schneiderman92, Zeltzer85, Zeltzer91, Zeltzer92]. In addition, with the benefit of a consistent underlying framework, different styles of interaction can be designed and supported including conversational interfaces [Bolt87, Foley87, Nickerson87, Negroponte89, Schmandt83], theatrical interfaces [Laurel86], direct manipulation [Hutchins86, Boies89, Schneiderman83], and visual programming languages [Cypher93, Haeberli88, Kass92]. This thesis has made use of many of the notions of these alternative interface styles, including an immersive environment with voice and gestural recognition for the Mission Planner and a visual programming environment for combining and sequencing camera primitives.

3.5 Human Perceptual Capabilities

Human perceptual issues also must be examined in any system that needs to present information effectively to an end-user. Cornsweet in particular provides an excellent introduc-

tion to human visual perception in [Cornsweet70]. Hochberg and Brooks present an extensive examination of human perception of motion pictures in [Hochberg87] which has been of particular use in this thesis.

Hochberg and Brooks identified three different theoretical mechanisms that might account for the observer's comprehension of change in camera position across temporal sequences of film. The first mechanism is closely tied to the perception of apparent motion of objects. This phenomena involves the discrete changes of the position of an object or objects between frames. The perception of apparent motion breaks down based on limits for the distance between the positions of the objects and the intertemporal spacing of the stimuli. These limits have been identified experimentally and can be used in part as a basis for the maximum camera movements per frame allowed in many of the demonstrated applications.

Another mechanism deals with overlapping cuts of a scene. This theory proposes that viewers integrate the successive views by extracting a transformation between the changes of position of familiar objects within the scene. This might explain one of the reasons that people often become disoriented and lost in the sparsely populated virtual environments. If no identifiable landmarks exist, then the perception of the direction of motion of the camera reduces to chance. Attempts have been made in this thesis to enrich the environments with identifiable objects.

The last mechanism for visual perception of camera position is based on the concept of a cognitive map. Cognitive maps form the basis of a style of architectural design expounded in [Lynch60] and [Passini92]. It is not immediately clear whether the cognitive map is symbolically represented or spatially represented, but in either case, viewers are able to build maps from successive views of an environment, and can use the map to stay oriented within the environment. One way to utilize cognitive maps is to enable explicit maps for the interfaces designed in this thesis. In addition, the maps can be dynamic maps which adjust to the user's position and orientation within the environment.

3.6 Cinematography

Art has often been an effective communication tool and can serve as a guideline to building effective interfaces. An extensive examination of the use of perspective in communication is discussed in [Kubovy88]. Even more appropriate to this thesis is presentation style as it has developed in the field of cinematography. Several books have been extremely useful for gaining an understanding of the film medium. Notably, Arijon [Arijon76] has a straightforward, deconstructivist style, with descriptions on filming any of a large number of situations. Some might consider his descriptions to be simplistic, but they are the perfect basis for deriving a large class of camera primitives. This class of primitives which I call projection constraints involve the placement of the camera based on the projection of an object onto the screen. These include issues of framing objects so that their relative sizes are appropriate, placing the camera so that the projected motion of objects on the frame is consistent across edits, and being able to control the projected gaze vectors of characters in the environment based on the placement of the camera. These constraints are described in greater detail in section 5.3. In addition to the work of Arijon, cogent explanations of cinematic techniques and style given in [Katz88, Katz92, Kawin92]; for photography [Cheshire94]; for editing [Reisz68, Thompson93]; and for cinematic theory [Nilsen61, Isenhour75, Burch81] have all been useful.

There have been some previous limited attempts at incorporating cinematic style in computer graphic systems including the excellent discussion concerning animation techniques by Lasseter [Lasseter87]. Previous work also includes techniques for special effects [Thalman86], the aforementioned automatic planning systems of [Karp90, Seligman91] and analysis [Potel76].

CHAPTER 4. TAXONOMY OF INTERACTIVE DOMAINS

4.1 The Problem Domain

The first requirement of the thesis is to generate a clear definition of what visual tasks a user might try to perform in a graphical environment, and what characteristics need to be associated with a camera to assist the user in accomplishing those tasks. I will enumerate a list of prototypical tasks, that will help drive the definition of an intelligent camera. This list is meant to be broadly representative of the kinds of visual tasks that users might wish to perform in a graphical environment. This is by no means a complete list of tasks but rather a list that will help generate ideas as to how an intelligent camera can aid a user. Also, solutions will not be proposed for all tasks, but rather a categorization of the tasks is attempted so that a systematic solution can be described. For each category, examples will be given, and a list of of characteristics for the camera control will be enumerated.

Except where stated otherwise, the user will not be changing the environment, but only acting as an observer. This restriction, while limiting, will help focus the analysis on the manipulation of the user's view and not on the means of interacting with objects in a environment. An overriding consideration in all these task domains is that the environment is perceived by the visual system of the operator and thus care must be taken so that the output of the system is well within human psychophysical abilities and expectations [Cornsweet70, Hochberg78].

This list in table 2 of interactive domains was arrived at through examining several papers [Adam93, Bishop92, Blanchard90, Blau92, Earnshaw91, Earnshaw93, Esposito93,

Fisher86, Greeenberg74, Zyda92, Bass92, Baeker87, Carroll87, Carroll88, Cotterman89, Landauer87, Norman87, Norman88, Norman90, Norman93, Schneiderman92, Zeltzer85, Zeltzer91, Zeltzer92, and others], and several brainstorming sessions with practitioners in the field. Different graphical applications were classified into one of four domains. This domains seem to encompass most of the different types of activities which people perform in interactive graphical environments.

4.2 Terminology

Word usage tends to be confusing when trying to formulate a taxonomy. One would like to use words that bring about instant understanding, but certain words are so overloaded that they might be misinterpreted. I use several terms and provide definitions for each of them. In general, I try to follow the formal dictionary definitions, but sometimes that is not possible since I could find no better word to describe what I mean. Briefly, here is a list of the terms for the taxonomy: environment, domain, application, application task, generic task.

The highest level of the hierarchy is referred to as a *domain*. The *domain* describes the basic endeavor that is being attempted. Within each of the domains are *applications*, and each of those *applications* is composed of specific application *tasks*. There are several generic *tasks* that are pertinent to many *applications* within many *domains*.

4.3 Taxonomy

To begin with, I broadly classify four primary domains in which most activities lie: exploration, planning, rehearsal, and control.

Table 2: Interactive Domains

Interactive Domains	Examples
Exploration	Scientific Visualization Architectural Visualization Database exploration Flight Simulators, MUDs
Planning	Mission Planning systems Surgical Planning systems Animation systems Film Previsualization
Rehearsal	Choreography tools Flight simulators Mission planning Surgical Rehearsal systems
Control	Teleoperation Modeling Surgery

4.3.1 Exploration

Explore, as defined in the American Heritage Dictionary, is to search into or range over for the purpose of discovery. In this area, I include such tasks as scientific visualization, medical visualization, and architectural visualization since they all involve examining some sort of spatial database. Control of the virtual camera allows the user to experience different parts of the spatial database. Exploration is not limited to visualization. Databases are starting to be expressed in spatial terms and techniques for moving through spatial databases are particularly important in this age of information overflow. Certain games (ranging from flight simulators to multi-user dungeons) allow the user to move through some alternate reality in an exploratory way.

Gregory Nielson, an extensive researcher in the field of scientific visualization, describes interactive scientific visualization in the following way:

> as related to those applications where the user interacts with the model and drives the simulation in hopes of "gaining new insight" or "creating a new design." The primary interface for this interaction is the visual images viewed by the user and the subsequent input based upon the user's perception and interpretation of those images. The emphasis here is on applications which involve physical models in three dimensional space [Nielson91].

Thus scientific visualization involves the end user gaining an understanding of the important information, events, and relationships implicit in high bandwidth, possibly multi-dimensional datasets. In scientific visualization, as well as medical visualization, and architectural visualization, the user must somehow achieve a correspondence between the information presented to him through the interface, and an internal representation of the spatial domain [Springmeyer92]. For some of these applications, there exist natural analogs for the information that is presented. For others, however, the information itself must be transformed and represented in a manner that can be understood by the user.

In medical visualization specifically, many feel that the imaging modalities of transmission and emission tomography, magnetic resonance imaging and ultrasound are revolutionizing medicine. Pernkopf [Pernkopf87] feels that "improved 3D visualization techniques are essential for the comprehension of complex spatial and, in some cases, temporal relationships between anatomical features within and across these imaging modalities."

In general, for these applications, the operator should be able to quickly *orient* himself in the environment, and *navigate* conveniently from one part of an environment to the other. Sometimes, the operator may be explicitly looking for a certain aspect of the environment, in which case the system is primarily used for *navigation* through the environment from one point to another. At other times, the user may be *wandering through* the environment with no particular destination in mind. Finally, the operator sometimes wishes to *examine* a certain aspect of the environment.

Some specific examples of applications in the exploratory domain include the following:
Large data set exploration: Many three-dimensional applications in scientific visualization

consist of the study of multidimensional physical phenomena. The scientist is free to fly within the simulation and therefore to focus interest on any part of the simulation, to study it in detail, or to allocate supercomputer time for a more precise simulation.

Architectural walkthrough: Systems such as these allow the user to explore buildings that are designed but not yet constructed, or buildings that no longer exist. An object of such a system is to visualize a building to permit the architect to prototype the building and to discuss with his client on the detailed desiderata for it. Specific tasks within an architectural walkthrough might be to examine the artificially constructed environment for emergency exit routes for obstructions; or to examine visibility paths from one point to another; or a human factors analysis of the environment could be performed.

Weather simulation: A simulation of a hurricane or a tornado involves the flow of air in 4 dimensions (space as well as time). The task would be to understand what circumstances lead to the formation of a hurricane by observing those air flows from different viewpoints and with different tools that might help analyze how the air flows change.

Some other examples include *molecular analysis, medical imaging,* and *exploration of data received from satellite pictures.*

In general, the visual requirements for performing exploratory tasks are related to moving through the environment, and being able to retrieve the spatial position of the virtual camera within the environment, and the relative positions between objects within the environment.

1. Change the viewpoint and direction of gaze in a fashion which makes sense to the user and is not disorienting or distracting. To do this, the camera must obey some restrictions discussed in section 3.5.
2. Allow the ability to specify separate points in the environment for convenient navigation between them. By convenient, I mean to limit the amount of computational or cognitive effort that the user needs to make.
3. Allow quick recovery of information about current position and orientation of the user. This is particularly crucial because of the tendency for users to get lost and disoriented in a virtual environment [McGovern91].

4. Allow efficient recovery of information about the relative positions and orientations of objects within the environment.
5. Constrain the movements of the user in a fashion that makes sense for the given domain (don't walk through walls in an architectural domain, keep certain objects in view in a scientific visualization domain). This is related to the first item because movement through obstacles can be very confusing to an observer. This involves collision detection and to a certain extent, the simulation of a camera as a physical object.

For a detailed analysis of one specific application in the exploration domain, see the description of the Virtual Museum in chapter 6.

4.3.2 Planning

"To plan" is defined as "to formulate a scheme or program for the accomplishment or attainment of something." In this area I include such diverse applications as surgical planning and simulation; mission planning & rehearsal; and film previsualization.

A planning task might consist of figuring out how to manipulate some objects within an environment, or might consist of specifying the motion of the camera itself for presenting the results to a non-interactive observer.

In describing one such task for orbital planning, Don Eyles of Draper Laboratories says the following:

> What is necessary is the ability to plan and then to monitor spatial operations which may be hard to see and hard to visualize. For this case, the ability to assume a God's-eye view and follow the orbits leading to rendezvous, to fly alongside in a phantom chase plane, to take the vantage point of an imaginary window in your own spacecraft, or the viewpoint of another, perhaps unmanned satellite, may prove to be useful. [Eyles91]

Example:

Animation system: An animation system permits change of view both to assist in the manipulation of objects and change of viewpoint for dramatic and narrative reasons. The resultant motion of the camera must be continuous and certain stylistic conventions, pri-

marily from cinematography, should be followed in order to make a comprehensible presentation.

Surgical planning system: In plastic surgery, the surgeon might wish to see the results of certain actions before performing them. The surgeon must be able to move the viewpoint both to *perform* the action and to *explore* the results.

While this domain shares many of the visual requirements of the previous domain, there are some differences. In the exploratory domain, it was assumed that the interactive user was exploring the domain for his or her own enlightenment. In the planning domain, the interactive user may be using the system to prepare a presentation for others. For this reason, camera motion needs to be smooth and purposeful [Thompson94]. In addition, more emphasis must be placed on the ability to position the camera based on the projected positions of objects onto the frame.

General visual requirements:

1. Change the viewpoint and direction of gaze in a fashion which makes sense to the user. This is the same as item 1 from the exploratory domain.
2. Allow quick recovery of information about current position and orientation of the user. This is the same as item 3 from the exploratory domain.
3. Allow efficient recovery of information about the relative positions and orientations of objects within the environment. This is the same as item 4 from the exploratory domain.
4. Constrain the movements of the virtual user in a fashion that makes sense for the given domain. This might require that the virtual camera behaves as if it has physical mass and moves dynamically, or it might involve collision detection with objects in the graphical environment. This is the same as item 5 from the exploratory domain.
5. Constrain the position, and perhaps the motion of the screenspace projection of an object or the relative projected distances between objects.
6. Allow a way of continuously specifying the motion of the camera between certain task based constraints.
7. Be able to incorporate rules for comprehensible presentations (cinematic conventions).

4.3.3 Rehearsal

"To rehearse" is defined as to perfect or cause to be perfect by repetition. Although not strictly considered rehearsal, I consider systems for instruction also in this area. As such, the best example of this type of area is a flight simulator which let's the user practice under a wide variety of conditions.

The visual task here is to achieve a *situational awareness* of objects in a dynamic environment. This may or may not involve varying levels of interaction with the objects in the environment. A good supervisory system would allow the operator to make predictions and decisions about events and behaviors of objects within the environment, and perhaps learn from the events that have already occurred.

Example:
Command and Control System (C&C): For instance, air traffic control. The operator should be able to view the interactions of many objects at whatever viewpoint is appropriate for the individual task. If it desired to detect and avoid collisions, attention can be brought to areas where potential collisions will arise. If dangerous or desirable situations arise within the domain, the system should indicate those situations to the user.

The general visual requirements of primitives are to assist the user in comprehending the spatial aspects of a time varying environment. To do this, the user should be able specify objects of interest and include them within the view, perhaps at certain locations in the frame. The virtual camera should be able to depict the scene from the viewpoint of any object in any direction.

General visual requirements:

1. Change the viewpoint and direction of gaze in a fashion which makes sense to the user. This is the same as item 1 from the exploratory domain.
2. Allow quick recovery of information about current position and orientation of the user. This is same as item 3 from the exploratory domain.
3. Allow efficient recovery of information about the relative positions and orien-

tations of objects within the environment. This is the same as item 4 from the exploratory domain.

4. Constrain the orientation of the world so that it makes appropriate sense (absolute up vector, or an up-vector based on the position of an object in the environment).

4.3.4 Control

By control, I mean to affect the movement or appearance of an object or group of objects. In this area, I include teleoperation (manipulating something at a distance); surgical assistance; CAD modelling, or animation production. I place animation in this area since the figures and the environment must be modeled and manipulated. However I consider the task of choreographing motion of the camera and objects in the environment to be a planning task.

Based on their experiences in the control of the Shuttle Remote Manipulator System, McKinnon and Kruk [McKinnon91] examine multi-axis control of a telemanipulator. They feel that,

> A fundamental issue in the design of the man-machine interface is the use of visual feedback. Visual feedback is normally the primary source of feedback information. Ideally, an unobstructed direct view of the workspace should be provided, but even if this is available the question arises as to the ideal view point.

The requirements of the visual interface is to orient the viewpoint in the best way to accomplish a given task. Some work in the field of telerobotics has already been performed that examines this problem [Philips92, Bejczy81]. One of the basic notions for this is for the operator to understand intuitively the correspondence between the axes of the view and the axes of the controls [McKinnon91]. In addition, the proper choice of perspective parameters and viewing conditions can greatly affect the mean-completion-time of pick and place experiments [Kim91].

Examples:
surgical simulation. The task might be a simulation (or actual performance) of endoscopic surgery where the surgeon controls the movements of an endoscope through a narrow inci-

sion in the body. Here it is crucial that the surgeon has some idea of the position of the instrument in the body.

telepresence/telerobotics: Telepresence aims to simulate the presence of an operator in a remote environment to supervise the functioning of the remote platform and perform tasks controlling remote robots. In supervisory control modes, a VR interface provides the operator with multiple viewpoints on the remote task environment in a multi-modal display format that can easily be reconfigured according to changing task priorities. To perform remote operations that cannot be performed autonomously by robots, the operator can switch to interactive control. In this telepresence mode, he is given sufficient quantity and quality of sensory feedback to approximate actual presence at the remote site.

Animation system. The view must be modified appropriately in order for an object to be modeled, or for its motion through space to be manipulated efficiently.

In general, the visual requirements are concerned with maintaining the visibility of a desired object to be manipulated and to making sure that the axes of control align with the visual axes of the resultant frame. Additional information or views may also be useful to helping the user accomplish the task.

1. Change the viewpoint and direction of gaze in a fashion which makes sense to the user. This is the same as item 1 from the exploratory domain.
2. Track the motion of a specified object.
3. Make sure a target object is visible.
4. Provide the user with a correspondence between the view's axes and the axes of the controls of the manipulation device.
5. Provide supplementary information that can aid in task completion. This starts to bridge the gap between a strictly graphic environment. Part specifications and status displays might be shown to the user while performing a task or specific instructions may be pulled up step by step.

4.3.5 Development cycle

These areas all overlap; for instance a good remote surgical system might include facilities

for exploring a medical database, planning a procedure, practicing the procedure and finally for performing the procedure. One aspect that each of the areas necessarily must deal with is presentation. The user must constantly be presented with intelligible information from the system.

It is interesting to note that a typical development cycle for processes might move from one area to the next area in a series of steps.The choice of camera control in each domain might be different, but choices in one domain might affect controls in another domain. For instance, it might be desirable to have some sort of correspondance between the method used during rehearsal and control. I will again use computer assisted surgery as an example (see figure 3). One of the first steps might be to take an extensive series of computer tomography data and *explore* this data to locate pertinent structures in the computer constructed model. If the general goal is the treatment of a cancerous tumor, this first step might involve classification of what is part of the tumor, what is not, adjacent organs that must be avoided, etc. After this first exploratory stage, the next stage would involve *planning* a treatment. The treatment might be a procedure for the removal of the tumor or radiotherapy which might involve orienting beams of radiation to intersect at the tumor. If extensive manipulation is eventually required, the planning stage might move into a *rehearsal* stage, where the surgeon could practice manipulation with devices that give a variety of forms of feedback, perhaps including haptic and sound as well as visual feedback. After the rehearsal stage, the surgeon may then wish to actually perform the surgery, perhaps using a computer assisted system, or perhaps manually. This is the *control* stage. Finally, the process can repeat itself when the surgeon tries to assess the success of the operation (exploratory), make corrections to the procedure (planning) and perform the revised procedure (control).

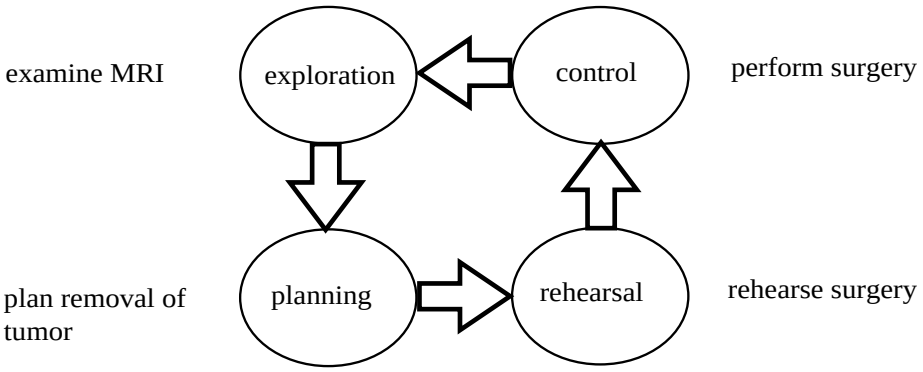


Figure 3: Surgical Simulation Process Cycle

4.4 Interaction

One important aspect of graphical environments is the level of interaction that is being supported. At one end of the spectrum is direct interaction in which the user continuously controls some aspect of the camera. This might be as simple as using a button to control the zoom of the camera, or it might mean tying the movements of the head and body of the user to controlling the position and orientation of the virtual camera within the environment. When this is achieved with very little lag and a head mounted display is used, the user may sometimes feel as if they were immersed inside the graphical environment. This phenomenon is known to the popular press as *virtual reality*, though since some consider the words virtual and reality an oxymoron, I will use the more rigorous term – *virtual environment*. Virtual environments also include means for establishing other sensory cues including binaural audio, and haptic feedback (force and tactile). If the environment that the user is interfacing with is not a simulation, but rather a real environment at a remote location, the term *telepresence* is used.

At the other end of the spectrum in interaction is nearly no interaction at all or almost no interaction. This could mean that the user of the system is viewing the environment in a prespecified or automatically generated fashion, perhaps by guidelines specified by the user or by another. If the behavior of the camera is not predetermined and is being changed automatically by the computer, then the camera is said to be behaving autonomously. One type of system that might contain autonomous camera control is an automatic presentation

system.

Table 3: Frequency of Interaction

Frequency of Interaction	Examples
Continuous	head mount, joystick control
Intermittent	Mission planner
Autonomous	Automatic Filming Agent

Yet another factor that is often considered in interactive environments is how the user is interacting with a large number of degrees of freedom in the environment. For a single camera in most graphical environments, there are seven degrees of freedom (three spatial, three orientation, and one field of view). These can be controlled by directly specifying one or them, or several of them might be derived from some user intention. If the user issues a sufficiently high level command, all the degrees of freedom for the camera might be determined.

Table 4: Style of Interaction

Style of Interaction	Examples
Direct Control of DOF's	Head mount, joystick
Mapped Control	Selecting with mouse
Symbolic high level specification	Voice input, gesture

4.4.1 Summary

The visual requirements for camera primitives is collected in the following list. Types of camera primitives (discussed in section 5.11) which can be combined to implement these

visual requirements are given in parenthesis and itemized in the subsequent list.

1. Always make sure that changes in the view make sense to the user (a,b,g).
2. The user should, in general, recover information about his position within the environment (f).
3. The user should be able to recover the relative positions of different objects within the environment, and the camera should be placed in positions where that information is presented (c).
4. Certain positions of the camera will allow completion of the task more conveniently (a,b,c,e).
5. In many domains, there are restricted positions where the camera should not travel, whether movement through walls is prevented, or restrictions to within a single room, or maintaining the visibility of certain objects (d).
6. For some domains, convenient movement through the environment is important. By convenient, I mean with little cognitive or computational effort on behalf of the user (d).
7. Certain rules and conventions should be followed when presenting the information to external viewers (g)
8. Different styles of interaction must be supported, including continuous, intermittent, and autonomous (or supervisory) control. (h).
9. Different levels of control should be provided with access down to individual degrees of freedom, on up to high level interpretations of commands. (h).

Briefly, those constraints in parenthesis (which will be discussed more extensively in section 5.11) are as follows:

a) Direct constraints on one or more DOFs of the camera.
b) Constraints on the derivatives of one or more DOFs of the camera.
c) Constraints on the screenspace projection of one or more objects from a camera.
d) Constraints on movement through the environment.
e) Constraints based on the visibility of an object within the environment.
f) Constraints based on a view of another camera.
g) Constraints based on stylistic and cinematic rules.
h) The entire framework provides for the straightforward combination and reusability of different constraints.

4.5 Tasks demonstrated in this thesis

4.5.1 Virtual Museum

The Virtual Museum is a spatial database containing works of art, either sculptures or pictures that are arranged in several rooms. It is an example of a task primarily in the *exploratory* domain. Various different levels of interaction are shown in the virtual museum including direct control of the camera parameters, constrained movement based on a single object, and nearly autonomous movement based on a guided tour calculation.

4.5.2 Mission Planner

As an example for the *rehearsal* domain, we show the mission planning system. This system allows the user to experiment with different lines of sight in order to understand a plan for flying a military mission. Again, various levels of control are shown. Simple, direct interaction, constrained interaction in a very similar fashion to the football game, and finally, limited autonomy.

4.5.3 Conversation

Filming a conversation via an autonomous agent is a simple demonstration of the ways in which the primitives described in this thesis can be combined and formed into behaviors. It is an example of task in the *planning* domain.

4.5.4 Virtual Football Game

Another *planning* task, with a somewhat different interface than the conversation is the virtual football game. This environment differs significantly from the virtual museum in that the museum was primarily a static environment that was large enough to require exploration. The virtual football game is a dynamic environment where the user is trying to watch the motion of several characters at once. In the virtual football game, we examine direct control of the camera through several simple widgets. We examine limited autonomy in using the system as a director's assistant. And finally we examine high level interaction in the form of the automatic generation of a sequence.

4.5.5 Visibility assistant

Finally we look at a simple experiment in the control domain. The task in this example is to perform some sort of manipulation on an object in the graphical environment. The visibility assistant moves the viewpoint around occluding objects to make sure that the object is always visible to the user.

CHAPTER 5. CAMERA PRIMITIVES

The following section addresses the central notion of camera control: that of camera primitives. Camera primitives are selected based on task level goals in the different domains discussed in the previous chapter. By specifying these goals in terms of constraints, the primitives can be expressed in a domain independent manner allowing them to be combined, reused, and sequenced as appropriate for the task at hand.

Camera primitives can be looked at both in terms of the task level goals they represent, and the formal, mathematical machinery that is involved in their specification and satisfaction. The first part of this chapter examines a variety of domains from which camera primitives can be derived. In the second part of this chapter, I examine formally the mathematical derivation of the constraint framework at the core of this thesis. I start with a discussion of the view transformation since it is central to the way in which a virtual camera transforms the environment into the image that the user sees, and then give specifications for constraints that can achieve the goals outlined in the first part. I also broadly classify the constraints into different types based on their mathematical structure.

This chapter does not discuss any interfaces for constructing or combining primitives. That is discussed in chapter 6.

5.1 Procedural Representation

A slight digression is in order before a discussion of camera primitives as constraints can take place. Initial attempts at specifying camera primitives began with the CINEMA system [Drucker92]. In this system, camera commands were embedded in a procedural, interpreted language which had built in commands for mathematical functions, and database

inquiries for object positions, visibility, and events.

5.1.1 Reusability of camera behaviors

The CINEMA system allowed for powerful programmatic specification of camera movements. High level commands from cinematography could be written in terms of lower level controls on the degrees of freedom and if the commands were designed properly, they could be reused. For example, the classic shot used by Alfred Hitchcock in the movie *Vertigo* could be encoded by specifying that the camera moved backwards as the camera zoomed in, maintaining the same framing of the character. Given a simple procedural definition, called vertigo_shot(character), this procedure can be added to a number of other behaviors which the director can call upon as needed. Other procedures were written that could take advantage of 6 degree of freedom input devices to help position the camera relative to objects within the environment.

```
proc vertigo_shot(obj, rate, no_frames} {
     // get the angle subtend by the object
     angle := get_angle_height(obj);
     // get the camera's field of view
     fov := cam_fov();
     // compute the percentage of the fov
     // which the object subtends
     percent := angle/fov;
     for (i=0;i<no_frames; i++) {
            // truck in the specified direction
            //at the specified rate
            cam_truck(rate);
            // set the field of view so that the
            // object subtends the same percentage
            // as before
            frame_it(obj, percent);
            render();
     }
}
```

Figure 4: Pseudocode for vertigo shot

5.1.2 Problems with the procedural representation

However, one problem with the CINEMA system was the difficulty in writing procedures

in a way that they could be combined with other procedures. This was a significant drawback since the entire purpose of the system was to provide the user with tools for simply achieving desired camera movements and if the user needed to rewrite a special purpose procedure each time a new movement was needed then the user had to be a skilled programmer in addition to a cinematic director. Related to this problem, was that it was difficult to write single procedures that were general enough. More often than not, constants needed to be used in a procedure that were only appropriate for a certain character and when applied to another character the procedure had to be rewritten. A wide enough base of initial procedures did make it possible for convenient rewrites for new procedures, but still, programming was required to use the system.

The successes and the problems of the CINEMA system led to the idea of controlling the camera on the basis of constraint satisfaction. Constraints are essentially an encapsulation of a user's intentions. They can be combined and generalized more conveniently than procedural programming, and have desirable behavior even if all the constraints can't be satisfied at the same time. The following section will describe how useful constraints were derived from a variety of disciplines.

5.2 Deriving Primitives as Constraints

Camera primitives can be derived from a number of disciplines. These disciplines tend to be distinct from the domains discussed in chapter 4 because they do not necessarily require a computer graphical environment but rather involve communication of visual concepts or useful algorithmic techniques from related fields. Some of the disciplines from which to derive camera primitives are as follows:

- Cinematography

There are a wealth of conventions, rules, and suggestions for the placement of cameras for filming various situations. These include framing conventions; editing rules; continuity rules, etc. By formalizing the widely circumstantial body of literature these conventions can be used in other domains. In general I call the types of primitives derived from cinematography *projective* constraints since they involve projecting objects from world space

into a framed screen space. These projective constraints are extremely useful since they find the position and orientation of the camera based on the desired position of objects within the frame. Only two works in the computer graphics literature touch upon finding camera parameters based on the screen space projections of objects. The first of these is Blinn's formulations [Blinn88] for creating planet fly-bys which are discussed in section 5.8.2. Blinn's work is far less general and is primarily suited to the specific task of a foreground and background object on the screen. The second work is by Gleicher and Witkin [Gleicher92] discussed in section 5.11.3. This work does not find camera parameters, but allows the system to update the camera based on screen space projections of objects once a desired set of camera parameters has already been found. The work presented in this thesis on projection constraints is general purpose and useful for finding camera parameters as opposed to just maintaining them.

- Task performance concerns

Naturally, task performance is extremely situation dependent. In general, the ones I mean in this category tend to be concerned with letting the user maintain the visibility of certain items of interest; or letting the viewer maintain context based on the orientation of oneself and the position of an object of interest in relation to other objects within the environment.These are constraints that let the user achieve a certain task which is often separate from controlling the camera itself. In general, the primitives derived from this category are *visibility* constraints, and constraints on the maximum change of any of the camera parameters.

- Physical limitations for cameras

These constraints are based on dynamic simulation for the camera and camera-related machinery (dollies, cranes, arms, etc.). If one considers these, the system could be made appropriate for preplanning the filming of actual situations or controlling real life robotic cameras. These constraints also include issues such as collision detection between the camera and objects in environment and collision-free *path planning* through the environment.

• Human Factors

There are certain basic limits for the human system to be able to comprehend input from the visual system. These limits tend to define preferred numbers of frames per second for the graphical environment and maximum angular movement rates for the camera. Many human factors problems in visual displays are due to equipment limitations, such as the limited field of view of many head mounted displays (HMD) or slow tracking of head movements in HMDs. However, care can be taken to constrain motions of the camera within the graphical environment so as not to produce images which violate some basic human factors measurements. The basic constraints derived from this domain are limits on the maximum changes of any of the camera parameters, and agreement between motions of the head and changes in the visual displays.

• Interface Design Principles

Since the framework that is described in this thesis is meant to serve as the underlying mechanism on top of which a variety of different interfaces is placed, special effort is made to make sure that effective interfaces can be built on top of the framework. However, in depth user interface design/testing/verification will not be performed. (See chapter 7 for a more thorough evaluation of the interfaces.)

5.3 Cinematic Constraints

One of the easiest sources of cinematic constraints are from a number of books intended for beginning practitioners in the field of film-making. This thesis uses several of those books as a reference for constructing cinematic primitives, notably *Grammar of the Edit*, *Grammar of the Film Language*, and *Shot by Shot* [Arijon76, Katz88, Katz92].

Roy Thompson [Thompson94] proposes a simple categorization of camera shots based on four elements which either may or may not change during the duration of the shot. These elements are the lens (zooming), the camera (panning, tilting, rolling), the mounting, (trucking, dollying, craning), and the subject. In his basic framework there are three types

of shots: simple shots, complex shots, and developing shots. A simple shot contains no movements of lens, camera, or mount, but can contain simple movement of the subject.

For a single person there are only a few kinds of simple shots made up of the following: extreme close-up, big close-up, close-up, medium close-up, medium long shot, long shot, very long shot, and extreme long shot. Pictured below are these shots along with the constraints and minimization functions that can be used to achieve the primitive using the constrained optimization framework described in detail in section 5.3. Briefly, the functions that are listed are the following: TC(obj) retrieves the world space coordinate of the top-center of the structure; BC(obj) retrieves the world space coordinate of the bottom center of the structure; Gaze(obj) returns a standard orientation vector for an object, Vec(a,b) returns a vector between a and b; and P(a) returns the projection of the world space coordinate onto a normalized screen space from {-1,1} in both the horizontal and the vertical directions.The primitive constraints can be chosen from a palette and modified with a text editor, encapsulated as the behaviors of an agent (section 6.3), or combined using a visual programming “drag and drop” paradigm (section 6.4).

Figure 5: Extreme close up
Usually a detail of the face or another object. Usually fills most of the frame.

MINIMIZATION FUNCTIONS

$$\left\| P\left(TC(nose)\right) - \{0, 0.9\} \right\|$$

$$\left\| P\left(BC(nose)\right) - \{0, -0.9\} \right\|$$

$$\left((Gaze(joe) \bullet vn) + 1 \right)^2$$

$$(Vec(vp, joe) \bullet vn) > 0$$

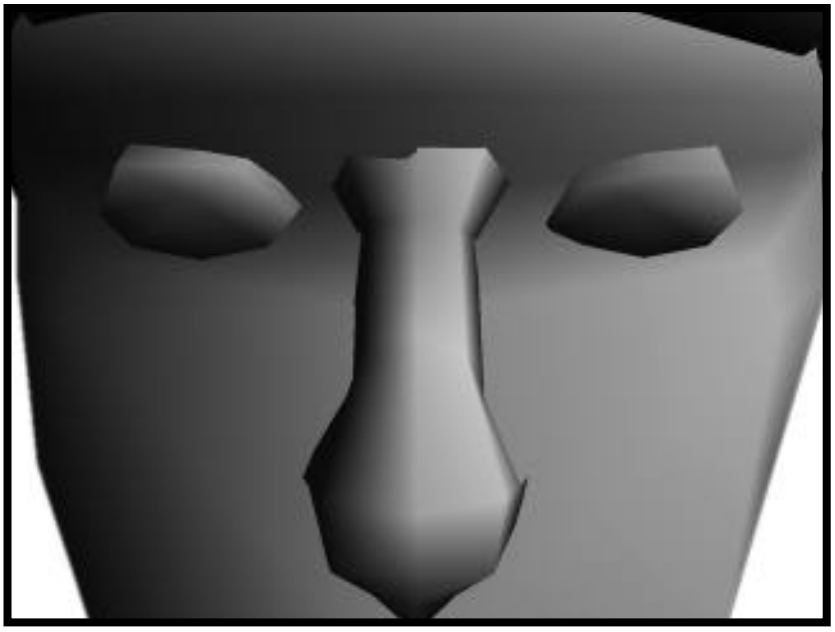


Figure 6: Big close up

Composed to show entire face but does not include the chin line or the top of the head.

MINIMIZATION FUNCTIONS

$$\left\| P\,(TC\,(nose)) - \{0, 0.3\} \right\|$$

$$\left\| P\,(BC\,(nose)) - \{0, -1.1\} \right\|$$

$$((Gaze\,(joe) \bullet vn) + 1)^2$$

$$(Vec\,(vp, joe) \bullet vn) > 0$$

Figure 7: Close up

Composed below the chin and may include the shoulders, but often not the top of the head.

MINIMIZATION FUNCTIONS

$$\left\| P\,(TC\,(head)) - \{0, 1.2\} \right\|$$

$$\left\| P\,(BC\,(neck)) - \{0, -0.8\} \right\|$$

$$((Gaze\,(joe) \bullet vn) + 1)^2$$

$$(Vec\,(vp, joe) \bullet vn) > 0$$

Figure 8: Medium close up

Composed with adequate headroom and framed above the elbow and below the armpit.

MINIMIZATION FUNCTIONS

$$\left\| P_{(TC(head))} - \{0, 0.7\} \right\|$$

$$\left\| P_{(BC(armpits))} - \{0, -0.9\} \right\|$$

$$((Gaze(joe) \bullet vn) + 1)^2$$

$$(Vec(vp, joe) \bullet vn) > 0$$

Figure 9: Med. close3/4

In the three-quarter profile version, the eye which is furthest from the camera should be approximately at the vertical center, allowing for "looking room."

MINIMIZATION FUNCTIONS

$$\left\| P_{(TC(Leye))} - \{0, 0.3\} \right\|$$

$$\left\| P_{(BC(armpits))} - \{0, -0.9\} \right\|$$

$$\left((Gaze(joe) \bullet vn) + 1 - \frac{\sqrt{3}}{2} \right)^2$$

$$(Vec(vp, joe) \bullet vn) > 0$$

Figure 10: Medium shot

Shot composed from subject's waist upwards, never above the waist because the edge of frame might be at same level as the elbow which would be visually confusing.

MINIMIZATION FUNCTIONS

$$\left\| P\,(TC\,(head)) - \{0, 0.7\} \right\|$$

$$\left\| P\,(BC\,(waist)) - \{0, -0.9\} \right\|$$

$$((Gaze\,(joe) \bullet vn) + 1)^2$$

$$(Vec\,(vp, joe) \bullet vn) > 0$$

Figure 11: MediumLg shot

Shot usually framed slightly above or slightly below the knee.

MINIMIZATION FUNCTIONS

$$\left\| P\,(TC\,(head)) - \{0, 0.8\} \right\|$$

$$\left\| P\,(BC\,(knees)) - \{0, -0.9\} \right\|$$

$$((Gaze\,(joe) \bullet vn) + 1)^2$$

$$(Vec\,(vp, joe) \bullet vn) > 0$$

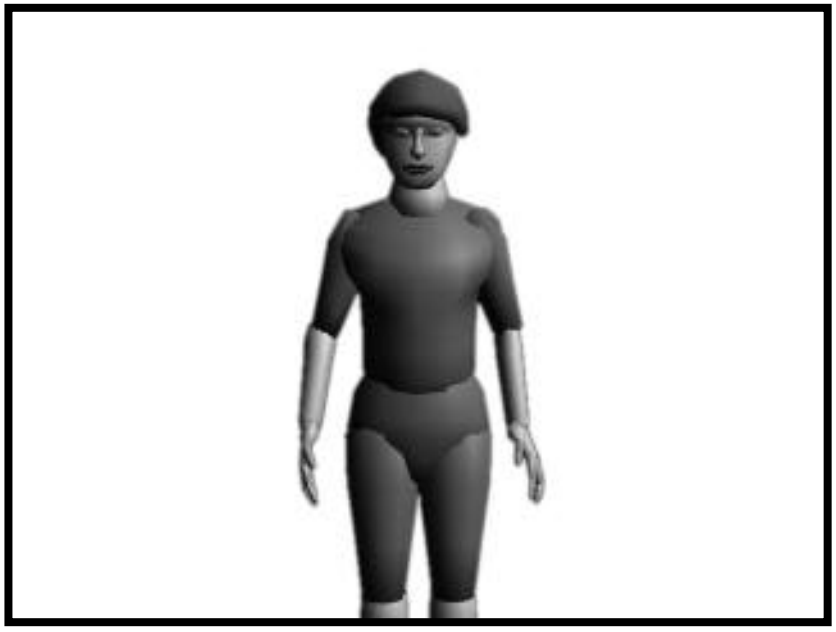


Figure 12: Long shot

Comprises the entire body and is framed below the feet and above the head with considerable headroom. Often used as an introductory shot since figures are identifiable and so is a great deal of of the scene.

MINIMIZATION FUNCTIONS

$$\left\| P\left(TC\left(head\right)\right) - \{0, 0.8\} \right\|$$

$$\left\| P\left(BC\left(feet\right)\right) - \{0, -0.8\} \right\|$$

$$\left(\left(Gaze\left(joe\right) \bullet vn\right) + 1\right)^2$$

$$\left(Vec\left(vp, joe\right) \bullet vn\right) > 0$$

Figure 13: Very long shot

Widest shot where figure is still recognizable (this is not determined automatically). Care must be taken for figure position (frame right, left, top, or bottom) for matching across edits.

MINIMIZATION FUNCTIONS

$$\left\| P\left(TC\left(head\right)\right) - \{0, 0.3\} \right\|$$

$$\left\| P\left(BC\left(feet\right)\right) - \{0, -0.3\} \right\|$$

$$\left(\left(Gaze\left(joe\right) \bullet vn\right) + 1\right)^2$$

$$\left(Vec\left(vp, joe\right) \bullet vn\right) > 0$$

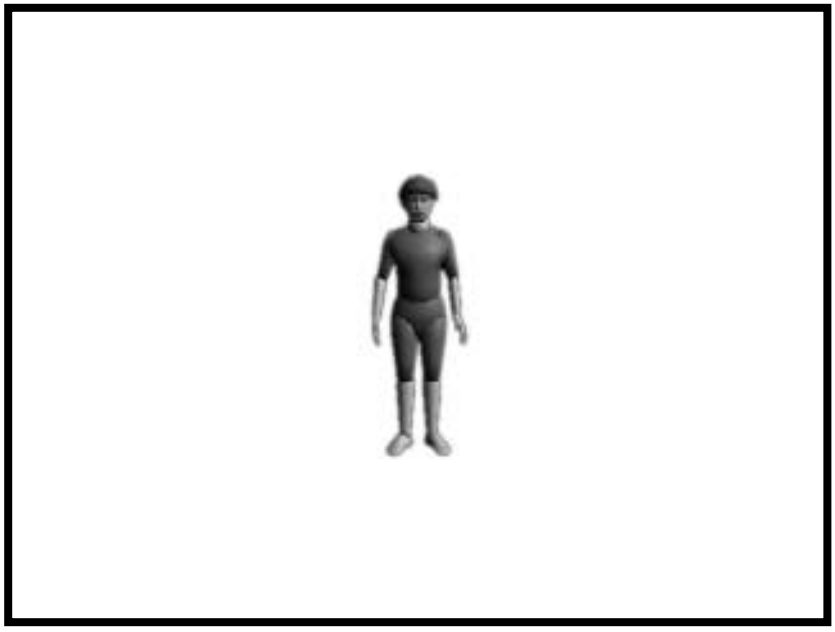


Figure 14: Extreme long
Also known as wide angle or wide shot. Figure is so small as to be unrecognizable (not determined automatically), but gives idea of geography and background.

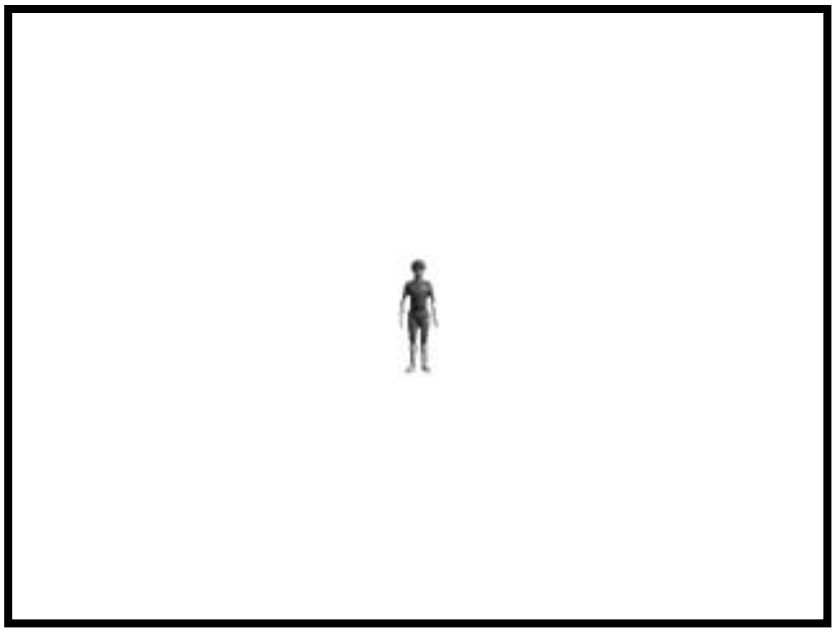
MINIMIZATION FUNCTIONS

$$\left\| P\,(TC\,(head)) - \{0, 0.2\} \right\|$$

$$\left\| P\,(BC\,(feet)) - \{0, -0.2\} \right\|$$

$$((Gaze\,(joe) \bullet vn) + 1)^2$$

$$(Vec\,(vp, joe) \bullet vn) > 0$$



For two subjects there are commonly the following kinds of shots: the two shot, and over the shoulder shots.

Figure 15: Two shot
This framing is a medium 2-shot. Usually characters are framed at the 1/3 and 2/3's lines on the screen.

MINIMIZATION FUNCTIONS

$$\left\| P\,(TC\,(head1)) - \{0.16, 0.8\} \right\|$$

$$\left\| P\,(TC\,(waist1)) - \{0.16, -0.8\} \right\|$$

$$\left\| P\,(TC\,(head2)) - \{-0.16, 0.8\} \right\|$$

$$\left\| P\,(TC\,(waist2)) - \{0.16, -0.8\} \right\|$$

$$(Gaze\,(joe) \bullet vn)^2$$

$$(Vec\,(vp, joe) \bullet vn) > 0$$

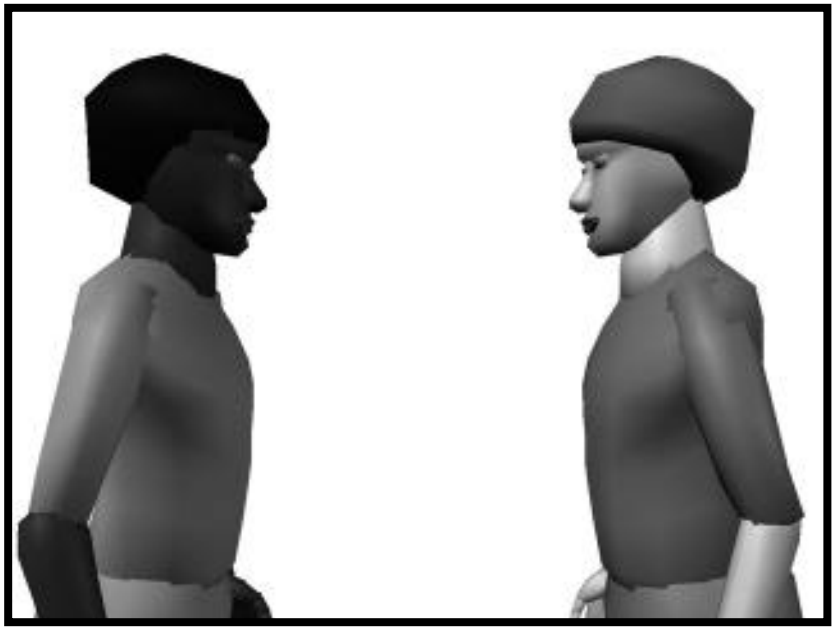


Figure 16: Over shoulder

Framing is based on emphasizing the person facing the camera. The person facing away from the camera has only part of his shoulder, neck, or head shown.

MINIMIZATION FUNCTIONS

$$\left\| P\,(TC\,(head1)) - \{0.16, 0.0\} \right\|$$

$$\left\| P\,(TC\,(head2)) - \{-0.16, 0.0\} \right\|$$

$$((Gaze\,(dave) \bullet vn) + 1)^2$$

$$(Vec\,(vp, joe) \bullet vn) > 0$$

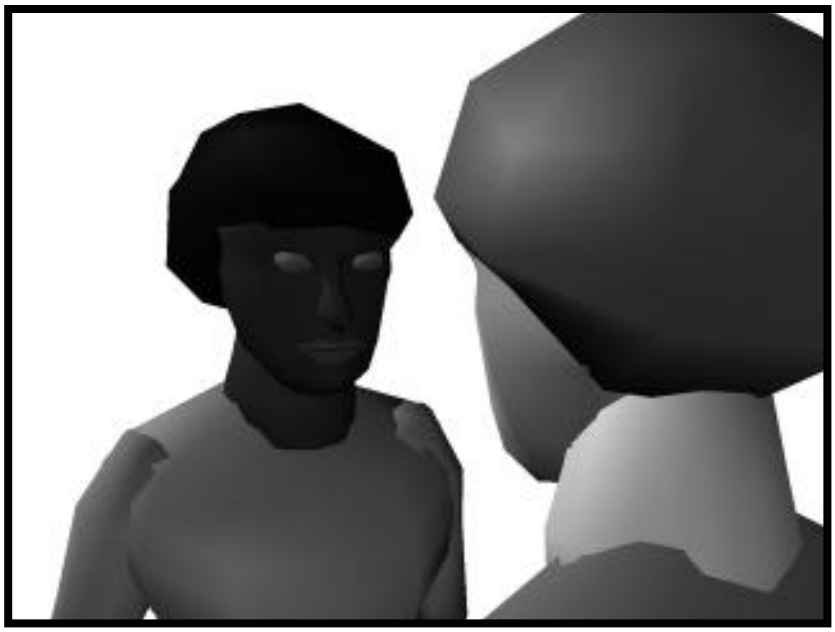


Figure 17: Over shoulder2

When filming a conversation, make sure that the positions of the characters stay on the same sides of the screens across cuts.

MINIMIZATION FUNCTIONS

$$\left\| P\,(TC\,(head1)) - \{0.16, 0.0\} \right\|$$

$$\left\| P\,(TC\,(head2)) - \{-0.16, 0.0\} \right\|$$

$$(Gaze\,(joe) \bullet vn) + 1$$

$$(Vec\,(vp, joe) \bullet vn) > 0$$

In addition to simple shots, Thompson defines two other kinds of shots: complex shots and developing shots. The complex shot may contain a lens movement, a camera movement, or simple subject movement, but no mounting movement. The complex shot should have a

static start and a static end and if the action or subject movement were frozen at any single point, then the resulting picture (frame) would resemble a simple shot. This is equivalent to specifying that a constraint is being satisfied throughout the duration of the complex shot. The developing shot can include movement of any or all of the 4 elements (lens, camera, mounting, and subject). Developing shots can be thought of as an interpolation between several simple shots perhaps with some additional constraints such as obstacle avoidance and visibility detection.

In addition to framing during a shot, editing between shots warrants some amount of discussion. According to Thompson, each edit should have a good reason for it based on including as many elements from the following list as possible:

- motivation
- information
- sound
- composition
- camera angle
- continuity

Motivation and information are regarded to be “high-level” issues and are considered to be out of the scope of this thesis. Sound during edits does not concern camera control. Single frame composition was just discussed in the previous section, and some generic rules exist for what kinds of framing can be combined via cuts while making sense to a viewer. For instance, when filming a conversation between three people, it usually does not make sense to have two people in the frame and cut to another frame with the other person in the frame without having the first person in the frame also.

According to Thompson, the camera angle is one of the most important elements of an edit. One principle is to make sure that each cut is from a different camera angle but never from more than 180 degrees (often less than 45 degrees if the same subject is being shot on both sides of the edit). Crossing the 180 degree line causes problems in continuity. Figures on either side of the cut will seem to be instantly facing the opposite direction than they were before. Figures that are in motion will suddenly change the direction of apparent

motion. Constraints can be used to require the projection of vectors of gaze or of motion to be approximately matched from cut to cut.

5.4 Task completion constraints

The constraints described in this section deal with positioning the camera in order to aid in task completion for object identification or manipulation. The constraints have been derived from a number of fields of study including earlier work in computer graphics, tele-operation and robotics. The primary examples are visibility constraints, alignment of manipulator control axes with the visual display, and positioning the camera based on the best view in order to identify an object.

5.4.1 Object Visibility

Several strategies can be devised to maintain the visibility of an object.The algorithms developed for this thesis are compatible with the constrained optimization framework allowing object visibility constraints to be combined with other constraints such as path planning and projection constraints. This work is in part based on the strategies suggested by [Philips92; Seligman91; Karp90].

5.4.2 Object manipulability

When manipulating objects with 2D manipulators, certain views are often better then others. For instance, there is often no way of conveniently mapping the motion of a user's mouse presses on the screen with a translation of the object in the same direction as the viewing normal. Also if motions of a manipulator move an object in a different direction than the corresponding one depicted on the screen, users often can not perform tasks well. These are constraints suggested by [Philips92] and [McCormick91].

5.5 Object appearance

A number of constraints can be formulated in terms of finding an ideal view for a particular object. This view usually implies that the object's projection must fill a certain amount of the viewport (a projective constraint). It also implies that the projection should provide as much geometric information as possible about the object [Kamada88]. One way to do

this is to take the basic visibility constraints and maximize the visibility of a number of preselected faces of an object. Attempts should also be made to minimize distortions of extreme linear projections (the field of view should not become too large).

5.6 Physical Limitations

In general, physical limitations come about from trying to simulate the motions of a real camera. One reason to do so, is to design a system to help previsualize the filming of a movie. By providing the proper physical restrictions on a simulated camera, the system can help design an appropriate environment for filming a scene. It can also help highlight difficulties or timing issues during filming. Furthermore, complicated shots can be planned and practiced before the expensive filming process.

Physical constraints also serve to help place natural constraints on camera movements. In the real world, a camera can not pass through objects, which can easily occur in a graphical environment, which is often extremely disorienting. Different kinds of mountings produce different stylistic effects, such as a natural easing in and out of a motion with a fluid head.

The constraints derived from the physical domain and demonstrated in this thesis are collision constraints; pathplanning constraints (where the camera can generate a collision free path from one point in an environment to another); and velocity constraints on changes in any of the degrees of freedom of the camera. These are described in more detail in sections 5.11.4 and 5.11.5.

5.7 Human Factors

Hochberg and Brooks [Hochberg86, Hochberg87] discuss a number of issues in the human perception of motion pictures. Those issues with the most direct bearing on the derivation of camera primitives are the ability of observers to comprehend changes in camera position across temporal sequences of film. One mechanism suggests that if the rate of change of any of the camera parameters from frame to frame is too large, then the observer may have difficulties if care is not taken to supply perceptual clues to the other potential mech-

anisms. This suggests that at least one important camera primitive is the ability to specify a maximum rate of change for any of the camera parameters. What that rate of change should be however, is extremely dependent on the update rate of frames and the content of the image. Another mechanism might be the ability of the observer to construct a transformation that relates objects in one image to objects in subsequent images. This construction of this transformation may be related to research by Shephard on mental rotation of objects [Shepard71]. To construct such a transformation though requires readily and uniquely identifiable objects in the image. Instead of producing a restriction on camera control, this mechanism might suggest a restriction on the content of the graphical environment. This restriction may also be the basis for an architectural design technique called wayfinding [Lynch60], where landmarks are placed in particular places to help keep people oriented. The final mechanism posits the existance of some sort of cognitive map which may be built up by the ability to locate and place familiar landmarks in a map in relation to each other. It is still a debatable issue of whether cognitive maps are represented internally as spatial maps or as symbolic maps. Evidence exists to support both hypotheses. This mechanism argues for a camera primitive that can be considered a meta-primitive. The user should be able to quickly and conveniently track the position of the camera from some external, map-like view. Many of the applications demonstrated in this thesis support this style of interaction. The definition of a constraint to limit the speed of motion of a camera is discussed in section 5.11.5 and that constraint is used in 6.2.

5.8 The Viewing Transformation

The following section presents the basic mathematical techniques which underlie the constraint framework.

5.8.1 Derivation of the standard Viewing Transformation

The fundamental operation of a virtual camera is to transform objects from a perspective view in the world space of a graphical environment into a device's display space. The following section describes the mathematical operations that occur to convert points from the world space in which they are originally represented, into a coordinate system that can be displayed on the screen. Much of this transformation can occur in the hardware of graphics workstations so it can be performed very quickly. Many of the constraints described in the

following section are based either on the world space positions and orientations of objects, or the transformed (projected) positions in terms of display space, so it is crucial to have a clear understanding of the view transformation process. The following section is taken in large part from a technical memo by Alvy Ray Smith [Smith84]. This description is simplified so as not to treat clipping and we or skewed viewing windows. Similar derivations can be found in several standard computer graphic references [Rogers76, Foley90]. For a more complete treatment, see any of these references.

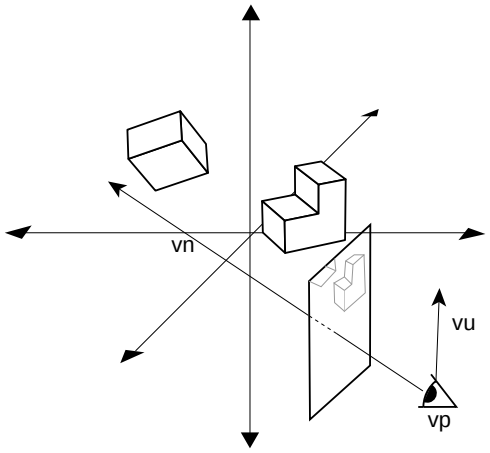


Figure 18: World Space

The term world-space refers to the mathematical representation of the 3D universe in which the objects are embedded. Model space refers to a coordinate system embedded in world space whose origin is attached to a particular object. Eye-space is a coordinate system whose origin is attached at the eyepoint from which a view is desired.

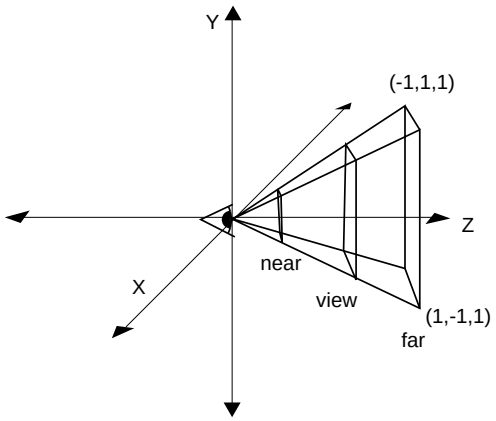


Figure 19: Eye Space

In general, the process begins by transforming all objects in the scene into a set of normalized viewing coordinates for which clipping is easy. Clipping of objects outside of the “view frustrum” (pictured in figure 19) is then performed. The transformation of the remaining points including a perspective projection is then performed.

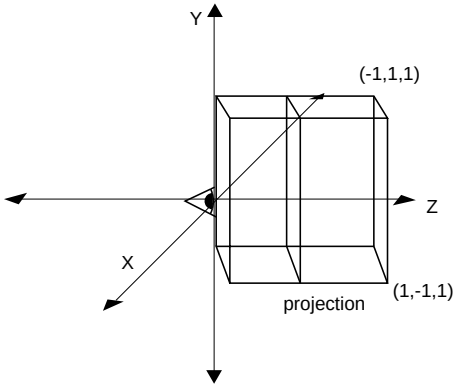


Figure 20: Normalized Coordinates after perspective transformation

Smith describes one conventional view specification which is a convenient way to understand and specify the parameters for the virtual camera. First, the location of the *viewp oint* (or eyepoint) is specified in world coordinates. The component of a *view up* vector which is perpendicular to a *view normal* vector gives the “up” direction. Next, the position of the view plane is specified by the *viewd istance* (which is along the viewnormal vector from

the viewpoint). The projection of objects onto this view plane is what will be mapped into a display. Lastly, the portion of the infinite view plane that is to be mapped onto the display is specified by a rectangular window relative to the point where the view normal intersects the view plane. For our purposes, we will assume that this rectangle is centered about the origin and is of fixed length and width. The viewing frustrum is then the portion of the viewing volume between the near and far clipping plane. (See figure 19). Typically, the first step of the viewing pipeline is transformation of the viewing frustrum into a *normalized frustrum* as pictured in figure 20.

This view specification is used in the following manner:
First, the normalizing transformation is calculated which converts points from world space into normalized view space (for convenient clipping). This is accomplished as follows:

1) Translate the viewpoint to the origin of the world system: (vp is the viewpoint)

$$\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & 1 & 0 \\ -vp_x & -vp_y & -vp_z & 1 \end{bmatrix} \qquad 1$$

2) Transform the world system to “eye-space”. This involves choosing a new basis for the space where one axis is the view-normal, another axis is the component of the view up vector perpendicular to the view normal, and the last component is the vector perpendicular to these two vectors. To calculate the component of the up-vector perpendicular to the view normal, the following equation can be used (where UP is the up-vector, and n is the view normal).

$$\mathbf{v} = \frac{\mathbf{UP} - (\mathbf{UP} \cdot \mathbf{n})\,\mathbf{n}}{\|\mathbf{UP} - (\mathbf{UP} \cdot \mathbf{n})\,\mathbf{n}\|} \qquad 2$$

Then the u vector is calculated form the view normal and this new v vector.

$$\mathbf{u} = \mathbf{n} \times \mathbf{v} \qquad 3$$

And finally the matrix to transform into eyespace is the following:

$$\begin{bmatrix} \begin{bmatrix} \mathbf{u} \end{bmatrix} & \begin{bmatrix} \mathbf{v} \end{bmatrix} & \begin{bmatrix} \mathbf{n} \end{bmatrix} & \begin{bmatrix} 0 \\ 0 \\ 0 \end{bmatrix} \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad 4$$

3) Add a matrix to scale the far face of the view volume to a unit square so that it lies at Z = 1 (where d is the view distance, f is the distance to the far face, and su,sv represent the half length and half width of the viewing window on the view plane):

$$\begin{bmatrix} \frac{d}{s_u f} & 0 & 0 & 0 \\ 0 & \frac{d}{s_v f} & 0 & 0 \\ 0 & 0 & \frac{1}{f} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad 5$$

Internally this can be represented in collapsed form as follows:

$$\mathbf{N} = \mathbf{N_L N_R} = \begin{bmatrix} \mathbf{u}^T & \mathbf{v}^T & \mathbf{n}^T & \mathbf{0}^T \\ -(\mathbf{u} \cdot \mathbf{vp}) & -(\mathbf{v} \cdot \mathbf{vp}) & -(\mathbf{n} \cdot \mathbf{vp}) & 1 \end{bmatrix} \begin{bmatrix} \frac{d}{s_u f} & 0 & 0 & 0 \\ 0 & \frac{d}{s_v f} & 0 & 0 \\ 0 & 0 & \frac{d}{s_v f} & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix} \qquad 6$$

4) A perspective transformation needs to be applied to spread the view volume into a rectangular prism (where n is the near distance and f is the far distance). For a derivation of this matrix see [Smith84] or [Foley91]:

$$\mathbf{P} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 \\ 0 & 0 & \frac{f}{f-n} & 1 \\ 0 & 0 & -\frac{n}{f-n} & 0 \end{bmatrix} \qquad 7$$

By concatenating the matrices (NL) (NR) (P) we have transformed the canonical viewing frustrum into a rectangular prism of width 2, height 2 and depth 1 centered on the z-axis; this coordinate system is commonly known as Normalized Device Coordinates (NDC).

5) If desired, the transformation can be taken one step further into real screen coordinates (where Xmin, Xmax, Ymin, Ymax define the portion of the display screen in image coordinates). The z coordinate can also be mapped into a desired range which is useful for depth cueing in certain calligraphic style displays. Commonly after this step, values need to be turned into pixel values by truncating the floating point values into integers:

$$\mathbf{D} = \begin{bmatrix} \left(\frac{Xmax - Xmin}{2}\right) & 0 & 0 & 0 \\ 0 & \left(\frac{Ymax - Ymin}{2}\right) & 0 & 0 \\ 0 & 0 & Zmax - Zmin & 0 \\ \frac{Xmax + Xmin}{2} & \frac{Ymax + Ymin}{2} & Zmin & 1 \end{bmatrix} \qquad 8$$

5.8.2 Blinn's Formulation: Where am I? What am I Looking At? [Blinn88]

Blinn discusses alternate methods of deriving the view transformation matrix. This work is of special note because of the task level nature of his formulations. In particular, he discusses four different modes which specify different behaviors:

1. Specify the viewing position and the viewing direction. This is the standard view transform described in the former section.
2. Specify the screen location onto which a foreground object should be projected and specify a looking direction. Find the location in space that makes

this situation true.
3. Specify the location and space and a screen location for a background object to be projected onto. Find the view direction that makes this situation true.
4. Specify the screen location of a foreground location and specify the screen location of a background object and calculate both the viewing position and the viewing direction that makes the situation true.

Blinn provides an algebraic derivation for each of the modes and discusses how to interpolate between the results of different mode specifications in order to create continuous camera movements. His formulation is useful, but relatively simplistic. In each of the modes, the field of view may not be altered in order to achieve the desired situation. Each mode must be special cased (there is a different procedure to use to calculate the necessary vectors for each mode). There is no way to find the "best" solution if certain conditions can not be achieved, or to be able to lock some of the camera parameters to a certain value.

Blinn's formulations lead naturally to a scheme based on constrained optimization, where each mode is essentially specifying different constraints that must be satisfied. By reformulating the problem in terms of constrained optimization, the solution process is easier and has the advantages of addressing all of these problems. There are however some disadvantages to an optimization approach which are discussed in section 5.10.

5.9 Object and Camera State Functions

In the following section, let q represent the camera parameters $q \in \Re_7$ where the 7 members of q are defined as follows (x,y,z, azimuth, pitch, roll, fov). Fov is defined between 0 and 180 degrees exclusively.

We can easily define a number of functions based on some object O. or some camera state vector q. Some example functions are listed in tables 5 and 6. After a description of some constrained optimization techniques, we will derive some basic camera primitives in terms

of these functions..

Table 5: Standard Functions of an Object

Function	Definition (in world coordinates)
points(O)	returns a list of vertices (or control points) for object O
bbox(O)	bounding box: (xmin, ymin, zmin, xmax, ymax, zmax)
centr(O)	centroid:((xmin+xmax)/2, (ymin+ymax)/2, (zmin+zmax)/2)
topcentr(O) or TC(O)	((xmin+xmax)/2, (ymin+ymax)/2, zmax)
botcentr(O) or BC(O)	((xmin+xmax)/2, (ymin+ymax)/2, zmin)
centr(O1,O2,...,On)	returns average of centroids of all objects
gaze(O)	returns standard orientation vector for object O
up(O)	returns the standard up vector for object O

Table 6: Standard Functions of Camera State

Function	Definition
vp(q)	view point (q_x, q_y, q_z)
vn(q)	view normal ($\sin(q_{azimuth})\cos(q_{pitch})$, $\cos(q_{azimuth})\cos(q_{pitch})$, $\sin(q_{pitch})$)
vu(q)	view up vector ($-\cos(q_{azimuth})\sin(q_{roll}) - \sin(q_{azimuth})\sin(q_{pitch})\cos((q_{roll})$, $\sin(q_{azimuth})\sin(q_{roll}) - \cos(q_{azimuth})\sin(q_{pitch})\cos((q_{roll})$, $\cos(q_{pitch})\cos(q_{roll})$)
proj(q,wsp) or P(wsp)	Project the worldspace point wsp given camera parameters q Construct the matrix N (equation 6) from vp(q), vn(q), vu(q), and matrix P from q_{fov}. Calculate screenspace (x,y) : $\begin{bmatrix} x & y & z & 1 \end{bmatrix} = \mathbf{NP} \begin{bmatrix} wspx \\ wspy \\ wspz \\ 1 \end{bmatrix}$ (transforming the world space point with a homogenous divide - the z coordinate should end up between 0 and 1 for unclipped points).

5.10 Constrained Optimization Techniques

General non-linear constrained optimization remains an unsolved problem [Fletcher80, Gill74, Press86]. Some describe the selection of procedures, initial conditions, and parameters to be used in an optimization as an “art” [Cohen92].

Several methods for solving constrained optimization problems have been discussed in the computer graphics literature. This thesis has explored using several of them for solving camera primitives. In general, an optimization problem can be viewed as a search over some manifold for a local minimum value. The usual approach for solving an optimization problem is to select a starting point and then find a direction to move in, and an amount to move by and iterate until a move in any direction would cause the objective function (the function being minimized) to increase. Constraints can be incorporated into the optimiza-

tion problem in several different ways. One way is to express the constraints as penalty functions and add them to the original objective to create a new unconstrained objective function to be solved. If there is no optimization to be performed, satisfying the constraints themselves becomes the optimization problem. By expressing only a certain kind of objective functions as energy values and the constraints can as forces. The search for a local minimum effectively becomes a forward simulation of a physical system can be used to bring the system to a minimum energy value subject to constraints. This is the technique used by [Barzel88, Pentland90].

Another method, which is particularly useful when the system is already at or near the minimum and the desire is to maintain certain constraints, is to solve a system in equations in terms of the derivatives of the parameters to be solved and find the velocities which force the state to stay in the Null-space of the solution, that is, to make sure that the constraints are always satisfied. This has the advantage of being a linear system in the derivatives of the camera parameters and can be solved efficiently. This is essentially the method used for the so-called through-the-lens camera control discussed in section 5.11.3.

Yet another technique is based on the idea that the gradient of the object function must be equal to some linear combination of the constraint gradiants for the solution to represent a constrained minimum. This leads to the use of Lagrange multipliers which multiply the constraints and add the resultant function to the objective function. Again, this turns the constrained problem into an unconstrained problem in the resulting objecting function. The Langrange multipliers correspond roughly to influences of the constraints on the objective function.

5.10.1 Sequential Quadratic Programming

The method used in this thesis is based on the technique of sequential quadratic programming.The following section is based in part on the extremely clear discussion presented in [Cohen92]. By combining Lagrange's methods with a Newton style search for a solution, the problem can be formulated as a sequence of quadratic subproblems that lead to a solution of the constrained problem. The gradient of the Lagrangian at a local optimum (S_*, λ_*) must be equal to 0.

$$\nabla L\,(S_*, \lambda_*) \;=\; 0 \qquad 9$$

We start at an initial guess for the optimum state, S, and the multipliers λ, of (S_0, λ_0). Expanding the $(k+1)^{st}$ iteration into a first order Taylor series around the k^{th} iteration and set it equal to 0 we get:

$$\nabla L\,(S_{k+1}, \lambda_{k+1})^{T} \approx \nabla L\,(S_k + \partial S, \lambda_k + \partial\lambda)^{T} \qquad 10$$

$$\nabla L_k^{T} + \nabla^2 L\,(\partial S, \partial\lambda)^{T} \;=\; 0 \qquad 11$$

where:

$$\nabla^2 L \;=\; \begin{bmatrix} \nabla^2_{SS} L & \nabla^2_{\lambda S} L \\ \nabla^2_{S\lambda} L & \nabla^2_{\lambda\lambda} L \end{bmatrix} \;=\; \begin{bmatrix} \nabla^2 R + \lambda^{T}\nabla^2 C & \nabla^2 C^{T} \\ \nabla C & 0 \end{bmatrix} \qquad 12$$

and R and C are the original objective and constraint functions respectively.
Using Newton's method, construct a linearized system around the current guess and equate the Hessian of the Lagrangian times a step $(\partial S_k, \partial\lambda_k)$, with the gradiant of the Lagrangian.

$$\nabla^2 L_k \begin{bmatrix} \partial S_k \\ \partial\lambda_k \end{bmatrix} \;=\; \nabla L_k^{T} \qquad 13$$

or

$$\begin{bmatrix} \nabla^2 R_k + \lambda_k{}^{T}\nabla^2 C_k & \nabla^2 C_k{}^{T} \\ \nabla C_k & 0 \end{bmatrix} \begin{bmatrix} \partial S_k \\ \partial\lambda_k \end{bmatrix} \;=\; \begin{bmatrix} -\nabla R_k^{T} - \nabla C_k^{T}\lambda_k \\ -C_k \end{bmatrix} \qquad 14$$

Since $\partial\lambda_k \;=\; \lambda_{k+1} - \lambda_k$, one can solve for changes in the state S and directly for the next set of Lagrange multipliers, λ_{k+1}:

$$\begin{bmatrix} \nabla^2 R_k + \lambda_k{}^{T}\nabla^2 C_k & \nabla^2 C_k{}^{T} \\ \nabla C_k & 0 \end{bmatrix} \begin{bmatrix} \partial S_k \\ \partial\lambda_{k+1} \end{bmatrix} \;=\; \begin{bmatrix} -\nabla R_k^{T} \\ -C_k \end{bmatrix} \qquad 15$$

This defines a sequence of quadratic subproblems, thus the name Sequential Quadratic

Programming. Each step performs a minimization of the Lagrangian subject to a linearized set of constraints.

This procedure can be modified to first move into a region where the constraints are initially satisfied (the feasible region) and then to guarantee that all movements toward the optimum solution remain in this region. Again, local minima can be a serious problem, especially if the region where the constraints are satisfied is discontinuous. If this is the case, the solution process might first bring the state into a region where the global minimum is not reachable.

In many of these methods, constraints can be considered to be either hard or soft, meaning that either the solution is invalid if the constraint is violated (hard), or the constraint can be violated in order to account for other optimization conditions (soft). In general, if the constraint is to be a soft constraint, it should be included as part of the objective function in the minimization through an energy based penalty term. If the constraint is to be a hard constraint, it can be incorporated into the solution in the following way:

1) It may be fixed at a certain value (if it is an equality constraint) and eliminated from the minimization,
2) It may be incorporated as a boundary value for one of the parameters (if it is directly one of the state variables), or
3) It may be a incorporated into a constraint equation that must be satisfied during the course of optimization.

For a more complete analysis of constrained optimization techniques, several good references are available [Fletcher80, Gill81, Press88].

The method used in this thesis is to formulate the problem in terms of constraints and minimizations on the state variables of the virtual camera directly and hand off the problem to the appropriate constraint solver. An implementation of Sequential Quadratic Programming, CFSQP [Lawrence94], described in appendix 4, was used as one of the primary methods of performing constrained optimization for the camera primitives. For soft constraints, the camera functions were specified as energy terms and incorporated into the

objective functions. Hard constraints were incoroporated into the quadratic programming problem through lagrange multipliers. Inequality constraints were incorporated by finding the set of inequality constraints that were active at any time (the active set) and combining these with the objective functions with non-zero The minimization algorithm CFSQP was chosen primarily for several reasons:

1) It is a general purpose constrained optimizer with a robust solving algorithm, and can identify halting conditions on the solution.
2) It can handle both equality and inequality constraints.
3) It can handle a wide range of constraint and objective functions, including both linear and nonlinear objective functions and linear and non-linear equality and inequality constraints.
4) The system can calculate derivatives of both the objective functions and constraint functions by finite differences if the derivative functions are not given. Obviously, the system can perform significantly better (both faster and more robustly) if explicit derivatives are given, but the system does manage to solve a wide variety of conditions.

A number of the constraints described in sections 5.11.1 - 5.11.7 are specified in the way that they have been formulated for input into the CFSQP constraint solver.

In general, input to the CFSQP is structured in the following way:

1) N scalar objective functions may be specified. The maximum valued objective function at any iteration is minimized for that iteration. This allows convenient user controlled weighting of the objective functions at any time during the optimization process.
2) Upper and lower bounds for the state variables can be chosen. The current iteration state is immediately moved to the nearest boundary value. This allows for extremely convenient specification of hard constraints for any of the state variables for the camera.
3) NINEQ inequality constraints both non-linear and linear may be specified.
4) NEQ equality constraints both non-linear and linear may be specified.
5) If the constraints can not be satisfied, the system will report which constraints were violated, though the system is currently not built to detect

why the constraints might fail (for instance if two contradictory constraints are combined). The system will also report failure to produce a minimum value in a specified number of iterations.

Interfaces for creating and combining constraints and objective functions are described in chapter 6. In general constraints and objective functions can be created in the following ways:

1) A text editor may be used to construct routines which can be loaded into the extended 3d interpreter at runtime. This has the advantage of being extremely flexible, but the disadvantage of being hindered by the run-time performance of the interpreter. A faster interpreter or a compiler would be desirable. An example is shown in appendix section 4.4.
2) The routines may be coded in C and compiled into the system. This has the advantage of evaluating extremely rapidly (often at over 15 Hz on an IRIS Indigo workstation), but the disadvantage of requiring compiling and linking for new combinations of constraints. An example is shown in appendix section 4.5.
3) Certain primitive constraints and objective functions (along with initial conditions) may be combined using a visible programming language which is described in section 6.4. These combinations may then be sequenced into automatic routines to film specific situations.
4) Constraints and objective may be embedded as the behaviors for a reactive agent. This is described in detail in section 6.3.

5.10.2 Local Minima

Constrained optimization problems can have a number of problems, including computational complexity and local minima. Since, in general, we only have 7 camera variables to optimize, computational complexity issues are usually not overriding though a multi-resolution approach might be appropriate for complicated higher dimensional searches. In fact, because of the solution method chosen, the greater the number of constraints, the faster the solution usually is. The local minima problem is however much more vexing. Our approach to avoiding local minima involves 5 prongs of attack:

1) Try to formulate the problem in such a way that there is guaranteed to be

no local minima. This is not always possible, but it is the basis for the techniques used for path planning and visibility calculation discussed in appendices 1 and 2.

2) Discretize space and use a depth first approach to searching the solution space.
3) Find an initial condition based on heuristic or geometric reasoning that might be close to a final solution.
4) Allow user assistance in the constraint solving process.
5) Restart the constrained minimization from a large number of initial conditions and find the lowest local minimum.

5.11 Camera Constraints Formalized

5.11.1 Direct constraints on DOFs in relation to the environment:

$$k1 \le q \le k2 \text{, where } \{k1, k2\} \in \Re_7 .$$

Implementation*:*

These constraints can be accomplished in one of two fashions, either as strict constraints, where the solution is not appropriate without the constraints being satisfied, or as "soft" constraints, where the solution should try to achieve the constraints, balanced with other constraints.

In the system that we have chosen to use, boundary values can be chosen as a special efficient form of a constraint. Thus the lower or upper bounds of any of the degrees of freedom can be chosen for the VC. Alternatively, if any state variable is to be fixed directly, they can be fixed and removed from the minimization function. Since it is especially easy to bound values of the state variables, the parametrization chosen in which to formulate the camera control does affect the convenience in the formulation of the camera control problem. This is counter to the statement of Gleicher & Witkin [Gleicher92] that the camera formulation is not important. It is my belief that the camera parameterization chosen can affect the ease in which certain camera primitives are specified. One example is based on the desire to constrain the roll vector of the camera to 0. By explicitly including a state variable for roll, it is particularly easy to constrain the variable. At other times, other parametrization are convenient.

For strict constraints boundary conditions are specified on the entire camera state vector. For soft constraints, minimize the quadratic function: where is the desired value for the ith camera parameter.

5.11.2 Direct constraints on DOFs in relation to a single object:

Table 8: Examples of Direct Constraints Relating to an Object:

Constraint	Purpose
x,y,z = centr(O)	Place viewpoint at the center of an object (to look from one object to another).
azimuth, pitch = gaze(O)	Set the camera to be the same direction as a character is looking. (If the two constraints are combined then the camera would view the environment from the character's point of view).
roll = up(O)	Set orientation of camera based on characters. Follow the roll of a plane, or align visual axes with a manipulator's axes.
azim, pitch = vec(O1, O2)	Set the camera's view normal to look in the direction of O2, from O1. Thus if the character is at O1, then O2 would be centered in the display for the camera. This is better described in terms of a projection constraint (see next section).

5.11.3 Projective constraints based on projection of an object:

$$P(q,F(O)) = \mathbf{sp}$$

where P is the projection operator described in table 6, F(O) is a function of the object position described in table 5 and **sp** is the screenspace position of the projection, $\mathbf{sp} \in \Re_2$. These constraints are really a subset of the previous section, but since it is such a fundamental constraint in describing the composition of a frame, it deserves its own section.

Implementation:

In TTL control, described by [Gleicher92], the solution strategy is simple. Assume that the

camera parameters are either appropriate for the constraint or nearly so. Changes in the camera parameters will have corresponding changes on the position of the projection of an object. If the projection of an object is described as $\mathbf{p} = \mathbf{h}(\mathbf{V}(\mathbf{q}, \mathbf{x}))$, where $\mathbf{p} \in \Re_2$ and $\mathbf{x} \in \Re_3$ is and h maps from $\Re_3 \rightarrow \Re_2$, where **V** is the viewing function and **h** is a projection operator, then

$$\dot{\mathbf{p}} = \mathbf{h}'(\mathbf{V}(\mathbf{q}, \mathbf{x}))\left(\frac{\partial}{\partial \mathbf{q}}\mathbf{V}(\mathbf{q}, \mathbf{x})\right)\dot{\mathbf{q}} \qquad 16$$

where

$$\mathbf{h}'(\mathbf{x}) = \begin{bmatrix} \frac{1}{x_4} & 0 \\ 0 & \frac{1}{x_4} \\ 0 & 0 \\ -\frac{x_1}{x_4^2} & -\frac{x_2}{x_4^2} \end{bmatrix} \qquad 17$$

or $\dot{\mathbf{p}} = \mathbf{J}\dot{\mathbf{q}}$ where **J** is the Jacobian of the projection and view operators. Since this is a linear equation, we can solve for the change in camera parameters $\dot{\mathbf{q}}$ by inverting the Jacobian. The Jacobian is not necessarily a square or full rank matrix so the pseudo inverse is used. When the pseudo inverse of J is multiplied by the desired $\dot{\mathbf{p}}$ we can find the desired $\dot{\mathbf{q}}$. By integrating this $\dot{\mathbf{q}}$ and adding it to the initial **q** we can find the final camera parameters that will bring about a desired projection **p** of the worldspace point **x**. The advantage to this approach is that it is extremely fast since the matrix is fairly small and fairly easy to invert.

There are however some disadvantages. The initial starting point needs to be close to the final position or this approach will not work. Although we can attempt to find a trajectory in screen space for the desired point to be projected onto, this has problems if the solution passes through a singularity (a point at which a small change in the view parameters brings about an enormous change in the resulting projected point). Care must also be taken to weight the contributions from the different parameters appropriately, or else the least squares solution inherent in the pseudo-inverse will preferentially treat some parameters more than others on the basis of the units that might have been used for measuring them.

This approach is best suited to maintaining constraints, especially when trying to manipulate the camera or objects directly subject to those constraints.

An alternate approach to formulating the problem as a minimization of the distance between the screen-space projection of a point and the desired screen-space location. This has the advantage that the solution does not tend to go unstable (as the other approach can do for large initial distances from the target location). Care however, must be taken in this approach that the desired solution is one that is appropriate, for instance even if the camera is facing directly away from the object, the projection operator would still produce a screen space projection at the desired position (though nothing would be seen because it is clipped from the view frustrum).

Table 9: Examples of Projection Constraints:

Constraint	Purpose
Proj(centr(O)) - (x,y)	Constrain the projection of the center of an object to lie at an exact screen space position.
(0,0) < Proj(centr(O)) < (1,1)	Constrain the center of an object to be projected somewhere on the screen.
(xmin, ymin) < Proj(centr(0)) < (xmax, ymax)	Constrain the center of an object to lie in some region on the screen.
Proj(centr(O)) < (xmin, ymin) || Proj(centr(O))>(xmax,ymax)	Make sure that the center of an object does not appear on the screen..
(xmin, ymin) < Proj(points(O)) < (xmax, ymax)	Make sure that all points of an object lie in some region on the screen.

Table 9: Examples of Projection Constraints:

Constraint	Purpose
Proj(pt1(O)) = sp1, & Proj(pt2(O)) =sp2	Constrain a vector in world space to lie on a vector in screen space (so that a gaze might be positioned in a certain direction on the screen). Also can be used to constrain the size of an object by specifying the top and bottom positions for the object. These were the types of constraints used in the section describing simple cinematic shots.
Proj(pt1(O)) = sp1, & Proj(pt2(O)) = sp2 && fov	By combining the previous constraint with minimizing the fov, the camera will zoom as much as possible while still keeping the two characters in view at the same time.
ycoord(Proj(pt1(O))) - ycoord(Proj(pt2(O))) = k	Constrain the height of the projected region to be a certain amount, independent of screen position. Thus if pt1 represents the type of a character's face, and pt2 represents the bottom, then this constraint can be used to make sure that the character's face takes up half the screen.

5.11.4 Constraints based on entire environment:

There are two broad classes of constraints that I classify in this area: visibility related constraints, and path planning constraints. They turn out to be intimately related.

Pathplanning

In path planning, the goal is to reach a certain desired position while preventing movement

through obstacles. This can be viewed as an optimization condition based on the current state's distance from the desired location with constraints that strictly prevent movement through the obstacles. One way of formulating this problem is to first polygonalize the environment, and then decompose all concave polygons into convex polygons, these constraints can be expressed as the intersection of multiple linear inequality constraints. Additional optimization conditions can be added so that the solution does not pass too closely to the object boundaries. Figure 21 shows the combination of these constraints. An additional constraint is added so that during any time step, the goal position for each iteration must be within a fixed distance of the starting state. This fixed distance increases with each iteration of the optimization. This prevents the state from changing to the optimal position immediately and creates a series of positions for the camera to travel along for an unoccluded path.

Because the path planning algorithm when formulated in this fashion is both numerically inefficient and prone to local minima, separate algorithmic approaches have been taken to solve the path planning problem specifically. These algorithms are discussed in appendix A1. Figure 22 represents one way of generating the constraint surface based on the sum of repulsive and attractive potentials which is useful in constructing a potential function which can then be minimized for camera position. The bumps in the potential function represent obstacles and the low point represents a desired goal position. This method has problems with local minima and methods to avoid local minima and alternate methods of forming the potential surface are discussed in appendix 1. The camera position is considered to be seperable from the camera orientation which is not always strictly true.

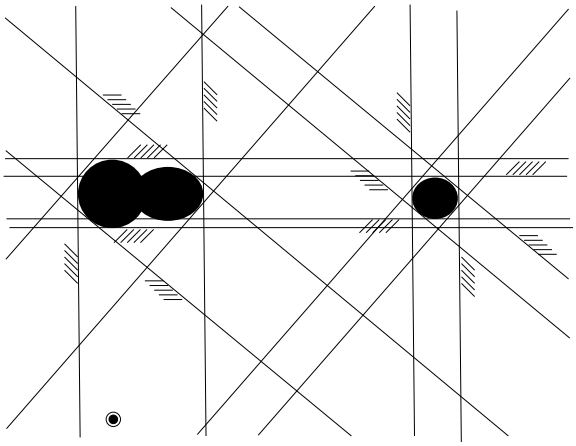


Figure 21: Path planning with intersection inequality constraints

Figure 22: Sum of “repulsive” and “attractive” constraints for path planning optimization

Visibility

Constraints for visibility are quite similar to path planning constraints. In general an allowable region is found, and a path to that allowable region is found through minimization. Specifically, visible regions to a certain point are first calculated and a function is expressed as the nearest distance to a visible region. This optimization function can now be added to any other optimizing functions in order to keep a certain object visible as it moves. One way of picturing the visibility constraint is from figure 23. The algorithm used in the visibility assistant for this thesis was slightly different and is described in appendix 2. It is based on a potential function for camera position based on the azimuth and pitch from the point of view of the target object. This restricts the camera to move along a hemi-

sphere of constant distance away from the target object and will not find visible positions that are nearer to the target object then the current camera position.

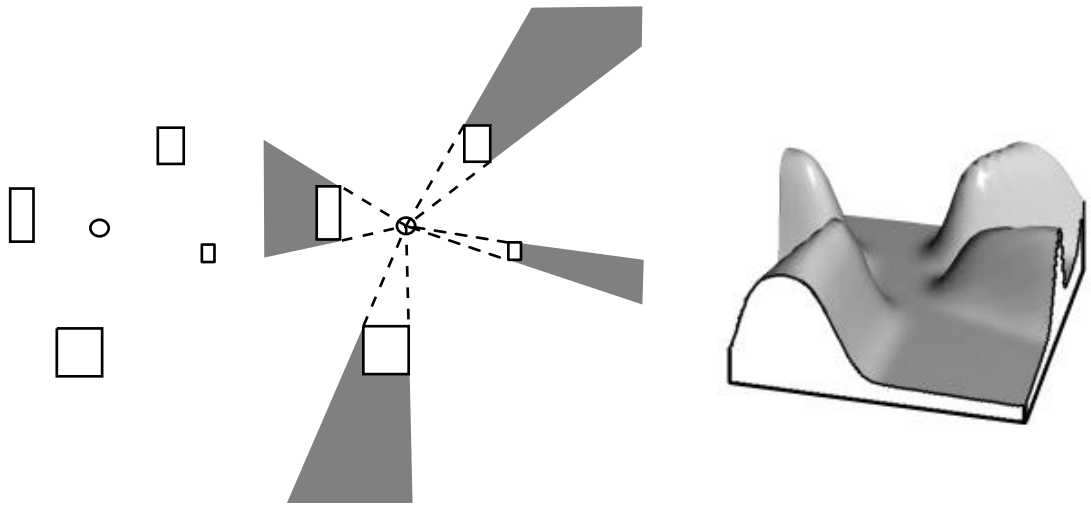


Figure 23: Visibility regions are the complement of shadows cast from a light.

5.11.5 Constraints on derivatives of DOFs:

$$k1 \leq \dot{q} \leq k2 \text{, where } \{k1, k2\} \in \Re_7 .$$

Implementation:

One method of incorporating derivative constraints is to solve for the rest of the constraints first and then use the derivative constraints as boundary values for the camera parameters. If a single maximum velocity is used for the entire duration of the camera movement, a “bang-bang” movement results where the speed of movement is either the maximum or nothing. Velocity profiles can be used to help ease into and out of camera movements. Another method of implementing this constraint, especially useful when they involve derivatives of functions of the camera parameters rather than parameters directly, is to calculate a new set of the pertinent camera values directly and tightly constrain the derived parameters while optimizing on the other parameters.

Table 10: Examples of constraints on derivatives of DOFs

Example	Purpose
d(pan)/dt < theta_max	Don't pan too quickly. This can be used to help maintain context and user orientation.
d(zoom)/dt < zoom_max	Limit the speed of zooming in or out.
d(right(q))/dt = speed	dolly to the right at a given speed. If a projection constraint is in operation at the same time, this has the effect of circling about an object at a given rate.

5.11.6 Changing constraints:

$$F(q1,t1) = k2;\ F(q2,t2) = k2$$

Constraint at time t1 differs from constraint at time t2.

Implementation:

Camera parameters can be found for constraints at time t1 and at time t2 and the values interpolated over time, or the constraints themselves can interpolate over time. For example, to pan from object A to object B, one might vary the projection of a virtual object which occupies a position interpolated between object A and object B's position at the beginning and end of the time period.

Table 11: Examples of changing constraints:

Example	Purpose
Proj(centr(O1)) = sp1, at time 1 && Proj(centr(O2)) = sp2 at time 2	Pan from object O1 to object O2 at a rate such that at time 1 the camera starts with object O1 projected to screen space position sp1, and at time 2, object O2 is projected to screen space position sp2.
Proj(centr(O1)) = sp1, at time 1 while tightly constraining position && Proj(centr(O1)) = sp1 at time 2 while tightly constraining viewing angle	Pan to follow object until time 2 and then move with the object to keep it in view.

5.11.7 Constraints based on another camera:

In a system with multiple viewports, one camera can be treated as any other object in the environment from another camera's view. All the constraints described in the previous section relating a camera's positions based on an object can be used.

Table 12: Examples of constraints based on other cameras:

Purpose
Track a camera or stay at a fixed location relative to the camera.
Produce alternate views that stay oriented with each other. For example, if one camera is showing a frontal view, then the other camera might always produce a view which is 90 degrees away from the other view.
If one camera is seeing this, then another camera might be constrained to do something related but in a completely different region of the graphical environment.

5.12 Blinn's formulations revisited

Using the constraints described in sections 5.11.1 and 5.11.3, it is trivial to reformulate the solutions to Blinn's modes of camera control discussed in section 5.8.2. All that needs to be done is combine a direct constraint on the camera parameters, and a projected constraint on an object position.

1. Specify the viewing position and the viewing direction. This is the standard view transform described in the former section.

Constrain the view position and view orientation values tightly with boundary values, or if it is intended to combine with other constraints, use the form of soft constraint described in 5.11.1.

2. Specify the screen location that a foreground object should be projected and specify a looking direction. Find the location in space that makes this situation true.

Constrain the view orientation values tightly with narrow boundary values. Minimize the function **||proj(q,x) - (xd, yd)||.** In other words, minimize the distance between the desired projection of the object **(xd, yd)** and the actual projection of the object **proj(q,x)**, where **x** represents the world space centroid of the object (centr(obj)), and **q** represents the camera parameters. Care must be taken that the derived camera position does not project behind the viewer. Another constraint can be added so that the vector between the view position and the object is facing the same direction as the view normal (**vn** • (**vp**-**x**) > 0), where **vn** represents the view normal component of the camera parameters and **vp** represents the view position component of the camera parameters.

3. Specify the location and space and a screen location for a background object to be projected onto. Find the view direction that makes this situation true.

Constrain the view position values tightly with narrow boundary values. As in mode 2, minimize the function **||proj(q,x) - (xd, yd)||**. The same constraint needs to be added to make sure that the derived camera position is pointing towards the viewer as opposed to away from the viewer.

4. Specify the screen location of a foreground location and specify the screen location of a background object and calculate both the viewing position and the viewing direction that makes the situation true.

Minimize two functions of the form **||proj(q,x) - (xd, yd)||** where there is a different world point **x** for each object and a different desired screen position **(xd,yd)** for each object. One additional advantage of specifying these modes in the form of constrained minimization is that we can also choose to set a certain camera parameter and have the solution achieve the best camera position possible. For example, we can choose to place object1 at **(x1,y1)** and object2 at **(x2,y2)** subject to the constraint that the camera does not roll at all.

CHAPTER 6. FROM TASK TO INTERFACE

Previous chapters discussed a taxonomy of domains, several styles of interaction in each domain were examined, and camera primitives were formally expressed in a constrained optimization framework. This section is devoted to an analysis of five specific applications and the development of interfaces for controlling the camera to accomplish tasks in each. The applications were chosen to illustrate a wide variety of types of interfaces that can be built on top of the constraint framework, and to demonstrate the fact that the framework's utility can span a sufficiently representative sampling of application domains.

The applications discussed here are a *Virtual Museum*, a *Mission Planning System*, a *Virtual Conversation Assistant*, a *Virtual Football Game*, and a *Visibility Assistant*. The *Virtual Museum* was used to examine an example in an exploratory domain. The *Mission Planner* is an instance of a task from the rehearsal domain. The *Virtual Conversation Assistant* and the *Virtual Football Game* are both tasks primarily from the planning domain, and the *Visibility Assistant* is a prototypical control domain task. Styles of interaction range from extremely tight coupling between the user and the degrees of freedom of the camera via a head mounted display or joystick control, to semi-autonomous path finding through a space, to a reactive camera agent which *senses* and *responds* to changes in the environment. A visual programming interface is also discussed to combine and sequence camera behaviors by dragging initial conditions, constraints, and controllers into camera agents.

6.1 Example: The Virtual Museum

Our first domain is the Virtual Museum [Drucker94]. A museum was chosen since it is a visually rich, spatially organized, information space [Miller92]. It is important to note that the museum represents any spatially organized database, and some tasks that might seem

nonsensical in the museum domain do make sense in an alternate, but similar domain. One alternate domain might be the exploration of data about a human body compiled from a variety of medical scans. This domain emphasizes the importance of the spatial organization of data. A well designed museum uses this spatial organization to make effective statements on the content [Sand94].

We divide the kinds of tasks that we wish to perform in the spatial database into two essential categories: exploring and navigating. By exploring, I mean a general search for information but not necessarily specific information. By navigating, I mean moving to a specific location within the environment. Orienting oneself is an important component for both of these categories.

Examples of the basic tasks that comprise the museum are shown in the following table. Equivalent tasks for medical exploration are also shown. This medical exploration might be either an examination of pre-gathered medical data, or perhaps on-line control of an arthroscope. The latter might be more suitably described as a control-oriented task, but since the primary goal here is to gather information, I will consider it in this section.

Table 13: Visual Tasks in an exploratory domain

Virtual Museum	Medical Exploration
View a painting or sculpture	View a structure in the body.
View several artworks sequentially.	Show several different structures.
View several artworks in an organized fashion.Use database capabilities to organize the information cognitively.	See an entire system of the body.
Browse through the museum based on spatial location.	Move through a human body, viewing structures.
Locate one's position within the museum.	Find the position of the camera (could be a tracked arthroscope).
Travel to a specific artwork seeing other artworks along the way. Don't confuse the user by moving through obstacles.	Move from the current location to a specifically identified structure, making sure that proper constraints are maintained (don't move in such a way as to damage the body).
Guided tour of the museum based on specific requests, or instructions of a third party.	Instructional tour of systems of the body.

Naturally, one of the first things that one wishes to be able to do in a museum is to see the artwork. One does not need to have a museum to see the artwork (especially a virtual museum) since one can be shown representations of the artwork in any form, such as a picture book. The virtual museum has one advantage over a picture book, of being able to place the user within the environment and show the relative scale of the works of art. In addition, there does not need to be any spatial organization of the material if one's only goal is to see specific pieces of art. However most museums are designed with some orga-

nizing principles, and the virtual museum allows the spatial organization to be perceived directly. The equivalent task in the medical domain is to look at a particular organ that has been already isolated.Ssince it might be difficult to isolate a structure, spatially moving through the body might be the best way to see that structure.

Another purpose of examining the museum might be to become familiar with the spatial layout as a prelude to visiting a real museum. In this case, a means of browsing through the space of the museum is necessary. However, if the controls for browsing the space are too obtrusive, the system forces the user to pay more attention to the controls than to browsing the space itself. For example, often, one does not get to see a new city if one has to drive through the city and pay more attention to the traffic and the street signs in order to get to a particular destination. One can sit on a tour bus and have a better view of the surroundings. Alternately, many people complain that if they don't do the controlling, they never are able to find their way through the environment without assistance later. No one solution to all tasks is appropriate, so an interface must support a wide range of different styles of interaction.

It is interesting to note that the spatial layout of space can be used as an organizing principle for human memory [Miller72]. Associating objects with positions along a path through a museum can aid in their recall. This same spatial organizing principle can serve to help enhance the experience of viewing the artwork.

Finally, the user might wish to be taken on a guided tour through the museum seeing different artwork in sequence. Again, this could be done through a picture book, but by being able to compare sizes of work in context can enhance the experience.

6.1.1 Implementation

The museum was designed in such a way that task assistants can be added as individual *camera modules*. A camera module is an encapsulation of the camera primitives along with some other interface components including initial conditions, controllers, and local state. As can be clearly seen from the description above, no one interface is best suited to performing all tasks. By expressing the task assistants in terms of combinable primitives,

not only can the primitives be reused for other domains, but new tasks can be built by combining existing primitives with new, specifically programmed ones.

Figure 24 describes the way in which the museum has been implemented.

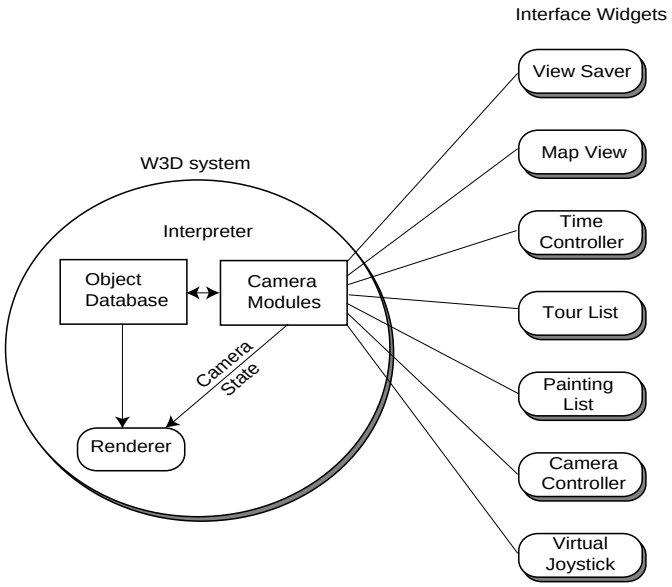


Figure 24: The Virtual Museum System

The Virtual Museum system is structured this way to emphasize the division between the virtual environment database, the camera framework, and the interface that is placed on top. Figure 24 is comprised of the following parts:

- The **extended 3D system** which is the core part of the system and is described in appendix 3.
- An **object database** for the virtual museum environment. The virtual museum has precalculated colors based on radiosity computations which the extended 3D system supports. The database also contains information about the placement and descriptions of all artwork within the museum.
- **Camera modules**: These will be described in detail in the following subsection. Essentially, they encapsulate the behavior of the camera for different styles of interaction. They are prespecified by the user and hooked to

various different interface widgets (several widgets can be connected to several camera modules). The currently active camera module handles all user inputs and attempts to satisfy all the constraints contained within the module to come up with camera parameters that are then used by the renderer in creating the final image. Currently, only one camera module is active at any one time, though if there were multiple viewports, their could be one camera module active per viewport.

- **Interface widgets**: The diagram also shows that there are 7 different types of interface widgets that can be used to control the camera within the museum. These different widgets illustrate different styles of interaction based on the task level goals of the user.

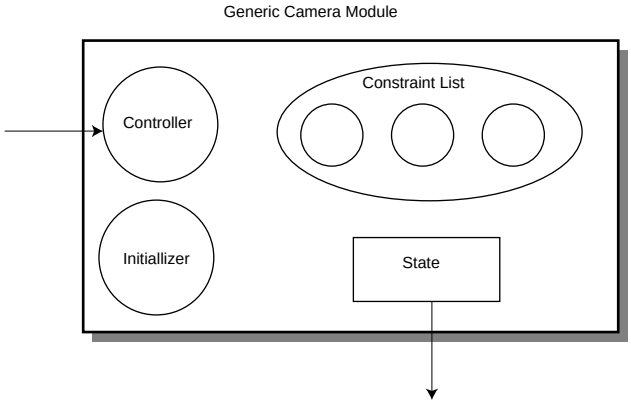


Figure 25: Generic Camera Module

Camera Modules: As shown in figure 25, the generic module contains the following:

- the local state: must always contain the camera position, camera view normal, camera "up" vector, and field of view. State can also contain values for the camera parameter derivatives, a value for time, or other local information specific to the operation of that module. While the module is activated, the state's camera parameters are output to the renderer.
- initializer: this is a routine that is run upon activation of a module, typical initial conditions are to set up the state based on a previous module's state.
- controller: translates user inputs either directly into the camera state or into constraints, there can be at most one controller per module.
- constraints: (camera primitives) to be satisfied during the time period that the module is active. Some examples of constraints are as follows:

- maintain the camera's up vector so it is aligned with a world up
- maintain the position of the camera at a certain height relative the floor
- maintain the camera's gaze toward a specified object
- keep the camera's position along a collision free path through the environment

In this system, the camera primitive can be viewed simply as a black box that produces values for some degrees of freedom (DOF) of the camera based on the methods described in chapter 5. The constraint solver combines these constraints to come up with the final camera parameters for a particular module.

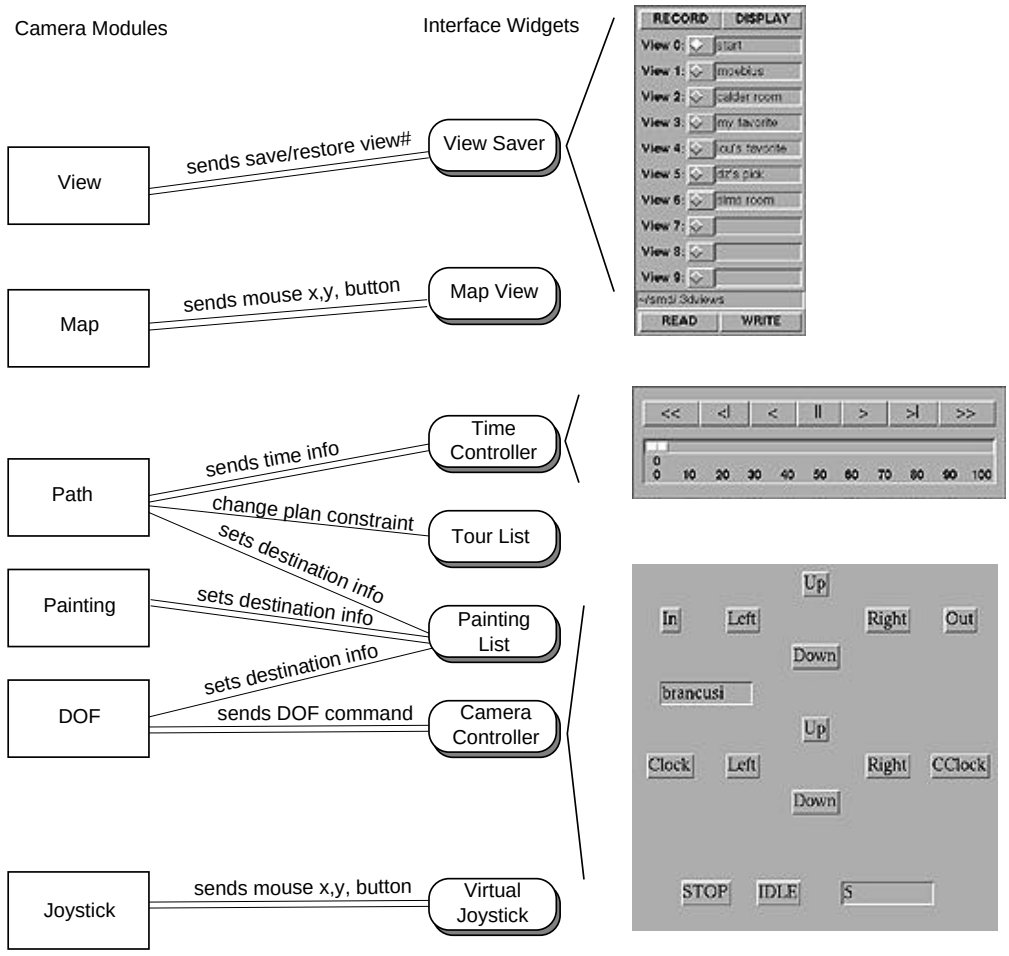


Figure 26: Wiring diagram between interface widgets and modules.

In the Virtual Museum system, camera modules are activated by selecting the corresponding interface widget. This widget also passes information to the controller of the module. The "wiring diagram" which shows what information is sent from the interface to the corresponding module, and which module is activated when the user presses an interface widget is shown in figure 26. A single line means that information is transferred from the widget to the corresponding module. A double line indicates that the widget activates the corresponding module.

Here is a description of what occurs when the user clicks on the *map view widget*. First, the corresponding map view module is activated, which means that this module's state will be used during rendering. The initializer for this module grabs the camera state from the previous module thus allowing the user to control the camera using one set of controls, and then adjust the position further using the map view. This module's controller maps the (x,y) position of the user's mouse click along with the corresponding button directly into a constraint on the current state of the camera. The *view saver's* module either grabs the current view and saves it as part of the local state information for that module, or retrieves a saved view from the local state information and sets the camera parameters based on that. The *joystick module's* controller maps the x & y location of the viewer's mouse click into constraints on the velocity of the virtual camera's motion through the environment. There is an additional constraint in the joystick module that prevents movement through walls. The *painting list* is connected to several different modules. One module's controller (the paint module) responds to a double click of the middle mouse button and sets its state based on the painting's position in the environment. In addition, a constraint is added to the DOF controller module that constrains the camera to point toward the specified painting. When double clicking with the left button, not only is this constraint added to the DOF controller module, but source information and destination information is added to the local state of the *path module*. The source information is based on the current state of the camera, the destination is based on the position of the painting in the environment. The *path module*

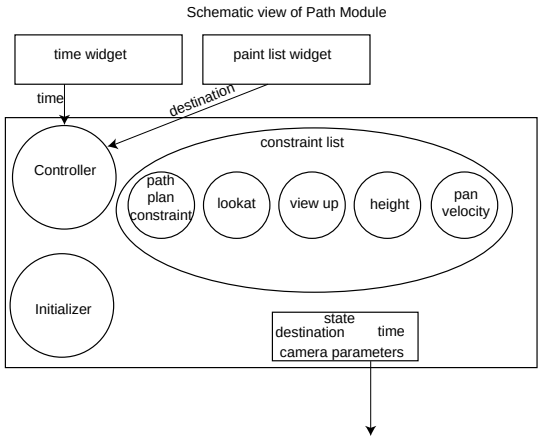


Figure 27: Schematic view of the “path” camera module

The path camera module is the most complicated module (see figure 27). It contains a primitive that calculates a path from a start position to a destination position (set when clicking on the painting list). It uses the local state's time (modified by the time widget) to indicate the current position of the camera in the (x,y) plane. The time widget can either set a particular time, or continuously update time in order to move forwards or backwards along the path. The path camera module uses several additional constraints in calculating the final camera parameters. The height is constrained to be a desired height off the ground (which is adjustable through the height constraint). The camera's up vector is constrained to always point in the same direction as the world up vector. The gaze direction is adjusted to look at the destination object when it is visible, or to look straight ahead (based on the current derivatives of the camera parameters) when the destination object is not visible. Furthermore, the gaze direction is constrained to change at a rate no greater than a specified maximum pan velocity. If instead of a single painting, multiple paintings have been selected, the path module's path planning constraint generates a guided tour through all the selected paintings. The immediate destination is kept track of by the controller and placed in the local state's destination slot. All the other constraints act in the same manner as before.

6.1.2 Results

An evaluation of the virtual museum is discussed in section 7.2.1.

Figure 28: Overhead view of museum

Figure 29: 4 shots of the museum along a computed path

6.2 Example: The Mission Planner

The mission planning system was designed to aid user's in enhancing situational awareness for pre-mission rehearsals and briefings. The system can use a conventional CRT display or a fully immersive head tracking display and a force feedback device. For input, a conventional mouse/window system is provided or more sophisticated voice and gesture recognition can be used.

The interface for the mission planning system was designed after a discussion with current experts in the field and references [Bate88, Chamberlain88, Penn89]. The system provides computational models of many of the elements of a mission, including g-load requirements for modifiable flight paths, and visibility detection for threats. The reader is referred to [Zeltzer92] for a more complete description of the mission planning system.

Basic visual tasks in the mission planner are shown in table 14.

Table 14: Tasks in the Mission Planner

Mission Planner
Give the user the view from any object in the environment.
See one object in relation to another object.
Give a reference view of the mission environment.
Track the movements of an object in the environment.
Allow changes of view that are not confusing.
Allow easy determination of lines of sight between objects, targets, and threats.

The camera control that is implemented in the mission planning system has two main requirements: 1) easy and convenient symbolic specification for the camera, and 2) maintain the user's awareness of the current context. One important aspect of the interface for the mission planner was the use of a head mounted display to provide immersion within the environment. Because of the immersion, the best way to operate the controls was via voice commands, since the hands were no longer able to operate a mouse/menu system. Using the voice necessitated mapping user's requests into a small set of concise commands which can be issued over the voice recognition system. The following commands are supported: saving and restoring views, panning, zooming, trucking, dollying, craning, tilting, rolling, look at an object, look from an object, "over-the-shoulder" from object 1 to object 2.

The look at object constrains the projection of the object to appear at the same position on the screen either as the viewpoint moves (if the user's view is already attached to an object) or as the object of interest moves. The look from an object constrains the virtual camera to be at a certain point within the cockpit of an airplane (or within a tank). If the user is not already looking at another object, the view vector is constrained to be along the direction of flight of the plane while constraining the view up vector to be aligned with the up vector of the plane (which banks for turns). The "over-the-shoulder" shots can be implemented with the same constraints that are used in an over-the-shoulder shot in a conversation (see section 5.3).

The second requirement prevents the system from changing the view too rapidly which might make it difficult to maintain context in the system. An additional constraint is added which specifies a maximum change of any of the camera parameters from one frame to another. The camera state will change this maximum amount and converge to the desired value over several frames. This permits panning from one object of interest to another object of interest, or moving the viewpoint from one point to another without losing context.

Lastly, a rudimentary visibility constraint has been added to the system which tests

whether an object is visible to a certain designated “threat” object. The version of the visibility constraint does not move the camera to a visible position (as described in section 5.11.4), but only indicates a boolean condition of whether an object is visible or not.

6.2.1 Implementation

The implementation of the mission planner is similar to that of the virtual museum.

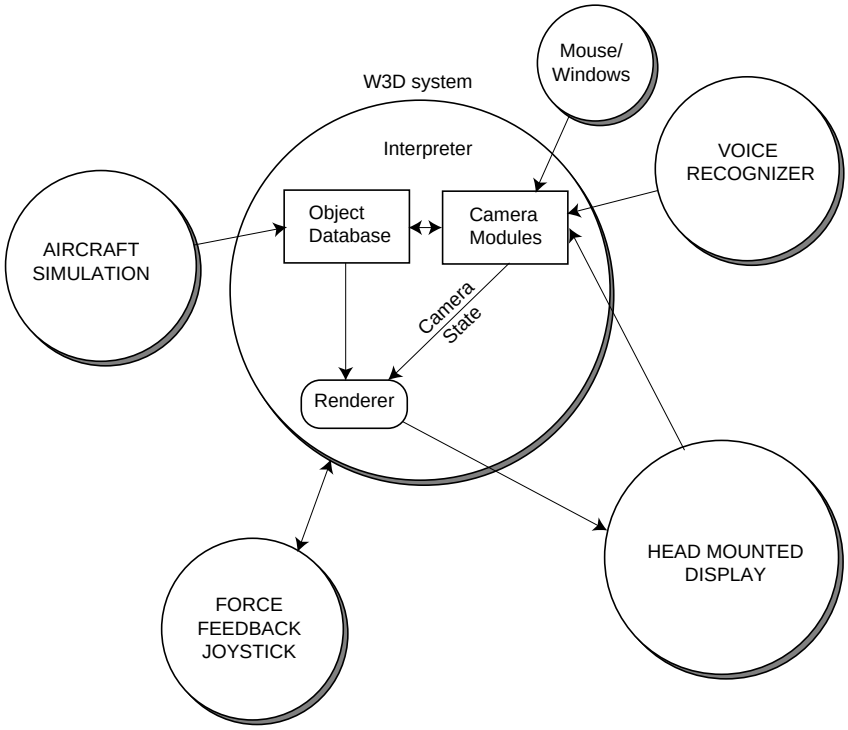


Figure 30: Overview of the mission planner

The mission planner system is implemented in W3D and interfaces with a headmounted display (VPL EyePhone), a voice recognition system (Articulate Systems Voice Navigator running on a Macintosh and connected to W3D via a serial connection), a force feedback device [Russo90, Minsky90], and an aircraft simulation running on a separate workstation. A typical camera module contains constraints for the projected position of an object, constraints on the maximum change of any camera parameters, constraints on the camera viewpoint, and the local state of the system.

6.2.2 Results

An evaluation of the Mission Planner System is presented in section 7.2.2.

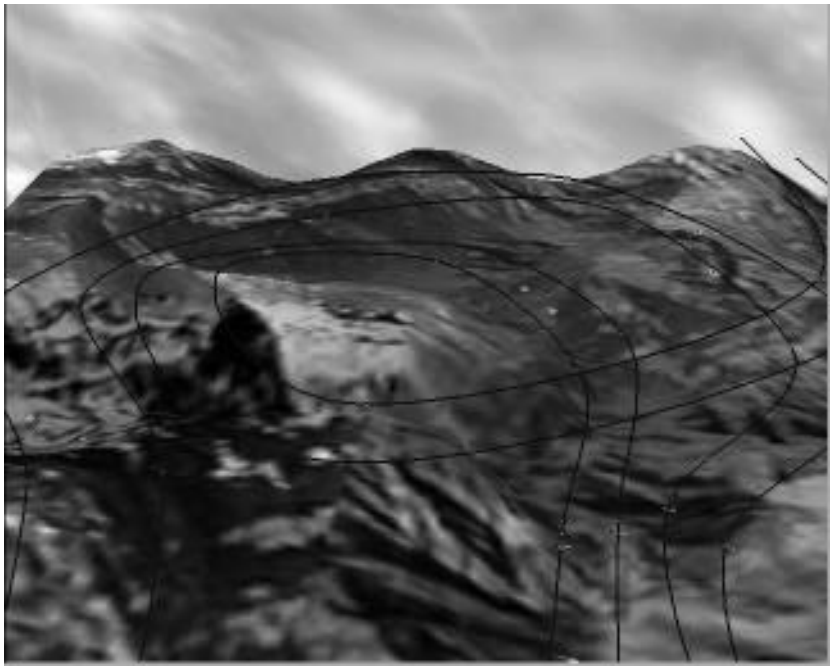


Figure 31: Overhead view of mission planning system

Figure 32: Over-the-shoulder shot in mission planning system

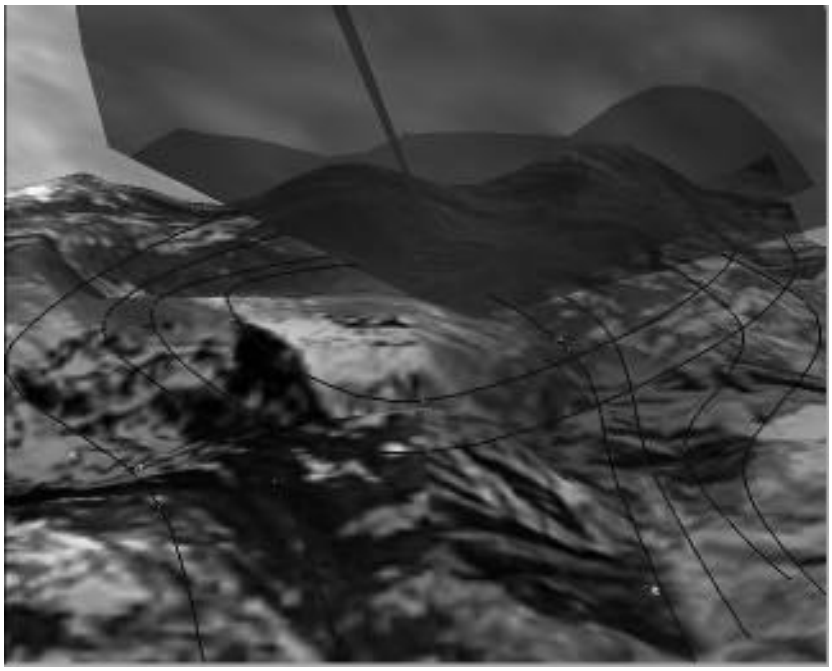


Figure 33: Visibility evasion from threat in mission planning system

6.3 Example: Filming a conversation

Filming a conversation is a good example of simple camera primitives that have been derived from a cinematic domain. It is a task primarily in the planning domain. The interface for the conversation filming example is based on the construction of an software agent, which perceives changes in limited aspects of the environments and uses a number of primitives to implement agent behaviors. The sensors detect movements of objects within the environment and can perceive which character is designated to be talking at any moment.

The following table shows the primary visual tasks that need to be accomplished in the conversation application.

Table 15: Tasks in Filming a Conversation

Filming a conversation
Move into the environment and focus on a particular character.
Find over the shoulder shots from each character to the other.
Generate close ups and medium shots of the characters.
Cut between primitive component shots following proper rules of editing.
Visualize camera location along with actors positions.

In general, the position of the camera should be based on conventional ways that have been established in filming a conversation. Several books have dissected a conversation and come up with simplified rules for an effective presentation [Arijon76, Katz88]. The conversation filmer encapsulates these rules into a software agent and can be used either as an automatic generation of film sequences, or as an assistant to a director or planner for a filming a sequence.

6.3.1 Implementation

The placement of the camera based on the position of the two people having the conversation (see figure 34). However, more important than placing the camera in the approximate geometric relationship shown in figure 34 is the positioning of the camera based on what is being framed within the image.

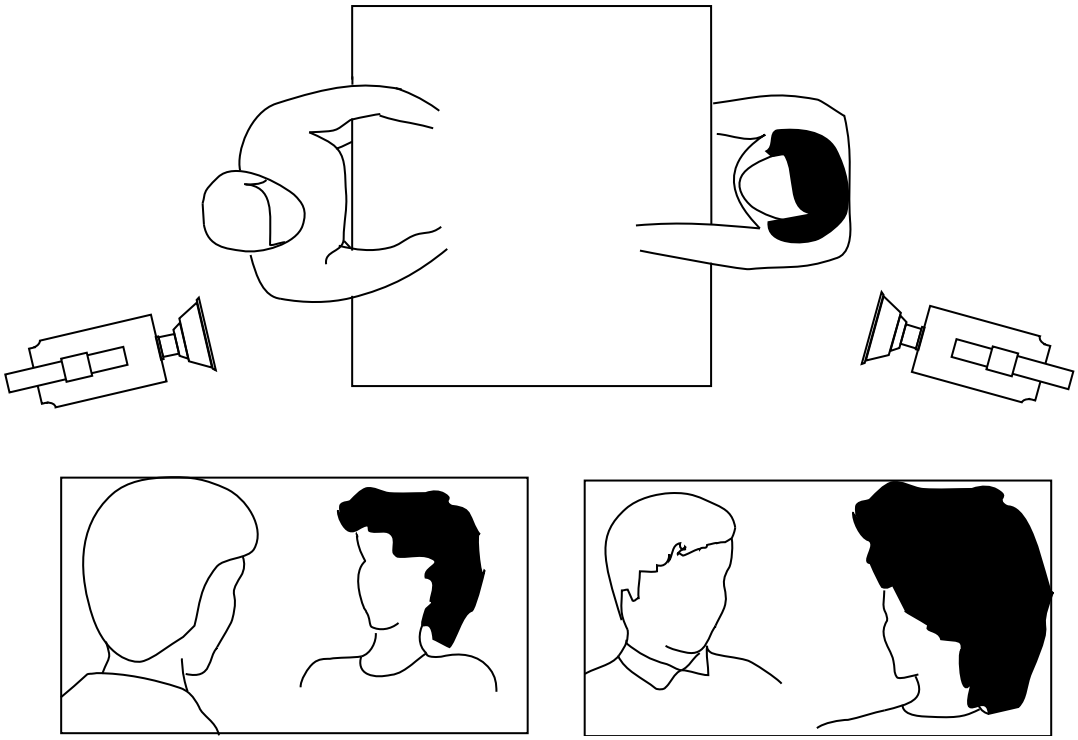


Figure 34: Filming a conversation [Katz88].

Constraints for an over the shoulder shot:

- The height of the character facing the view should be approximately 1/2 the size of the frame.
- The person facing the view should be at about the 2/3 line on the screen.
- The person facing away should be at about the 1/3 line on the screen.
- The camera should be aligned with the world up.
- The field of view should be between 20 and 60 degrees.
- The camera view should be as close to facing directly on to the character facing the viewer as possible.

Constraints for a corresponding over the shoulder shot:

- The same constraints as described above but the people should not switch sides of the screen; therefore the person facing towards the screen should be placed at the 1/3 line and the person facing away should be placed at the 2/3 line.

The diagram can be used to find the initial positions of the cameras if necessary, but the constraint solver should make sure that the composition of the screen is as desired.

The Conversation Software Agent

This is a prototypical agent with fairly little intelligence, but kept simple to illustrate the design decisions. The agent contains a rudiementary reactive planner which pairs camera behaviors (combination of camera primitives) in response to sensed data. The agent will have two camera behaviors: one for when character 1 (Steven) is speaking; and one for when character 2 (David) is speaking. The agent needs to have sensors which can “detect” who is speaking and direct the corresponding camera behavior to occur. The agent can also sense the position of any of the characters in the environment.

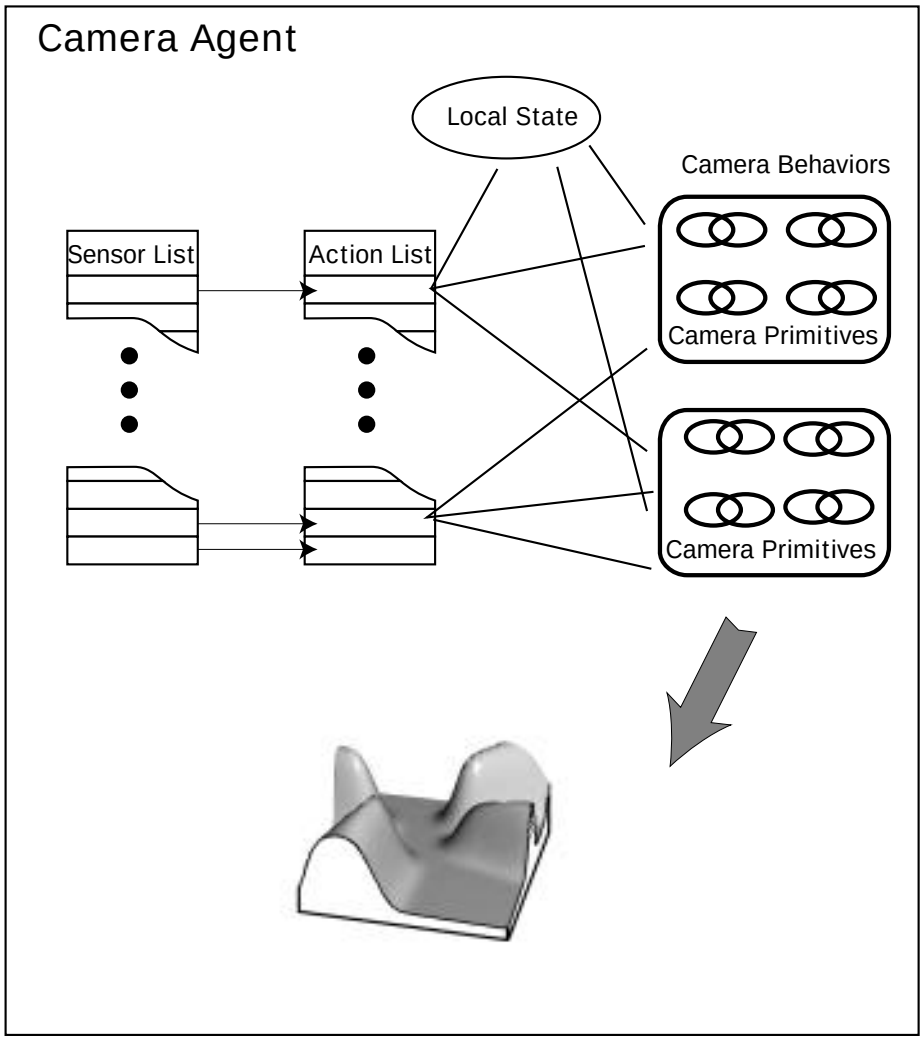


Figure 35: Overview of camera agent

The agent has a sensor_list, paired with an action_list. Each sensor in the sensor_list produces a boolean value upon evaluation; they can be considered high-level sensors with lower level analog sensors feeding values into them to decide whether they are satisfied. When a sensor is satisfied, the corresponding action is fired. Sensing and acting is assumed to occur quickly, significantly faster than the frame rate of the environment, so at any one instant the modeled world is assumed to not change state.

The agent is called upon to evaluate all its sensors for every frame. More than one sensor

can evaluate to TRUE for any time step, and thus more than one action can occur at the time step. Currently, the corresponding action occurs immediately upon the sensor returning a TRUE value and the sensors are evaluated serially in the order they were placed onto the sensor list. Care must be taken in the construction of the actions so that conflicting behavior will not result.

Actions do not directly move the camera, they can be used to change state either in the agent itself, or set up conditions for the camera behaviors. For instance, one sensor can be constructed that detects if any character in the environment has changed position significantly. If so, then a message is sent to all camera behaviors indicating that when they become active, they must reevaluate their state. Otherwise, when they become active, no calculations need occur and they can simply move the camera to their previously calculated state. This is useful for decreasing the computational load of the camera behaviors and allows some measure of precalculation to occur.

The most significant part of the agent are the camera behaviors which are constructed from the primitives discussed in section 5.11.3. This agent has two camera behaviors: over the shoulder of character 2 looking at character 1; and over the shoulder of character 1 looking at character 2 The behaviors are achieved by combining the primitives of section 5.11.3 as follows:

BEHAVIOR 1: Over the shoulder of character 2 towards character 1:

- PRIMITIVE: character 2's center is constrained to appear on the right third, middle of the screen.
- PRIMITIVE: character 1's center is constrained to appear on the left third middle of the screen.
- PRIMITIVE: the camera's gaze is adjusted to be as close to the opposite of the gaze between character 1 and character 2 as possible while satisfying the 2 above conditions.
- PRIMITIVE: the up vector is locked into place.
- PRIMITIVE: the field of view is locked between 45 and 60 degrees.
- PRIMITIVE: no part of character 2 can cross the 1/3 line right of the screen.

- PRIMITIVE: no part of character 1 can cross the 1/3 line right of the screen from the other side.
- PRIMITIVE: the camera is pointed in the general direction towards character 1 as opposed to away from character 1.
- PRIMITIVE: the camera is pointed in the general direction towards character 2 as opposed to away from character 2.

BEHAVIOR 2: Over the shoulder of character 1 towards character 2. This is the exact opposite of the behavior 1, but with the projected positions of the objects remaining on the same sides of the screen. This prevents passing over the 180 degree line from shot to shot.

- PRIMITIVE: character2's center is constrained to appear on the right third, middle of the screen. (same as in behavior 1)
- PRIMITIVE: character1's center is constrained to appear on the left third middle of the screen. (same as in behavior 1)
- PRIMITIVE: the camera's gaze is adjusted to be as close to the opposite of the gaze between character 2 and character 1 as possible while satisfying the 2 above conditions. (This is the opposite of behavior 1)
- PRIMITIVE: the up vector is locked into place. (same)
- PRIMITIVE: the field of view is locked between 45 and 60 degrees. (same)
- PRIMITIVE: no part of character 2 can cross the 1/3 line left of the screen (opposite side of screen)
- PRIMITIVE: no part of character 1 can cross the 1/3 line left of the screen from the other side.(opposite side of screen)
- PRIMITIVE: the camera is pointed in the general direction towards character 1 as opposed to away from character 1.
- PRIMITIVE: the camera is pointed in the general direction towards character 2 as opposed to away from character 2.

An additional behavior can be added that might be used as an establishing shot, or a shot when neither of the two people are talking. This would be a two shot of the two characters facing each other.

BEHAVIOR 3: Side view of characters:

- PRIMITIVE: character 2's center is constrained to appear on the right third, middle of the screen. (same)
- PRIMITIVE: character 1's center is constrained to appear on the left third middle of the screen.(same)
- PRIMITIVE: the camera's gaze is adjusted to be as close to perpendicular to the gaze between character 2 and character 1 as possible while satisfying the 2 above conditions. (This is different from behaviors 1 and 2)
- PRIMITiVE: the up vector is locked into place (same)
- PRIMITIVE: the field of view is locked between 45 and 60 degrees. (same)
- PRIMITIVE: no part of character 2 can cross the center line right of the screen (center of screen)
- PRIMITIVE: no part of character 1 can cross the center line right of the screen from the other side.(center of screen)
- PRIMITIVE: the camera is pointed in the general direction towards character 1 as opposed to away from character 1.
- PRIMITIVE: the camera is pointed in the general direction towards character 2 as opposed to away from character 2.

A deeper analysis of the way that the primitives are combined is in order. From behavior 1, we can classify the different kinds of primitives into 2 different categories: soft constraints (those constraints that do not need to be met exactly), only the best solution need be found among conflicting constraints; and hard constraints (those constraints that need to be satisfied exactly).

First, for the "soft" constraints that don't need to be satisfied at the same time, the solution will try to minimize the maximum of these constraints at any one time. In this behavior, it is not possible to place the center of object 1 at a certain place, AND the center of object 2 at a certain place while making the camera gaze along the vector between object 1 and object 2 (the only way for this last condition to be true is if the center of object 1 and the center for object 2 were projected to the SAME point on the screen). Thus these three

primitives are formulated into an optimization problem where the system tries to minimize the maximum of any violations of these constraints.

The next category of primitives are those for which the solution would be INCORRECT if the constraint is violated (hard constraints). The broad category is further subdivided into several types. There are bounds on the individual degrees of freedom for the camera: make the roll angle equal to 0 (equality); keep the field of view between 45 and 60 degrees (inequality). There are constraints on multiple degrees of freedom of the camera: look towards the object as opposed to away (this constraint is necessary due to the fact that it is mathematically equivalent for a projection of an object to be from behind the camera as it is to be in front of the camera). There are also inequality constraints based on the projection of an object: make sure that no part of the object 1 appears on the left hand side of the screen and no part of object 2 appears on the right hand side of the screen.

The advantage of designing the camera agent in the fashion described above is that the camera agent is reactive. By reactive, I mean that the agent can be set into any environment in which its sensors can work and it can locate the positions of the characters and it will film the actions in the manner specified. If the characters change positions, it will still manage to frame the characters in an acceptable fashion or inform the user when the constraints can not be satisfied. Thus, this agent is reusable across a wide range of environments, containing no special parameters that would make it only appropriate for a single particular environment. The behaviors encapsulate reasonably accepted cinematic rules, and the process of sensing and acting makes the agent automatically construct a sequence of shots in the style specified in figure 34.

6.3.2 Extensions to agents:

Care was taken in constructing the behaviors so that implicitly no cinematic rules were violated. Sensor action pairings can be made more sophisticated so that sensors can check the existing camera state so that no action which will violate a cinematic rule will be subsequently fired.

All the actions described above dealt with discontinuously changing the camera parame-

ters (in other words, cuts). Camera movements can also be supported in several fashions. Once final satisfactory conditions have been calculated, the camera can move from its current state to the final state by a certain velocity profile (ease in, ease out, with a maximum change in any of the camera parameters). Another way to account for camera movement is to include it as part of the optimization problem. Change in the camera state can be penalized along with the goals of the camera, so that any changed in camera state is balanced with maintaining the last specified state.

6.3.3 Results

The following figure shows an over the shoulder shot automatically generated by the conversation filming agent.

Figure 36: Agent generated over-the-shoulder shot.

6.4 Example: the Virtual Football Game

The virtual football game represents a task chosen from the planning domain where the environment is extremely dynamic (as opposed to the relatively static environments of the museum and the conversation). A football game was chosen because there already exists a methodology for filming football games that can be called upon as a reference for compar-

ing the controls and resultant output of the virtual football game. Also, the temporal flow of the football game is convenient since it contains starting and stopping points, specific kinds of choreographed movements, and easily identifiable participants. In addition, a visual programming language for combining camera primitives into camera behaviors was explored. Finally, an interface, on top of the visual programming language, based directly on the way that a conventional football game is filmed was developed.

It is important to note that there are significant differences between the virtual football game and filming a real football game. Although attempts were made to make the virtual football game realistic; three-dimensional video images of players were incorporated and football plays were based on real plays [Korch90], this virtual football game is intended as a testbed for intelligent camera control and not a real football game. In the first case, we are not currently concerned with controlling robotic cameras, since there are a host of other constraints that would need to be implemented to deal with speed and configurational limitations that we can ignore. In the virtual game, the system has complete knowledge about the entire environment, both in terms of where all the objects are in the present and where they will be in the future, it knows when the ball will be thrown, and when it will be caught. The user has complete control over the passage of time in the virtual football game, being able to stop it, reverse it, speed up or slow down. The virtual cameras for visualizing the football game can move to anywhere, including within another object or flying along side it. The system can ignore any of this information, or constrain the abilities of the virtual cameras, as appropriate to the test that is being performed.

The basic visual tasks in the virtual football game are as follows:

Table 16: Tasks from Virtual Football Game

Football Game
Set up cameras in certain prescribed positions.
Track the ball from any camera.
Isolate a player (meaning, show just the player and one or two nearby players).
Show the view from a prescribed camera, and show replays from other prescribed cameras.
Keep two players in view at the same time.
Position the camera in an over-the-shoulder shot from the quarterback to another player.
Show the field from the point of view of any player or the ball itself.
Move with the ball during a play.

This information is based on a discussion with a sports director from WBZ-TV news in Boston, MA. The first five tasks are typical commands that the director indicates to the cameramen.The last three tasks can not be done in a real football game since it would involve both moving the camera onto the field, and a camera that could fly through the air with the ball. These were visual tasks were added to demonstrate the power of the camera framework.

6.4.1 Implementation

The overall structure for the football game is extremely similar to that of the virtual museum and mission planner systems. It is shown in figure 37.

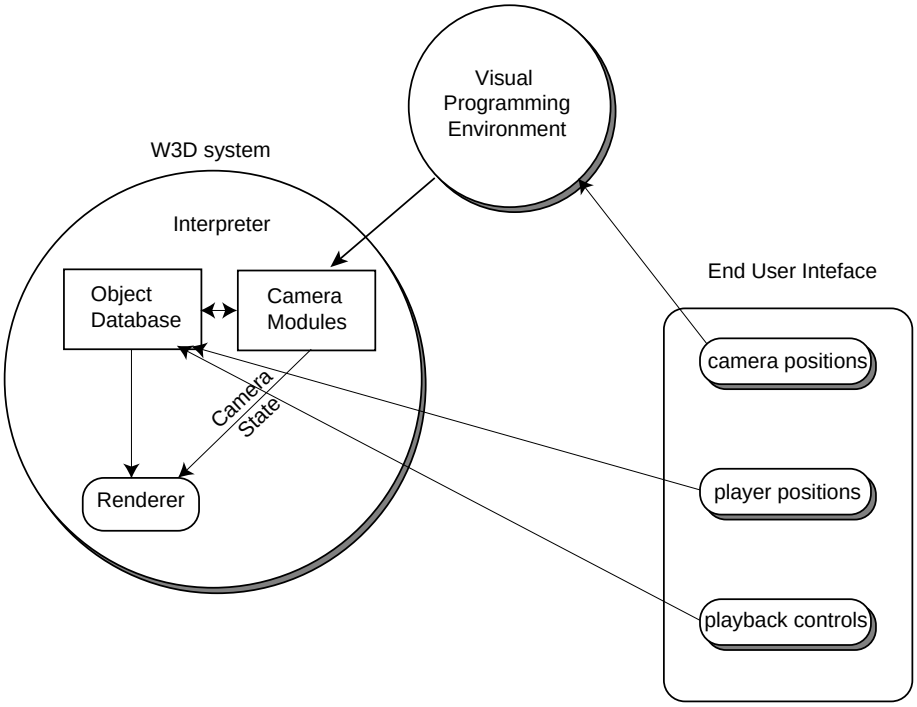


Figure 37: Overview of virtual football game

Figure 38 shows the visual programming environment for the camera modules. The currently active camera module's camera state is used to render the view of the graphical environment. Modules can be connected together by drawing a line from one module to the next. A boolean expression can then be added to the connector to indicate when control should be shifted from one module to the connected module. It is possible to set up multiple branches from a single module. At each frame, the branching conditions are evaluated and control is passed to the first module whose branching condition evaluates to TRUE.

Constraints can be instanced from existing constraints, or new ones can be created and the constraint functions can be enterred via a text edittor. Information for individual constraints can be entered via the keyboard or mouse clicks on the screen. When constraints are dragged into a module, all the constraints in the module are included during optimization. Constraints can be indicated to be hard or soft constraints in which case they are incorporated in different ways into optimization problem (see section 5.10). Constraints

may also be grouped so that slightly higher level behaviors composed of a group of low level primitives may be dragged directly into a camera module.

Initial conditions can be dragged into the modules to force the minimization to start from those conditions. Initial conditions can be retrieved at any time from the current state of the camera. Camera modules can also be indicated to use the current state to begin optimization when control is passed to them from other modules.

Controllers can also be instance from a pallette of existing controllers, or new ones created and their functions entered via a text editor. If a controller is dragged into the module, it will translate the actions of the user subject to the constraints within the module. For instance, a controller that will orbit about an object may be added to a module which constrains the camera's up vector to align with the world up vector.

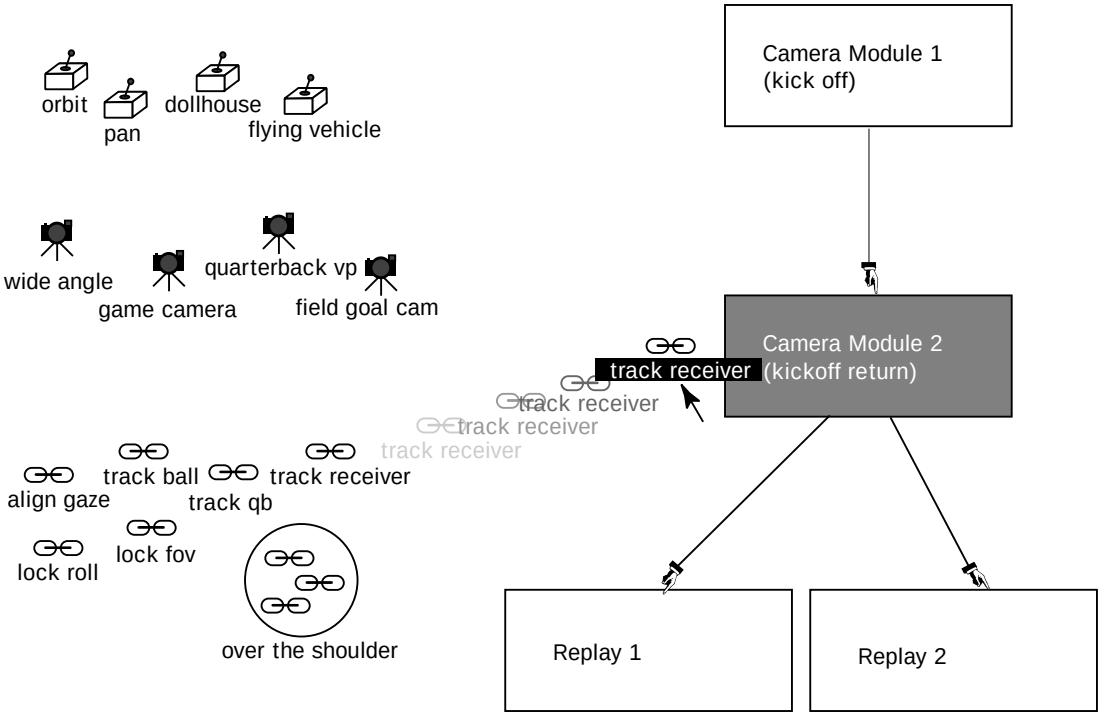


Figure 38: Visual Programming Environment for camera modules

The end user does not necessarily wish to be concerned with the visual programming lan-

guage for camera control. An interface that can be connected to the representation used for the visual programming language is shown in Figure 39.The interface provides a mechanism for setting the positions and movements of the players within the environment, as well as a way to control the virtual cameras. Players can be selected and new paths drawn for them at any time. The players will move along their paths in response to clicking on the appropriate buttons of the football play controller (shown in figure 40). Passes can be indicated by selecting the appropriate players at the appropriate time step and pressing the pass button on the play controller.

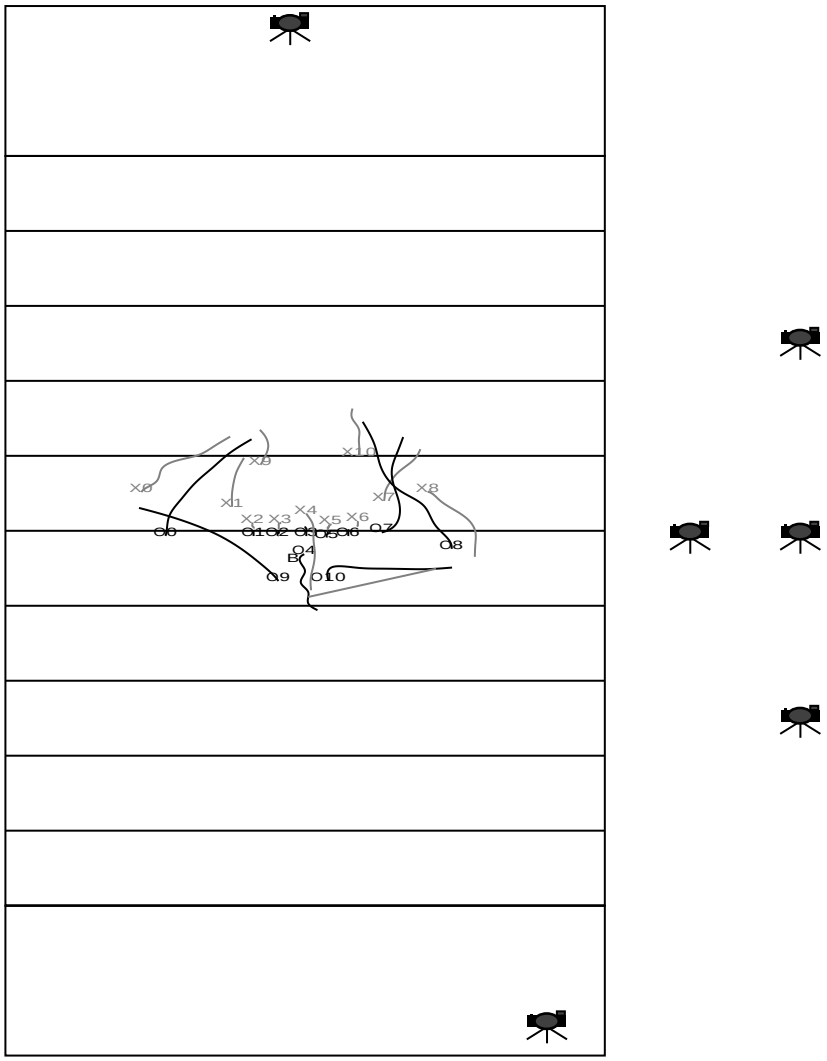


Figure 39: Overhead view of the football game

Figure 40: Playback Controller

The user can also select or move any of the camera icons the viewpoint is immediately shifted to that of the camera. Essentially, pressing one of the camera icons activates a camera module that has already been set up with initial conditions and constraints for that camera. Cameras can be made to track individual characters or the ball by selecting the players with the middle mouse button. This automatically adds a tracking constraint to the currently active module. If multiple players are selected, then the camera attempts to keep both players within the frame at the same time by adding multiple tracking constraints. The image can currently be fine-tuned by adjusting the constraints within the visual programming environment. A more complete interface would provide more bridges between the actions of the user on the end-user interface and the visual programming language.

6.4.2 Results

An evaluation of the virtual football game is given in section 7.2.4.

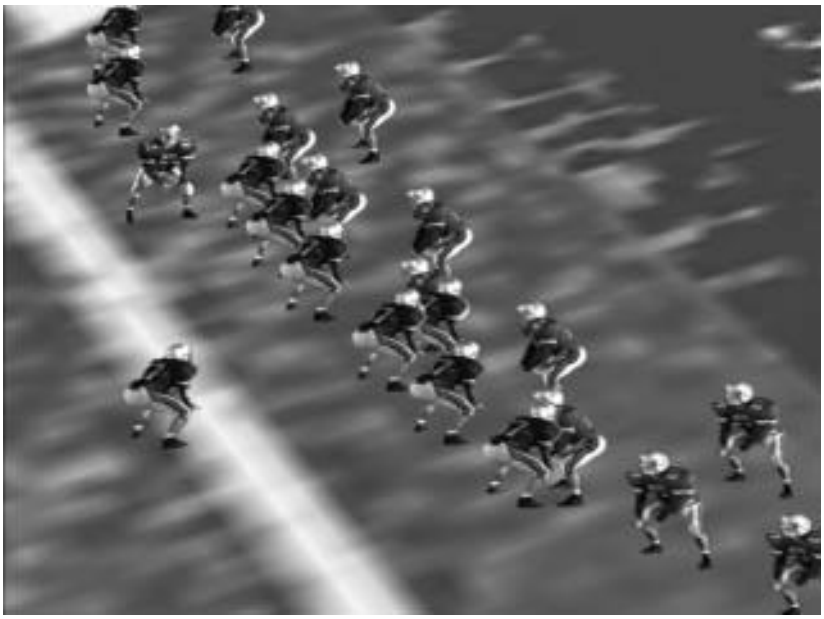


Figure 41: View from “game camera” of virtual football game.

6.5 Example: Visibility Assistant

The last example is a prototype visual task from the control domain. It illustrates the ability of an intelligent camera to assist the user in performing manipulation style tasks by maintaining a viewpoint where a certain goal object is visible. The camera primitives demonstrated in this example could be combined with other camera primitives that would align the control axes with the visual axes.

Because this is simply a demonstration of a visibility assistant, the only visual task for this application is to keep a single goal object in view.

6.5.1 Implementation

Figure 42 represents an overview of the visibility assistant. In general, the visibility assistant monitors the positions of all the objects in the environment and automatically adjusts the camera modules to present an unobstructed view of an object. The user can interact directly with the visibility assistant by telling it to only update the view on demand. The camera primitive for visibility is discussed in detail in appendix 2.

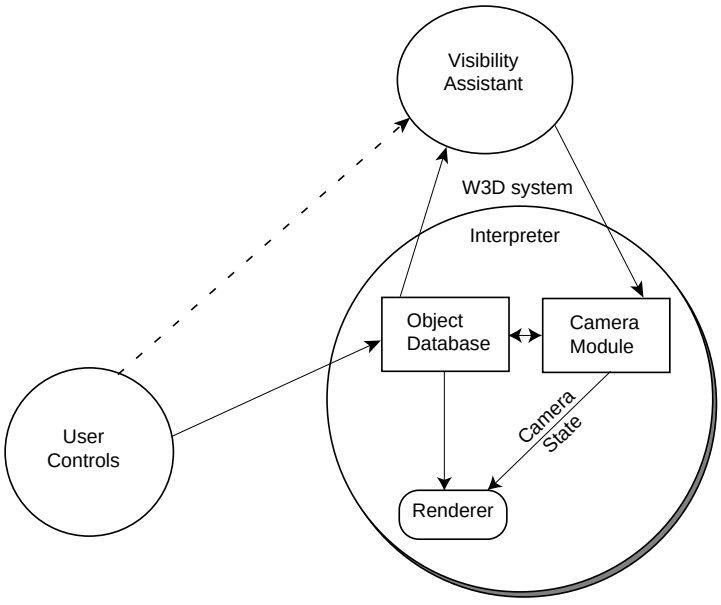


Figure 42: Visibility Assistant Overview

The following code fragment illustrates how the visibility assistant is called from a routine.

```
proc doit {} {
    # grab the current view
    set q1 [grabview]

    # find a view where we can see the goal location
    set q2 [findvis [vp] [centroid goal]]

    # move to that view slowly
    loop i 1 20 {interp_views $q1 $q2 [div $i 20]; render}
}


proc findvis {vfrom vto} {
    global vals

    savestate

    # make background white
    bg 1 1 1

    # look from goal object towards orignal location
    vp $vto
    vn [minus $vfrom $vto]

    # make far clipping distance same as length between goal
    # and camera location
    vdepth 0.1 [enorm [minus $vfrom $vto]]

    # use software rendering
    hardware 0
    screensize 0 0 127 127
    render2file /tmp/vis {} {}

    # render an image
    render

    hardware 1
```

```
    # ask other program to find visible position for camera
    send tkvismap {after 1 {ckvis [winfo name .] /tmp/vis}}

    # wait until other program responds - it will set the variable
    # vals when it is finished.  It is done this way because it can
    # take as long as 30 seconds and the send statement would time out
    # with no response if we used set vals [send tkvismap {ckvis /tmp/vis}]
    # ckvis first generates a potential surface from the visibility map
    # and then follows it down to the nearest visible region
    tkwait variable vals

    # convert from map to pan and tilt values
    set vals [frommap [lindex $vals 0] [lindex $vals 1]]

    # pan first, then tilt
    cam_pan [mult -1 [lindex $vals 1]]
    cam_tilt [mult -1 [lindex $vals 0]]

    # find new location for camera
    set dist [enorm [minus $vfrom $vto]]
    set newvp [plus $vto [mult $dist [vn]]]
    vp $newvp

    # make new camera look directly at goal object
    lookat $vto 0

    # find camera state to return
    set q [grabview]

    restorestate
    return $q
}



proc savestate {} {
    global savebg savescreen savedepth

    # save view parameters, background and clipping planes
    vpush
    set savebg [bg]
```

```
    set savescreen [screensize]
    set savedepth [vdepth]
}


proc restorestate {} {
    global savebg savescreen savedepth

    # restore view parameters, background and clipping planes
    bg $savebg
    screensize $savescreen
    vpop
}
```

6.5.2 Results

An evaluation of the visibility assistant is given in section 7.2.5.

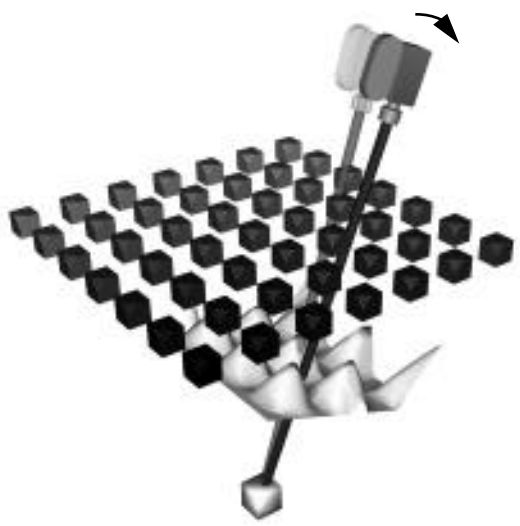


Figure 43: Visibility Assistant

CHAPTER 7. EVALUATIONS OF CAMERA CONTROL INTERFACES

This chapter evaluates the effectiveness of the camera framework at several different levels:

- Is the framework proposed useful across a sufficiently representative sampling of domains? Do the camera primitives assist the user in completing tasks in the examples?
- How convenient is it to place new interfaces on top of the framework?
- How well do the camera primitives work? This can be looked at from a computational point of view and a stylistic point of view.

7.1 Framework sufficiently representative:

The prototype applications that have been chosen have been selected to be from each of the domains described in chapter 4. The virtual museum is an application primarily in the *exploratory* domain and several different styles of interaction have been demonstrated for different tasks. The conversation and virtual football game both represent tasks from the *planning* domain. The primary difference between these two is based on the kind of interface that has been constructed. In the conversation, a well defined, encapsulated agent with different behaviors in response to different events has been constructed. In the football game, a visual interface for combining and sequencing camera primitives has been demonstrated, and a special purpose interface based on the requirements of real football directors has been built. The mission planning system represents a task primarily from the *rehearsal* domain. Different requirements, such as hands free operation, has necessitated another, significantly different interface. Finally, the visibility demonstration represents one aspect of the requirements of a *control* task.

In the following section each of the examples is examined in terms of the kind of assis-

tance it has provided. Help for determining the quality of this assistance has been from domain experts including Michael Sand (a museum designer), Eric Eisendratt (a sports director for WBZ-TV), Glorianna Davenport (in her capacity as a documentary film maker), and Professor Tom Sheridan (an expert in teleoperation and supervisory control). Quotes have been included from these domain experts when appropriate.

7.2 Types of assistance:

In the introduction, a number of ways in which human reasoning and planning can run into problems were described. This analysis will in part be devoted to seeing how those problems have been alleviated by the camera primitives that have been provided.To review, that list is as follows (for a more complete description, see section 2.1.3 or [Norman92]):

1. Lack of completeness.
2. Lack of precision.
3. Inability to keep up with change.
4. A heavy memory load.
5. A heavy cognitive/computational load.

7.2.1 Types of assistance in the Virtual Museum

Lack of completeness.

In any database related application, the system can contain knowledge represented in a variety of formats which the user does not have access to. In its first and simplest form, the Virtual Museum contains knowledge of all the pieces of art within the museum, where they are located, and their ideal viewing position. Through a simple user request (currently a listbox with a mouse selection though alternate means such as voice recognition might be more appropriate in a totally immersive environment) the virtual camera can be transported instantly to a location and angle to view the selected artwork.

Associated operations can be performed on the basis of specific domain knowledge that the computer contains for the museum.

Let me give you a rational of why I think your project is good. A very typical

> problem in a museum is for a visitor to come to a problem that they're not conversant with and understand what choices they have at this point; the menu problem. Are there any specials today? What time of day is it? How long will this take? A series of contextual things that the computer can be aware of but the user might not be. If you could go to a lobby kiosk and describe yourself to the computer and say that I have a 5-year old with me and I also have my mother in law with me who has trouble walking and who doesn't want to see breasts (she get's upset by nude paintings), and it's my 3rd visit here and I haven't been here in 8 months, the computer can automatically regurgitate to you, using your rule set, an optimal path since we're only open for another hour and a half today; etc. The rule set could construct a tryptic for the visitor and a print out which gives you a timed intervalometer, saying spend 10 minutes here, 15 minutes here, and your 5 year old will love this, and it has a set of decisions that the curators and you have conspired on. For instance if you haven't been here for 8 months, you must see this new exhibit because everybody enjoys that. So you've immediately given someone a personalized tour that's unique to them for the moment. It can generate informed decisions based on your input, and even give you choices once it's come up with options too, secondary and third level decisions [Sand94].

Lack of precision.

The virtual museum allows automatic placement at precisely the best point for viewing certain objects in the museum (based on preselected opinions of the designer).

> That would be useful in some of the walkthroughs that I've built for demonstrations to clients. You can click on a particular object, or set up a prefixed view that is appropriate for that object. Kodak has this "stand here - use f-12 and take a picture" located at all sorts of famous sights which allows tourist to create the perfect take home shot [Sand94].

A heavy memory load.

The system can use internal memory to recall specific views that the user has saved or even show different portions of the environment that have already been explored. Orientation, seems to be intimately related to memory, since remembering the movements made before can sometimes be the only method of locating oneself in an environment. In the Virtual Museum, orientation within the environment is provided for via a map-view which contains the user's location and direction of gaze within the museum.

> Giving you several ways to look at something is very important. Different people have different predilections. Some people will love the plan view that you've got there. Other's would find it very confusing, others might want an orthographic projection, other people would just like the point of view. Other people might want an iconic view, like an MBTA map compared to a road map. You don't have to presume that one size fits all. The great thing about the computer is that you can provide any one that the person wants. If the person wants words and a list, that's fine [Sand94].

Inability to keep up with change.

The Virtual Museum is primarily a static domain so this is not a consideration in this application.

A heavy computational/cognitive load.

In this case, overly repetitive situations, or situations where there are too many variables to control can be greatly eased by the museum interface. When moving the virtual camera through the museum, the user must constantly be specifying the desired position, orientation, and direction of movement within the museum. The interface provides a number of ways to ease the repetitive, complex nature of the task. First, the motions of the user's mouse presses can be mapped in such a way to minimize the number of degrees of freedom being controlled. In this case, forwards or backwards on a virtual joystick constrains the speed of the virtaul camera's movement through the environment, right to left constrains the direction the view is turning (center implies no turn). The height of the virtual camera is constrained to be the same height throughout control. While this limits the degrees of freedom that are controlled to a manageable number, the user must still provide continuous input. Alternate modes of control let the system take over movement of the viewpoint to a calculated path to a specified goal location. The user can control the view direction alone if desired or have the view direction point either straight ahead or at objects of interest along the way. In addition, the system can make more use of internal knowledge and calculate the best path from a particular location to another particular location, avoiding obstacles within the environment and taking user requirements into account (for instance, the user might want to avoid passage through certain areas - such as non-handicap accessways). The virtual museum can assist in several other ways to shift the computational burden from the user to the computer. The system constrains the movements of the

virtual camera from passing through walls. This prevents rapid changes in the image which can be confusing to a user.

> Does it find it's own trajectory? You have some sort of rule set? That's terrific! That would be very useful. Did you ever read the writings of Kevin Lynch. He has some good ideas about this in his "A View from the Road" book. He wrote one talking about the experience of driving. As you're driving, you're cognizant of the things that are going by, and we really take our sense of place from the conglomeration, this gestalt of experiences and not just from the destination and he and I discussed ways in which you could come up with a new iconography that would be a new type of road sign, that would have to do with signs and combinations that were happening [Sand94].

7.2.2 Types of assistance in the Mission Planner System

Lack of completeness.

The mission planner contains physically based simulations of the behaviors of the aircraft in the environment. The user does not need to be familiar with calculating the g-forces based on banking the plane since the simulation can perform those actions for the user.

Lack of precision.

The mission planner can constrain the view exactly aligned with the axes of the plane which may vary due to banking and other movements. The system can be used to look from any object in the environment to any other object, and lines of sight can be easily and precisely determined.

Inability to keep up with change.

Since the mission planner represents a dynamic environment, it is important that it assist the user in tracking moving objects, or placing the viewpoint along moving objects looking towards other objects. The user does not need to make any active effort to observe changes in the environment.

A heavy memory load.

Sharp discontinuities between views make it difficult to understand the relationships between objects within the environment. By constraining the pan rate of the virtual cam-

era, the system can be used to help create and maintain a cognitive map of the mission planning environment.

A heavy computational/cognitive load.
The system can map simple, high level voice commands from the user into actions for the virtual camera in the environment. The user does not need to control individual degrees of freedom of the camera at any time but can easily constrain the camera to move with or to follow objects in the environment.

7.2.3 Types of assistance for Conversation Agent

The conversation agent shows potential in many areas. It is a first stab at encoding cinematic rules into a high level language that can be used in a variety of different situations. It is a reactive system which can change its response based on changes within the environment. It can also relieve the user from the burden of low level control of the camera.

Lack of completeness.
One of the most interesting possibilities enabled by camera primitives is the ability to create a high level language which incorporates cinematic rules. The rudiments of this language have been demonstrated by being able to perform a medium shot, or an over-the-shoulder shot, but much more work can be done. The system can aid those that know at a high level what they want, but don't want to know the details of controlling a virtual camera in a graphical environment. Or the system can offer a first pass suggestion to how a shot should be framed. The user can then choose this shot or alternate shots to help previsualize how a sequence should be shot.

Lack of precision.
The ability of the system to find the camera position based on framing specifications is particularly exciting. This was one of the biggest problems with previous systems that have been used including the CINEMA system. It was always difficult to find an appropriate position for the camera. It's also exciting that there's a precise level of control related to what's in the frame as opposed to just where the camera is in space. That's much more accessable to an actual moviemaker.

Inability to keep up with change.
Another exciting potential of the system is its ability to respond to a changing environment. As the characters are moving about the system might eventually be able to make choices on how to film the situation based on stylistic rules and higher level knowledge of the narrative structure in the situation. For instance, if one character stands up in a scene, it may be appropriate to follow him by panning and tilting, or it could be qualitatively different to follow him by moving the entire base of the camera around. A complete system must incorporate both audio and plot elements in order to continue research on a flexible, reactive agent.

A heavy memory load.
The system can help maintain continuity from shot to shot. It can automatically ensure that certain objects are in view across cuts and it can maintain framing conventions across edit boundaries. Even more significantly, once a higher level language is developed which includes cinematic style, continuity of style throughout entire sequences could be maintained.

A heavy cognitive/computational load.
The system can first ease the cognitive load of understanding the environment by allowing the user to recover the positions of objects and the camera in relation to each other. It can also, as previously discussed, take the high level framing specification and find a position for the camera that satisfies the diretor's goals. When a director is not satisfied with a shot, the system might be able to offer alternate possibilities placing different emphasis on the director's goals.

7.2.4 Types of assistance for Virtual Football Game

The virtual football game system can assist in the following ways.

Lack of completeness.
By providing the system with the knowledge of what type of play might be transpiring, the system can choose a style of viewing that might be most appropriate. The system can act

as a kind of expert system for filming football games.

> When we're out there filming a game, the director quickly gives rough instructions to all the cameramen and they know just what to do. They can tell in the first moments of the play whether it will be a passing play or a running play and they know how to cover each play [Eisendratt94].

Lack of precision.

In shooting a real football game, one of the biggest problems is for the camera man to respond quickly enough to movements of the ball in order to track it accurately. Given absolute knowledge about the position of the ball, the virtual football game can always track the ball precisely.

> When a play is taking place, we never cut from one camera's view to another because it might be confusing and because we might miss some action. The cameramen are doing their best to keep the ball in view at any moment and they often don't have much time for anything else than that. It would be great if we could automate some of that in filming a real football game like you've done in the virtual football game. It really might bring about whole new possibilities for covering a game [Eisendratt94].

Inability to keep up with change.

The user can specify certain objects that are to be tracked and let the system perform the rest. Furthermore, certain conditions can be specified, for instance, keep two certain characters in view at the same time and the system will maintain those conditions.

> This goes back to the lack of precision issue. If we can automatically follow any player and the ball in real life, that would help our jobs a great deal. The only thing is then is that you'd want to have more cameras to cover more possibilities. I'd like a camera to catch the reaction shot of the coach while a play is happening and not have to sacrifice any of the cameras that I'm using to cover the play. In really high-budget games like a SuperBowl, you've got all the cameras you need, but in other games you've only got the 5 or 6 cameras set up in the way you have it set up in the virtual football game [Eisendratt94].

Heavy cognitive/computational load:

Many situations in filming the a football game repeat over and over. By encapsulating a set of rules into a camera module, the modules can be used over and over with small variations due to stylistic preferences. Also, currently, filming a football game usually takes at

least one director, and at least 6 camera people each who has a specific job during filming the play. By being able to automate both the choice of jobs and the actual filming itself, the system could greatly ease the computational load for a director, and the director could concentrate more on the style of the presentations.

> It does start to get to be a kind of repetitive task filming a game. But the interesting stuff is when things go wrong with a play, or catching the reactions of players when special things happen. I don't think you could automate that, though you certainly could automate some of the rest like following the play as you've done and catch some of the other things by hand [Eisendratt94].

7.2.5 Types of assistance for Visibility Assistant

Lack of completeness.

The visibility assistant can keep track of the positions of all the objects in the environment and even if the user does not know a particular position of an object, the assistant can be used to find a view where that object is visible.

> I think it would be interesting if you used the system to help keep track of views of people besides just views of objects. This could be related to some work that is being done in Computer Supported Cooperative Work. People could direct the camera by "pulling" the camera to face them, or show other people views of things by "pushing" the camera to a certain point of view. It would be especially interesting if you could somehow find the camera constraints that might support this kind of behavior.[Sheridan94].

Lack of precision.

The change of view can be made so that the camera moves the minimum amount in order to place the object in view.

Inability to keep up with change.

The system can automatically keep track of the movements of all objects in the environment including both occluding objects and the goal visible object. The viewpoint can be changed constantly to keep the object in view or only on user request (since constant changes of the view might be disorienting for the viewer).

A heavy cognitive/computational load.

The computational burden of tracking an object and making sure it is visible has been removed from the user and transferred to the intelligent camera interface.

> It's very important that the user has some level of choice when the system chooses views. Motion parallax is an extremely useful set of depth cues and we found that in experiments, users really needed that to perform better. In addition to a visibility constraint, Harry Das did some experiments for automatic view selection for controlling a telemanipulator. He tried a view that tried to maximize the angle between the camera and the lines which connected the end-effector and the goal and obstacle objects. It seems that you could do that fairly easily in the context of your framework[Sheridan94].

7.3 Convenience of the framework

The convenience of the framework still remains to be proven. Although the framework has been used in a number of diverse applications, I have been the only programmer to use it so far. Several projects where others will incorporate the framework for controlling the camera. One researcher will use the framework to design a cinematic previsualization system. Another researcher will use the framework as the basis to control the camera in an interactive, immersive, narrative environment.

7.4 How well do the camera primitives work?

This question can be addressed in three different ways. First, do the primitives achieve the desired goals of the user. Second, how efficient is the framework for achieving those goals. And third, does the output of the primitives look right stylistically to the user, and is the output sufficiently customizable to give the user of the system sufficient stylistic control over the final output.

One of the problems of trying to thoroughly examine the effectiveness of the primitives are that they can be combined in an infinite number of ways. It is impossible to check to see if all the combinations do eventually converge to the desired results. One basic problem in all systems based on constrained optimization is how the system deals with local minima.

7.4.1 Local Minima

Several methods have been developed to alleviate the problem of the camera settling into a locally optimal solution which is not necessarily an appropriate solution. Sometimes this situation is not a problem at all but a desired result since local optimums may be sufficient.

The first method of dealing with local minima is to explicitly design the algorithm to generate a constraint surface that does not contain any local minima. This is the method used for one type of path planning and the visibility algorithm. In both these methods, a distance function from a goal location was generated by propagating a wave away from the goal. The wave moves around all the obstacles in the environment and thus guarantees that the goal location will be the only minimum in the system. However if more than one constraint is combined, this condition can no longer be guaranteed.

Another method of escaping from local minima was explored in the context of path planning by discretizing the space and using a breadth first search of the gradient of the surface. Thus the system is guided by optimization but if it settles in a local minimum that is known not to be the goal, the system can search further and further away from the local minimum, until a new minimum direction is found.

Yet another method of overcoming local minima is to use external knowledge to guide the initial location for starting the minimization. This was used for some of the simple projective camera constraints such as the over the shoulder shot. If the user starts the minimization with the camera located somewhere on the line (but not between) that connects the two objects that are the goals of the primitive, the system usually does not get trapped in local minima.

Finally, a last method that can be used is to restart the minimization process from a variety of locations in the environment and to eventually use the lowest minimum. This is similar to the method of simulated annealing and has been extremely successful at solving a number of nearly intractable problems. On a sufficiently fast system, perhaps a massively parallel one, this might be an extremely robust way of dealing with local minima.

Somewhat surprisingly, in the five systems demonstrated, local minima were rarely a prob-

lem for the constraint solver. Local path planning (appendix 1.3 – non-wave propagation) was the constraint most prone to local minima. Occasionally, some projective constraints would also be trapped in local minima when the solution was started at a completely arbitrary position. A “nudge” from the user usally alleviated the problem. Sometimes, it was better to formulate the problem for certain constraints as “hard” constraints, and then later relax the requirement and incorporate them as “soft” constraints once a better initial condition was found for the optimization.

7.4.2 Efficiency

The efficiency of the constraint framework does of course depend upon the number and type of constraints and optimization functions being attempted. Currently, the system can usually solve a problem containing 3 non-linear optimization functions and 9 nonlinear inequality constraints in approximately one tenth of a second on an IRIS Indigo system.

The algorithms for path planning and visibility determination involve extensive calculations for determining the constraint surface before optimization. However, once these surfaces are calculated, the solution is extremely rapid. The visibility calculation for a typical scene takes less than 4 seconds on an IRIS Indigo system. Currently, the system is using the built in software rendering to generate the visibility map and the speed of this part of the algorithm could be sped up considerably by using the hardware renderer of the workstation. However, the most time consuming part of the algorithm is propagating the distance wave from the visible regions. This algorithm is readily amenable to parallelization which could bring about significant speed enhancements. In the path planning algorithm, most of the constraint surfaces can be precalculated so that the paths can be found in milliseconds on an IRIS Indigo system. The precalculation can take up to thirty seconds depending upon the number of nearest neighbors used for expanding the wavefront.

A thorough algorithmic analysis for the CFSQP is provided in [Lawrence94] and is not discussed in this thesis.

7.4.3 Stylistic Expressiveness

This is the most difficult quality to assess, but many attempts have been made to make

some of the primitives both stylistically flexible and for their output to look correct. To a certain extent, this is discussed in section 7.2.3.

In the pathplanning primitive, there are a number of parameters that can be controlled including the closest distance that the camera may be to an object as it passes. Also, the number of directions that the camera can move from any discretized location on the constraint surface has been examined along with the affects on the resultant paths. One key point of the path planning primitive is that it treats the position of the camera separately from its orientation. While this makes the computation and search of the potential function possible, it may lead to the somewhat inhuman behavior of the planned path. By using multi-resolution optimization methods, it might be possible to plan a path that also contains optimization conditions on the orientation of the camera during planning. Another noticeable problem with the path planning constraint is the way in which it travels through doorways. Since the distances function that is propagated out from the doorway moves equally in all directions, the camera will often approach the doorway at an oblique angle which is extremely disconcerting. This can be overcome by changing the way the distance function propagates from the doorway, or by adding constraints to the interpolating spline. Finally, the path planning does not constrain the velocity of the camera at all, so that the speed of movement along the spline is now determined completely independently. Further constraints might be appropriate to allow easing in and out of movement or slower movements at points of interest.

The visibility constraint currently moves to the nearest visible area, but that area might be extremely small. A way of balancing the nearest area with the largest area might be useful stylistically.

Some of the other camera primitives might be used as a basis for forming a high level language for stylistic expression. This could enforce stylistic consistency across sequences. For instance, if a situation is tense, a constraint could be added that prevents the camera from ever being more than a certain distance from an object or that the projection of all objects of interest be a certain size or greater. Or if low angles are preferable for a situation, then the camera's position can be constrained to always be from below a certain level.

There is no inherent style in these primitives themselves, but only in the ways that they can be combined.

CHAPTER 8. CONCLUSIONS AND FUTURE WORK

8.1 Conclusions

This thesis has taken a systematic approach to the problem of controlling a virtual camera within a graphical environment. The first step involved generating a classification of different interactive graphical domains. This taxonomy has been used to derive the visual tasks that are required in each domain. The taxonomy may be useful for deriving other, non-visual tasks, for instance if someone wishes to explore mechanisms for end-user programming in interactive graphical environments, it would be necessary to provide methods for each of the domains described in the taxonomy.

In addition to the taxonomy, pertinent methods and techniques have been examined from the areas of cinematography, human factors, teleoperation, and robotics to help define camera primitives for accomplishing visual tasks. Particularly novel are *projection* camera primitves that help define the position of the camera based on a desired configuration of the resulting image (see section 5.11.3).

A framework based on constrained optimization for combining and reusing camera primitives has been proposed and constructed. Primitives can be encoded as constraints and can be combined in a number of different fashions ranging from hard constraints, where a solution is incorrect if the constraint is not met, to soft constraints where the system tries to balance among a number of conflicting constraints.

On top of the framework a number of different example applications have been built. The examples demonstrate not only many different styles of interfaces, but were selected as a

representative sampling of the domains described in the taxonomy.

The virtual museum represents the exploratory domain. The virtual museum tied widgets and mouse clicks to the activation of different modules constructed from the camera primitives. The mission planner is an example from the rehearsal domain. The mission planner uses an immersive environment and high level commands with a voice recognition system. The conversation filming agent represents an application in the planning domain. Camera primitives are encapsulated into the behaviors of a reactive agent which can automatically incorporate rules for presenting the scene to an external observer. The virtual football game is also an application in the planning domain. A visual programming language has been developed to easily combine and sequence camera primitives. The visibility assistant is an example of an application in the control domain. The camera responds to changes in the environment to keep an object constantly in view allowing the user to perform a task effectively. The examples were evaluated by consulting domain experts in each of the areas and by identifying the ways in which the camera could assist the user in perfoming tasks within each application.

8.2 Future Work

A good thesis is not an end but a beginning. There are many things that can be done to extend this work, both to improve it and to push it in new directions.

8.3 Improving current work

Using TCL as a prototyping language for the development and testing of new camera primitives made it possible to try out many different ways of encoding and combining primitives. However when the same routines were re-coded in C, the performance was more than two orders of magnitude faster. An automatic way to compile TCL-code, or a more efficient interpreter such as an embeddable Scheme would be a welcome addition to the the extended 3d system.

Nearly all the camera primitives have relied on the constraint solver’s built in ability to find gradiants through forward differencing. By including a method to evaluate derivatives

symbolically such as those suggested in [Gleicher92], [Cohen92], or [Kass92], the system could be made more robust and more efficient.

Higher dimensional manifolds would be interesting to explore, especially for the path planning and visibility constraints. For more dimensions than three, multi-resolution optimization techniques would probably be needed. The path planning and visibility constraints lend themselves to parallel computation and this would be an interesting avenue of research. Path planning through a dynamic environment is still a very difficult problem and research in that direction would be also be interesting.

8.4 Extending the current work

This thesis has shown that camera primitives can form the basis for the behaviors of software agents. More sophisticated agents that can actively decide among a number of built in behaviors, or perhaps to combine primitives into new behaviors on the fly present exciting possibilities. The software agents can be designed to automatically present information in a coherent fashion or be used within interactive environments to guide the way the scene is depicted. Multiple agents with different goals and perceptions can each show a different representation of the graphical environment to different observers.

Whether the camera primitives are embedded in software agents, or combined and sequenced explicitly, a higher level, cinematic language needs to be developed. The proper language could permit an ease of interaction with graphical environments that does not exist today. Stylistic expression in cinematography has just been touched on in this thesis. It would be interesting to attempt to quantify an analysis of cinematic style and attempt to incorporate that analysis into a software agent. The camera primitives discussed in this thesis are a basis for the actions of the agent, but not for the reasoning.

The convenience of the framework is still somewhat unproven. It needs to be used as the basis for many different user interfaces. The process of building an interface takes several iterations of design and user testing. It would be desirable to build a number of interfaces for tasks ranging from cinematic pre-visualization to automatic filming for interactive narrative environments.

APPENDIX 1: PATH PLANNING

The following chapter describes the algorithms for pathplanning used in this thesis.

The problem of finding a collision free path through a complicated environment has been examined a great deal in the context of robot motion planning. There have been several attempts at incorporating pathplanning systems into a graphical environment, or using the special capabilities of graphics hardware to assist in path planning [Lengyel91]. In general, the problem can be thought of as either vector-based approaches or bitmap approaches, somewhat akin to hidden surface removal in computer graphics. The vector based approaches involve decomposing the problem into an equivalent graph searching problem by constructing visibility graphs or connected regions [Lozano-Perez80, Brooks83]. The bitmap approaches involve discretizing space into regular occupied or free cells and traveling through bitmap from one adjacent cell to the next [Lengyel91, Barraquand89, Latombe91].

Schröder and Zeltzer implemented an algorithm introduced by Lozano-Perez [Lozano-Perez80] in a virtual environment system called BOLIO [Schröder88, Zeltzer89]. A visibility graph was constructed based on the projection of all the objects in the environment onto the floor plane. The actor's position and the destination position were then connected to the visibility graph and the A* algorithm was run to search the visibility graph. The entire algorithm needed to be rerun whenever an object was moved. The visibility graph method tends to produce paths that graze objects as closely as possible as well as paths with straight lines connected to other straight lines which may be an unnatural way to move a camera. The algorithm also does not take advantage of the graphics hardware capabilities present in a graphics workstation. The path planning scheme described in this

paper uses a room-to-room visibility graph to first determine the overall path for the camera, but then uses other more appropriate techniques for negotiating each room.

The local path planning technique used here is somewhat based on [Latombe90] in which the scene is rendered from an overhead view and a bitmap is constructed with each pixel representing either free space or an obstacle. This bitmap was then turned into a configuration space by growing each obstacle region by the size of the moving object for several different orientations. In our system, we assume a spherical size for the camera so the configuration space does not need to be concerned with rotation. A numerical function was propagated through the bitmap from a destination location to the current location and an appropriate path through the configuration space was found by following the downward gradient of the numerical function. Their goal was not for camera motion planning or even for graphics animations, but to use a graphic workstation to assist in robot motion planning. Their paths were not necessarily suitable for camera movements due to the distance metric which they chose to propagate through the configurations space. They propagated the numerical function only until it reached a given starting point. In contrast, our algorithm is designed to be used in a building environment, precomputing as much as possible, and is specifically tailored to controlling a camera in a natural fashion.

The pathplanning process is decomposed into several sub-algorithms, many of which can be precomputed in order to speed calculation as much as possible. First, a general description of the overall process is given, then more detailed descriptions of each sub-algorithm follow.

The problem of traveling from one point in the museum to another point is first decomposed into finding which doors to travel through. A node to node connectivity graph is precomputed based on the accessibility between adjacent rooms in the environment. Accessibility can either be indicated by hand, or by an automatic process which uses a rendered image of the building floor, clipped at door level, and a simple visibility test between points on either side of a door. This visibility graph can be updated based on special accessibility requirements (such as handicapped access between rooms).

Traversing the graph is done by a well known graph searching technique called A* [Hart68]. The A* process, discussed in section 1.1, produces a list of "straight-line" node-node paths. Paths then need to be computed between each node to avoid obstacles within each room.

The process of finding the path from a doorway to any point within a room, or finding the path from any point in the room to the doorway is discussed in section 1.2. This algorithm is optimized for finding paths that originate or terminate at a doorway, so another algorithm must be used to navigate from one point to another point within a room. This second algorithm, described in section 1.3, can also deal with a partially dynamic environment as opposed to the strictly static environment discussed in the first algorithm. Finally, a method for generating a guided tour through the environment is discussed in the last part of section 1.4.

A1.1 A*

The A* algorithm is based on [Hart68]. It is guaranteed to return a path of minimum cost whenever that path exists and to indicate failure when that path does not exist.

As discussed in Robot Motion Planning [Latombe91], the A* algorithm iteratively explores the node-graph by following paths that originate at a particular node. At the beginning of each iteration, there are some nodes that have already been visited, and some that are as yet unvisited. For each node that has already been visited, only the path with minimum cost to that node is memorized. Eventually the destination node is reached (if that node is reachable), and the minimum cost path can be reconstructed. Since the A* is such a common algorithm, readers are referred either to [Hart68] or [Latombe91] for a description of the implementation.

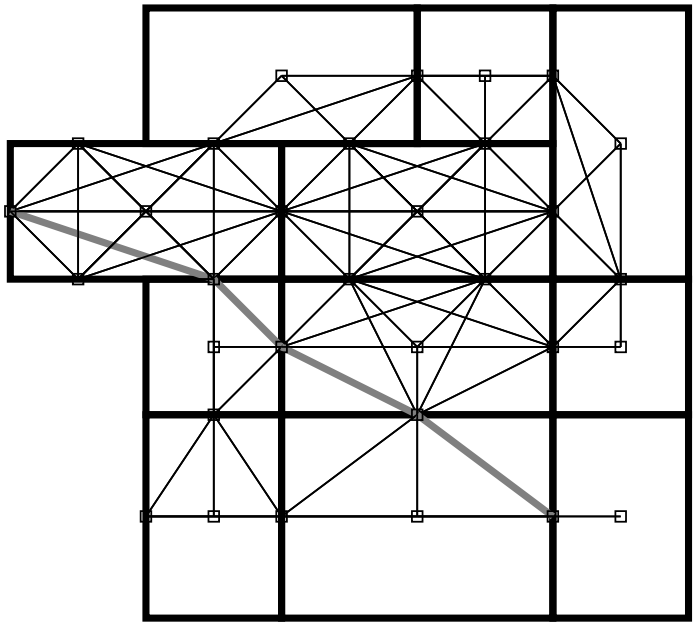


Figure 44: Room connectivity graph for the museum with a path found by A*

A1.2 Room to Room Planning

Once the A* algorithm has produced a list of node to node connectivities, each of the rooms must be negotiated from one doorway to the next in turn. The method we use is somewhat similar to that of [Barraquand89] except for the following: we use a different distant metric more suited to natural motion, we pre-compute and store a navigation function from each door for a room, and we fit the results using a spline for a final representation of the path.

To avoid obstacles within the room, we plan a path based on a two dimensional projection of the obstacles in the room onto the plane of the floor. Much of the following work can be done in a preprocessing stage so that the actual computation of a path through a room is extremely rapid. The 2D projection of the room can be rendered using the hardware rendering of a graphic workstation at whatever resolution is appropriate for the path planning. Subsequently a global numerical navigation function [Barraquand89] is calculated in a wavefront expansion from each of the doorways. A separate navigation map is stored for

each doorway into a room. To demonstrate, a Manhattan (L1) distance metric is used for the following example, the Manhattan distance metric implies that only the 4 cells surrounding a cell to the N, S, E and W are considered neighbors.

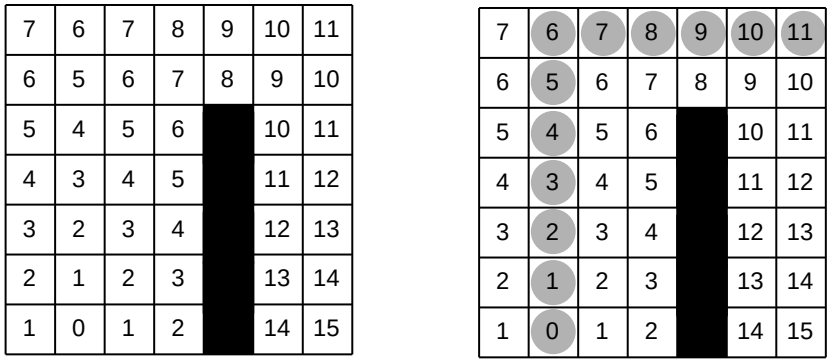


Figure 45: Navigation function calculated with a Manhattan metric

Once the navigation function is computed for a room, it is possible to travel to anywhere within the room by simply following the gradient of the distance function from the goal point back to the origin of the navigation function. There are a few problems that exist in using the algorithm as is:

- the paths generated by the algorithm tend to graze objects as closely as possible which is unacceptable for camera motion. To fix this, the objects are increased in size by a fixed amount in all directions. This prevents the navigation function from passing too close to any object in the environment.

- the paths generated from using a Manhattan metric produce paths that are unacceptably aligned to the major axes. By using a different distance metric, we were able to generate paths that made movement along more axes possible. See figure 46.

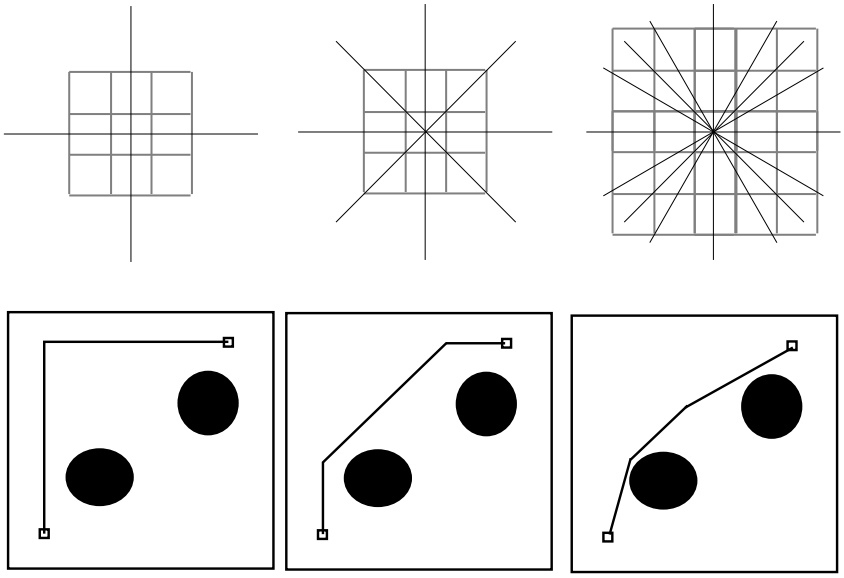


Figure 46: 3 distance metrics and resulting paths.
L1 is shown on the left, L2 in the middle, and L3 on the right of the figure. L1 allows 4 distinct directions of movement. L2 allows 8, L3 allows 16. We used L4 (not pictured) which allows 32 directions
.

- the paths produced are discretized into the space of the rendered image and must be converted into continuous paths in the space of the room. We can transform the points into the proper space using an affine transformation, and then fit a spline curve to the points using a least squares curve fitting method to find the best path. The control points are chosen to be as evenly spaced as possible while minimizing the difference between the spline and the sample points. We can also apply additional tangency constraints at the starting and ending points to make sure that the path goes through doorways in a perpendicular fashion.

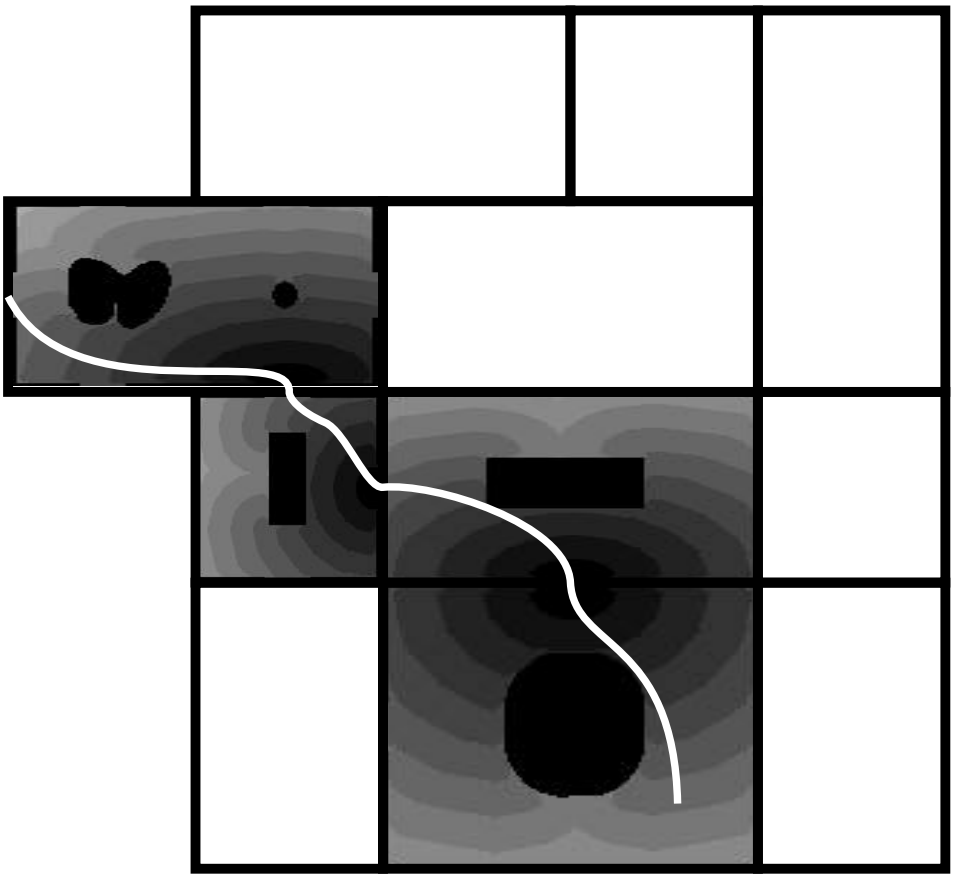


Figure 47: An eventual path through 4 rooms of the museum.

Figure 47 shows an eventual path through the museum. The navigation function that was used for each room is pictured. Usually the navigation chosen for a room is the one generated that leads to the exit door of that room. In the final room, the algorithm is run backwards and calculates a path from the destination location to the entry room. The resultant path is reversed and combined with the other paths.

A1.3 Travel within a Room

Path planning using the global navigation function as described in section 5.2 is extremely convenient because all the computation intensive work can be performed in a preprocess-

ing stage (all the renderings of the scene, and the propagation of the distance function along the image, for each doorway). The final path planning process is extremely rapid on a typical workstation (less than .5 seconds on an R3000 SGI). There are, however, 2 drawbacks to this algorithm:

- it does not deal with planning a path from one point within a room to another point within the room. Because the navigation function is calculated from the doorways of a room, we can conveniently find a path from any point in the room to a doorway, or from a doorway to any point in the room. But we can not easily find a path between two points in a room except via a doorway
- it does not deal with dynamically changing environments. The entire, computation intensive parts of the algorithm must be rerun whenever an obstacle in the environment moves.

To address the problems described above, an alternate path planning algorithm loosely based on [Barraquand91] can be used. More computation needs to be done for this algorithm so it is only used when necessary.

Again, as much preprocessing as possible is performed to make the algorithm as interactive as possible. As before, the static part of a scene is projected onto a 2D plane by graphics hardware. Wavefront expansion is used to propagate a penalty distance function outwards from each object. The wavefront expansion is stopped as soon as the wave meets another wave coming from some other object (or from another place on the same object). We can use a Manhattan (L1) distance metric, but we keep track of the origin pixel of each wavefront. For each pixel, we can then calculate the Euclidean distance to the nearest object. This preprocess generates a distance map which can be turned into a repulsive gradient field by using a function like a/dn where d is the distance, a and n are constants that can be chosen for the task. An absolute cutoff value beyond which repulsion effects are ignored can be used if desired.

At run-time, an attractive potential is created to the goal destination (using a function of the form c*dn where d is the distance and c and n are chosen for the task) and this is

summed with the repulsive potential. Any moving obstacles can also generate a repulsive potential. The sum of the potentials produces the overall gradient.

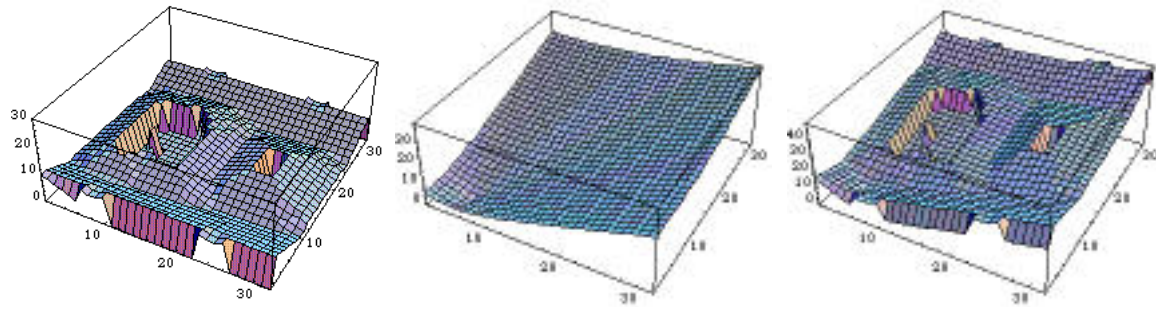


Figure 48: Calculating a path potential function.

A precalculated repulsive potential is added to a run-time attractive potential to produce the final navigation function on the right. This is used to guide a breadth first search through potential space to find the resultant path.

Simple gradient following tends to get trapped into local minima. Instead of always following the gradient, the gradient information in the discrete grid is used as a breadth first guide in a search of the entire grid space. When the algorithm heads into a local minima, the algorithm essentially backs out of the minima on its way to finding the appropriate path to the goal. Again, the algorithm produces discretized paths which must then be fit by splines to produce a continuous path.

A1.4 Tour Planning

Finally, we developed an algorithm to generate the shortest path that will view all the artwork that is specified by the user. In a similar fashion to the point to point navigation, the tour planner divides the problem up in several stages. First, the algorithm locates all the rooms that are slated to be visited. Then, an exhaustive search is made of all the paths that connect each room. This is an exponential time algorithm, but since there is a relatively low branching factor for each room (as well as a fairly small number of rooms), the algorithm is still rapid enough to be used interactively. After the rooms have been ordered, the paintings within each room need to be ordered based on the entry and exit doors (visit the

painting first which is closest to the door from which the room is entered, and visit the painting last next to the exit door). At this point we have a list of paintings that will be visited in the order specified. The algorithms discussed in the previous three sections can be used to plan paths between each of the paintings and the results can be combined into the global tour.

APPENDIX 2: VISIBILITY DETERMINATION

One method of determining visibility is quite similar to the method used for planning paths through an environment. The path planning constraint produces a 3 dimensional surface based on the x and y position of the camera, and a distance from a single known goal location. This algorithm can be easily extended to another dimension by propagating the wavefront through a volume rather than a flat surface. The visibility algorithm produces a 3 dimensional surface based on the azimuth and pitch from the viewpoint of an object and a distance from the nearest visible point. This algorithm can also be easily extended by taking volumes into account.

Figure 49 shows an example of the visibility problem from both an oblique view and the camera's view.

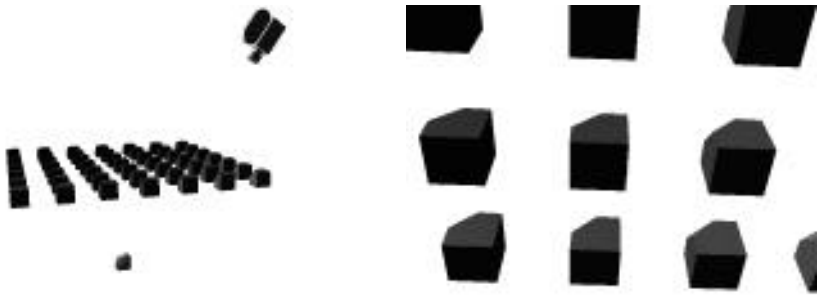


Figure 49: Visibility problem: oblique view and camera view.

The goal for the camera is to find a view where the small object at the bottom of the figure is visibility.

The first step is to create a shadow volume from the viewpoint of the goal object. This can be done in object space efficiently with BSP trees (see Chin89). Instead of a shadow vol-

ume, this version creates a 2 dimensional rendering from the viewpoint of the goal object looking towards the initial location of the camera. This rendering is then used to guide in the construction of a potential field. All the points that are visible from the object are given an initial value of 0. All obscured points which neighbor visible points then receive a value of 1. The wave front propagates into the obscured region with all points in the obscured region receiving the lowest value of the wave front that reaches them. The rendering and the visibility potential map is shown in figure 51.

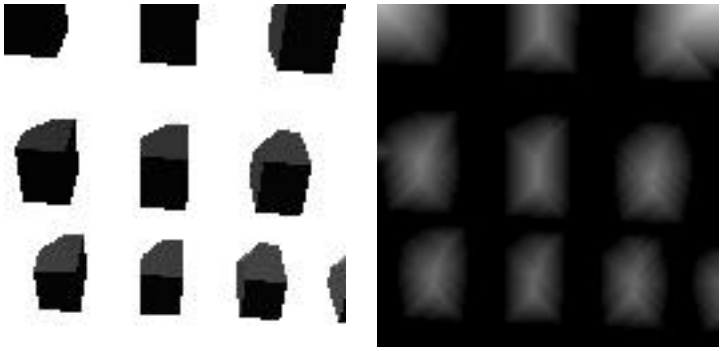


Figure 50: Visibility map construction

This map is really a potential field based with axes for the azimuth and pitch from the viewpoint of the object, and height of distance from a visible region. See figure 52.

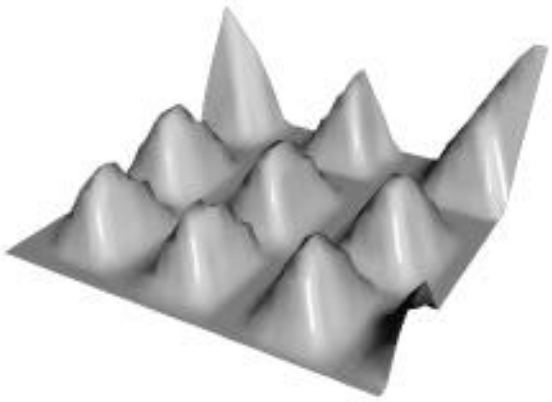


Figure 51: Visibility potential map

This potential map is then followed from the initial location down to the nearest location

in the visible region. The camera is then placed along the line connecting the goal object's position with the new location on the map. The distance between the camera and the object is currently constrained to remain the same. The final position of the camera, and it's view are shown in figure 52.

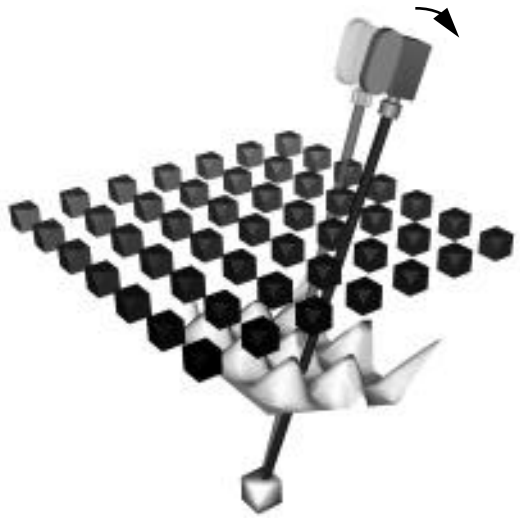


Figure 52: Visible position for camera.

One disadvantage of the method is that it works best for closed environments. However two ways of overcoming this limitation is to either set the z clipping plans so that no object further than the current position of the camera is rendered into the visibility map. An alternate method is to use the z-buffer values instead of the image to calculate the visibility map.

Another problem is that the visibility map must be recomputed whenever anything in the environment moves. Fortunately, with graphics hardware, this can be accomplished rapidly. Visibility map calculation takes on the order of 2 seconds on an IRIS Indigo workstation.

APPENDIX 3: GRAPHICAL ENVIRONMENT SYSTEMS

The following section describes the extended 3d graphic system.
Extensions to the 3d environment which was originally described in [Chen92] include the following: TK (a toolkit for X-window widgets); [incr tcl] (an object oriented extension to tcl); a port to the Silicon Graphics Graphics Library (GL); support for a head mounted display; better communication support; visibility calculation; radiosity; raytracing; video objects; spline fitting and generation; quaternions; and a general constrained optimizer. This adds to an existing base of tools for dynamic simulation, extensive math and linear algebra libraries; Denavit-Hartenberg notation; finite element analysis; a general purpose embeddable interpreter; and multiplatform hardware and software rendering support.

The extended 3d system has been crucial as a prototyping tool for the creation of several graphical environments including all the environments described in this thesis: mission planner; CINEMA system; virtual museum; conversation; virtual football game; and several others: pumping it up (by David Chen the author of the original system); and an animation (S.I. with Tinsley Galyean).

Converters have been written which translate a variety of different file formats into files readable by the extended 3d system including subsets of RIB files (those produced by Swivel 3D); objects produced by Wavefront; files produced by the Vertigo system; and a subset of DXF files.

A3.1 TK

TK is an object oriented toolkit built to provide X widget functionality from tcl. It provides rapid prototyping of widgets and convenient generation of interfaces for various

graphical environments. Extensive use of the canvas widget (a structured graphics editor) was used for the map-view in the museum; the action view of the football game; and the interactive graphical programming of camera modules.

A3.2 Communication libraries

Through the addition of TK, interprocess communication is possible between any processes running within TK through TK's send function. This has greatly facilitated independent development of algorithms without having to incorporate the algorithms within the extended 3d system.

An alternate, more special purpose, yet faster method of communication is through the use of unix pipes. Processes can be spawned by 3d which can then communicate with the subprocesses through pipes. One advantage of this is that a special protocol can be used to send binary data back and forth. In addition, the overhead for communicating over the pipes is less than the more general and flexible interprocess communication provided by the send function.

A3.3 Head mounted display/dataglove

Support for multiple viewports and hardware tracking was added to extended 3d. It has currently been used with VPL eyephones. Tracking devices have included the polhemus isotrack and the Ascension Bird. Tracking information is incorporated into 3d either through the send mechanism or through pipes to specifically spawned processes which access the serial ports.

An application which also uses the dataglove was implemented using pipes to a serial process which reads the position of the polhemus attached to the dataglove and also returns the flex values for each of the finger sensors. These flex values were then used to adjust the Denavit Hartenberg parameters of a simulated robot hand which handled all forward kinematics for the model.

A3.4 Radiosity/Raytracing/Visibility

Radiosity is a graphical rendering technique which allows extensive precomputation based on an energy balance occasion for light propagating through the environment. Calculating the global illumination of an environment with radiosity greatly enhances the realism of the perceived space. Of particular importance are shadows and other natural environment cues which help the user orient themselves within the space. It is because of this enhanced perception of the environment, and because it incurs no loss of display speed, that radiosity has been included in the extended 3d system.

To add radiosity functionality to the 3d system the object database is converted into a format acceptable by the public domain raytracer known as RayShade [available via ftp at weedeater.yale.edu]. The visibility calculation libraries from this raytracer have been incorporated into extended 3d. Once in this form visibility testing between any point in the environment and any other point in the environment can be performed. Additional structures are added that store the amount of radiosity gathered at each vertex and thus at each patch within the graphical database. Adaptive subdivision is also supported. Finally, after extensive adaptive subdivision methods of converting the resultant complex mesh into a texture map (for significant increase in the speed of rendering). The database can be stored along with either the resulting vertex colors or texture maps and reloaded so that radiosity calculations can be done in advance of interaction.

The visibility database can be a greatly simplified version of the actual database, since it simply acts as a mask to prevent light from traveling through objects. This visibility database enables arbitrary visibility testing in the environment.

```
rad_load_database filename
rad_checkvis
rad_shoot [sub]
rad_subdivide
rad_update [gamma]
```

Rad_checkvis checks the visibility between two world space points based on the radiosity database.

Rad_shoot computes one round of shooting from the patch with the maximum amount of unemitted radiosity. If the sub flag is included, then adaptive subdivision of the database

occurs based on the conditions set in the rad_subdiv call.

Rad_subdiv sets subdivision conditions and limits.

Rad_update updates the vertex colors of the database based on the radiosity values stored at each vertex. If gamma is specified then the color values are scaled by e^gamma.

A3.5 Video Objects

Video objects were created because of the current ability of graphic workstations to display texture maps using hardware capabilities. Textures can add a great deal of realism to the image without incurring any loss in performance. This is particularly important in creating environments which have human beings in them. It is especially important when specifying camera positions and movements to be able to see a detailed representation of the human including gaze direction and expression on the face. Modelling humans geometrically is still a current research direction in Computer Graphics and sufficiently realistic models tend to be made of an extremely large number of polygons, or surface patches (on the order of 10,000+).

The basic strategy for the creation of a video object is to digitize an object from a number of multiple viewpoints (typically 8 or 16 views from angles around the object). Once these views have been digitized, and an appropriate alpha channel is created for the background, the textures are loaded into the machine. The video object is then represented geometrically as a single square polygon scaled to the correct size for the object in relation to other objects in the environment. When viewing the scene, the polygon representing the video object is first oriented to face the viewer. Then, the appropriate texture map is selected and mapped onto the video object based on the angle that the object is meant to be facing (a normal vector is stored with the video object and can be changed so the object faces different directions). See figure 53.

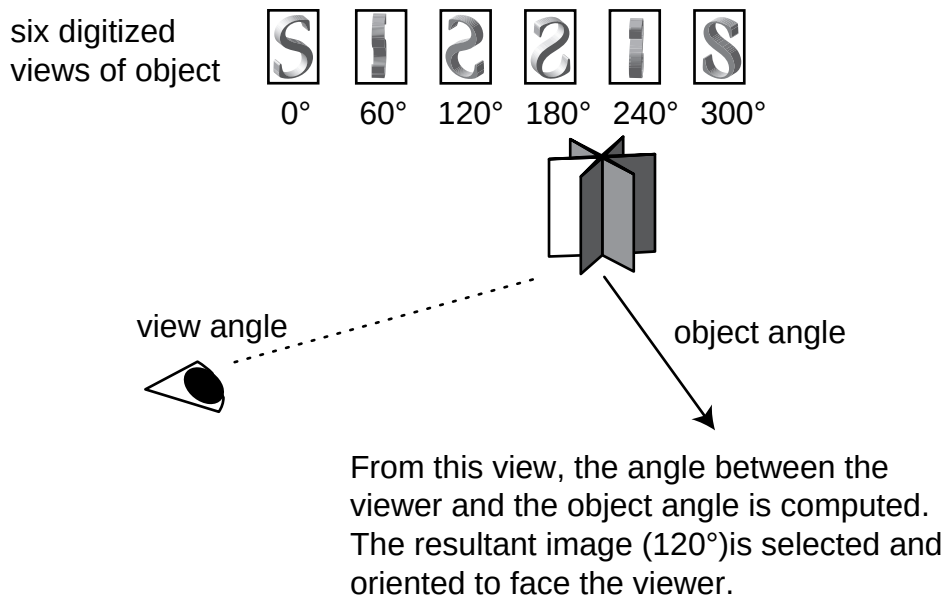


Figure 53: Video Objects

This creates the illusion of a three dimensional object through the use of many two dimensional textures. Additionally, we can digitize movements of the objects from multiple angles and choose the image not only based on the appropriate angle, but also based on the appropriate image within a sequence of images. Because of the capacity of hardware texture memory, we can only use a limited number of video objects, and especially moving video objects. Currently, images are digitized to a resolution of 128x128 bits, which is quite high enough for a good resolution image. At this resolution, each “view-frame” of a video object takes 65536 bytes. Typical static objects need to have either 8 or 16 views for a true sense of 3-dimensionality thus requiring 524,288 (or 1,048,566) bytes for storage of the texture map. Thus with no loss of speed due to swapping of texture memory, 9 video objects (or 9 animation steps for a single video object) with 16 views each, can be used on a SGI reality engine with 9 megabytes of texture memory with no performance degradation due to swapping memory.

```
ivido texture_map_root numimages object_name
vidimage object_name
```

Ivido creates a video object and loads the specified texture maps into the directory / vid_textures. If the textures already exist there, then only the object is created and no more textures are loaded. The number of images can either be 1,8, or 16. The proper angle number is automatically appended to the name of the texture map. Texture maps be stored in the form map_name.rgba.angle.

Vidimage calculates the angle that the object should be rotated in order to face the viewer, and then calculates and maps the image on the object based on the angle between the object's internal normal and the viewer to object direction.

A3.6 Object Oriented Tcl [incr tcl]

[incr tcl] was designed by [McClelland92] to be used as an objected oriented extension to tcl in a similar fashion that C++ is an object oriented extension to C. It provides for object encapsulation of methods and variables and multiple inheritance. It was used extensively in the implementation of camera modules and camera agents and made programming in the 3d environment a joy.

A3.7 General Optimization

A general purpose optimization procedure was embedded in the extended 3d environment. The system used was a "Feasible Sequential Quadratic Programming " (FSQP) written by [Lawrence94]. The procedure was embedded in such a way to allow for tcl routines to act as the objective function, the gradient of the objective function, constraint functions, and their gradients. If no derivative is specified, the optimization can calculate the derivatives by finite differences.

The details of the operation of the fsqp solver and the 3d interface are described in appendix 4.

A3.8 Spline fitting and evaluation

Support for general purpose spline creation, fitting, and interpolation is now incorporated

into the extended 3d system. Fitting is accomplished through a least square adjustment of control points which have been distributed equally along the arc length of the points to be fitted. For more information on the technique used see [Barsky83]. Splines can be turned into polylines that are displayed in 3d and can be incrementally updated. Positions along the splines can be calculated to provide for a means of smooth keyframed movement for objects and cameras.

```
m2splinefit inputm2 numcontrol controlm2
m2spline controlm2 interpolation outputm2
m2splineval controlm2 time
m2obj matrix obj
m2cat mat1 [mat2 ... matn] matoutput
m2hermite controlm2 steps outputm2 [tension]
m2hermiteval controlm2 time outputm2 [tension]
```

M2splinefit calculates the control points of a B-spline with the specified number of control points which best fits the input points. This allows convenient smoothing of noisy data.

M2splineval and M2spline use the control points calculated from m2splinefit to generate either a single 3 dimensional output or a 3xn matrix of outputs where n equals the number of control points times the number of steps specified.

M2obj turns any matrix into a polyline to be displayed in the system. This permits convenient displays of object or camera paths.

M2cat concatenates any number of m2's into one large resultant m2s. The matrices need not have the same number of columns, but the result has the same number of columns as the maximum input matrix and has number of rows equal to the sum of the number of rows in each of the input matrices. Extra columns are filled with 0's.

M2hermite constructs a Kochanack style tension/bias hermite spline through the specified points. Input can be n-dimensional and output will be mxn based on the number of input elements specified and the step size.

M2hermiteval returns one point on a Kochanack style tension/bias hermite spline through the specified points. Input can be n-dimensional while output is 1xn.

A3.9 Quaternions

A quaternion based representation has been incorporated along with utility routines to translate between a rotation matrix based and quaternion based representations. Quaternions enable convenient interpolation of key framed matrices both for the general objects in the system and for the camera. For more details on quaternions, see [Shoemake87].

```
quattom2 quat m2
mtoquatn m2 quat
viewtoquatn quat
```

Quattom2 converts the specified quaternion into the 4 x 4 rotation matrix m2.

Mtoquatn converts the rotation portion of a 4x4 matrix into a normalized quaternion.

Viewtoquat converts the view matrix into a quaternion.

APPENDIX 4: FEASIBLE SEQUENTIAL QUADRATIC PROGRAMMING

The method for solving constraints described in this thesis is implemented using the CFSQP Package provided by Craig Lawrence, Jian L. Zhou, André L. Tits of the Electrical Engineering Department at the University of Maryland. The author is reachable via phone: 301-405-3669 or email: andre@eng.umd.edu. The CFSQP Package is c-code for solving large scale constrained non-linear (minimax) optimization problems, generating iterates satisfying all inequality constraints. Much of this section is taken from the User's Guide for the package.

CFSQP provides functions for the minimization of the maximum of a set of smooth objective function subject to general smooth constraints based on a modified version of sequential quadratic programming. If the initial guess is infeasible for some of the constraints, the algorithm first attempts to generate an initial starting point that is feasible to all boundary conditions and constraints. Subsequent iterates for minimizing the objective functions all satisfy these constraints. The user provides functions which calculate the objective functions and constraint functions. The user can either provide functions that calculate the respective gradients or have the algorithm do so by finite differences.

Formally, the problem is of the form:

$$\text{(P)} \qquad \text{minimize} \quad \max_{i \in I^f} \{ f_i(x) \} \quad \text{s.t.} \quad x \in X \qquad 18$$

where $I^f = \{1, \ldots, n_f\}$ and X is the set of point $x \in R^n$ satisfying the following:

$$
\begin{aligned}
& bl < x < bu \\
& g_j(x) \le 0,\ j = 1, \ldots, n_i \\
& g_j(x) \equiv \langle c_{j-n_i}, x \rangle - d_{j-n_i} \le 0,\ j = n_i + 1, \ldots, t_i \\
& h_j(x) = 0,\ j = 1, \ldots, n_e \\
& h_j(x) \equiv \langle a_{j-n_e}, x \rangle - b_{j-n_e}
\end{aligned}
\qquad 19
$$

where $f_i : \Re^n \rightarrow \Re,\ i = 1, \ldots, n_f$ with $bl \in \mathbf{R}^n$ representing the lower bounds for *x*, and $bu \in \mathbf{R}^n$, representing the upper bounds for *x*. The functions $g_j(x)$ represent inequality constraints, the first $n_i$being nonlinear and the next $t_i - n_i$ being linear, where $g_i : \Re^n \rightarrow \Re,\ i = 1, \ldots, n_f$, $c_i \in \mathbf{R}^n$, $d_i \in \mathbf{R}^n$. And the functions $h_j(x)$ represent equality constraints, the first n_e being nonlinear, and the next $t_e - n_e$ being linear, $a_i \in \mathbf{R}^n$, $b_i \in \mathbf{R}^n$.

A4.1 The CFSQP algorithm

The algorithm proceeds as follows:

1) If the initial guess does not satisfy the linear constraints, CFSQP generates a point satisfying these constraints by solving a strictly convex quadratic program (QP).

2) Next, if the initial guess (or the generated initial point) does not satisfy the nonlinear inequality constraints, CFSQP attempts to generate a point $x_0$by iterating on the problem of minimizing the maximum of the nonlinear inequality constraints.

3) Nonlinear equality constraints are turned into inequality constraints using a scheme from Mayne and Polak [??ref].

$$h_j(x) \le 0,\ j = 1, \ldots, n_e \qquad 20$$

4) The original objective function $\max_{i \in I^f} \{ f_i(x) \}$ is replaced by the modified objective function:

$$f_m(x, p) = \max_{i \in I^f} \{ f_i(x) \} - \sum_{j=1}^{n_e} p_j h_j(x) \qquad 21$$

where p_j, $j = 1, \ldots, n_e$ are positive penalty parameters that are iteratively adjusted.

5) The resulting optimization problem only involves linear constraints and nonlinear inequality constraints, which are all satisfied at successive iterates.

6) The basic SQP direction d^0 is first computed by solving a standard quadratic program using a positive definite estimate H of the Hessian of the Lagrangian. d^0 is a direction of descent for the objective function.

7) The direction is further modified to ensure that the resultant point lies within the feasible region for nonlinear inequality constraints.

Further details on the search used to solve the SQP are found in the user's manual or [Lawrence94].

A general interface to CFSQP has been incorporated into the 3d program allowing callback functions for the objective functions, the constraint functions, and their derivatives to be written in TCL. This allows convenient experimentation with different minimization functions and constraints, however does tend to run fairly slowly (30 seconds is needed for a typical camera constraint to be run). Once proper results have been achieved for a give constraint, the constraint functions an be manually translated into C and the resulting minimization usually will run at frame rates (15 Hz). Currently, most of the functions that have been tried have not specified gradient functions but have relied upon the CFSQP to calculate the gradients by finite differences. Specifying gradient functions would improve the performance even more and a scheme such as described in [Gleicher91] would be useful for efficient computation of the gradients.

A4.2 Detailed description to 3d fsqp interface.

```
fsqp nparam nineqn nineq neqn neq [-gradobj func] [-grad-
const constraintfunc] [-print] [-nf numfuncs] [-mode mode]
```

```
[-miter maxiters] [-eps epsilon].
```

Nparam: number of variables in the state vector.
Nineqn: number of nonlinear inequality constraints.
Nineq: total number of nonlinear inequality constraints. (Nineq-Nineqn = number of linear inequality constraints)
Neqn: number of nonlinear equality constraints.
Neq: total number of equality constraints. (Neq-Neqn = number of linear equality constraints)
-gradobj: (optional) for specifying the name of the function that calculates the gradient of the objective functions, if it is not specified CFSQP calculates the gradient internally by finite differences.
-gradconst: (optional) argument for specifying the name of the function that calculates the gradient of the constraint functions, if it is not specified CFSQP calculates the gradient internally by finite differences.
-print: (optional) flag to print detailed information during the minimization process
-mode: (optional) tells CFSQP to use alternate scheme for solving the minimization process. This alternate scheme does not require improvement on each successive iterate but requires improvement in at most 4 iterations. The scheme requires slightly fewer evaluations of the objective functions.
-miter: (optional) specifies a maximum number of iterations to try before the optimizer gives up. Defaults at 200 iterations, but solution is usually found before then.
-eps: (optional) specifies an epsilon for which a new iterate is considered to be the same as the previous iterate, defaults at 1e-5.

When the procedure is called for the first time, the following vectors are set up:

```
fsqp_state: state vector of specified number of parameters
fsqp_bl: lower bounds on the state vector
fsqp_bu: upper bounds on the state vector
fsqp_display: state information at each iteration to be
displayed by the fsqp_display routine, if display is
turned on (fsqp_display 1).
```

Initial guesses should be placed in the fsqp_state vector and the resultant minimization will be returned in the state vector.

The procedure will call the following tcl functions for the objective and constraint functions:

```
proc fsqp_obj_tcl {{n 0}} {
     switch $n {
            {1} { calculate value for objective function
1}
            {2} {calculate value for object function 2}
            {etc}
     }
     return $val
}
proc fsqp_cnstr_tcl {{n 0}} {
     switch {n} {
            {1...nineqn}{first nineqn nonlinear inequal-
ity constraints calculated}
            {nineqn...nineq} {next nineq-nineqn linear
inequality constraints}
            {nineq...nineq+neqn} {next neqn nonlinear
equality constraints}
            {nineq+neqn...nineq+neq}{next neq-neqn lin-
ear equality constraints}
     }
     return $val
}
proc fsqp_obj_grad {{n 0}} {
     # optional routine to compute the gradient of the
     # objective functions
}
proc fsqp_cnstr_grad {{n 0}} {
     # optional routine to compute the gradiant of the
     # constraint functions
}
proc fsqp_display {iter} {
#    optional routine to display the results during
#    iterations of the constraint solver
}
```

A4.3 Hardcoded FSQP Camera Primitives

Several hardcoded versions of camera constraints are provided in the functions

```
fsqp_display [0|1] turn on or off iteration display
fsqp_put wsp1 sp1
fsqp_put2 wsp1 wsp2 sp1 sp2
fsqp_over wsp1 wsp2 sp1 sp2 flag [w1 w2 w3]
fsqp_both wsp1 wsp2
```

Fsqp_put causes the world space point wsp1 {x y z} to be projected onto the screen space position {x y} subject to boundary conditions.

Fsqp_put2 cause the world space point wsp1 {x1 y1 z1} to be projected onto the screen space position {spx1 spy1} and the world space point {x2 y2 z2} to be projected onto the screen space position {spx2 spy2} subject to boundary conditions.

Fsqp_over performs an over the shoulder shot attempting to project world space point wsp1 {x1 y1 z1} onto the screen space position {sx1 sy1} and the world space point wsp2 {x2 y2 z2} onto the screen space position {sx2 sy2}. The flag indicates whether the vector from obj1 to obj2 should be reasonably aligned with the camera's view normal or the vector from obj2 to obj1. Finally, the terms w1, w2, and w3 provided added control by weighting the three objective functions (the first projection wsp1->sp1, the second projection wsp2->sp2, or the gaze direction).

Fsqp_both minimizes the field of view while including the projections of both of the wold-space positions in the frame.

A sample tk widget is provided which sets or releases bounding conditions on any of the parameters is shown in figure 54.

Figure 54: Simple bounds control window for fsqp.

A4.4 TCL-Code to implement over the shoulder constraint

The following section shows the code that can be used to implement an over-the-shoulder shot discussed in section 6.3. First the purely TCL version of the code is presented, and then a translation of the same code into C is given. This demonstrates not only how constraints can be prototyped within the interpreted environment, but also how to translate the prototypes into code that can be used interactively. This code would be far more efficient in either case if gradiants were computed as opposed to just allowing the system to compute the gradiants through forward differences.

```
#####################################################################
# overtheshoulder.tcl                                               #
#                                                                   #
# Steven M. Drucker                                      4/29/94    #
#                                                                   #
# example code to demonstrate over-the-shoulder constraint          #
# called from tcl in extended 3d                                    #
#                                                                   #
#                                                                   #
#    source overtheshoulder.tcl                                     #
#    setup                                                          #
#    doit                                                           #
#                                                                   #
#####################################################################


#############################################################
#                                                           #
```

```
# routine to set up initial conditions                  #
#                                                       #
#########################################################
proc setup {} {
    global iteration
    global obj1 obj2
    global w1 w2 w3

    # load and set up target objects
    io cutcube.asc cu
    io cutcube.asc cu2
    so .25 .25 .25 cu
    so .25 .25 .25 cu2
    co 1 0 0 cu2
    to -1 0 0 cu2
    to 1 0 0 cu

    # set relative weights for the different constraints
    set w1 1
    set w2 1
    set w3 1

    # set the target objects for the minimization
    set obj1 cu
    set obj2 cu2

    # initialize the feasible sequential quadratic minimizer with
    # 7 state variables
    fsqp_init 7

    # set lower and upper bounds on roll (in radians)
    m2ele 5 -.01 fsqp_bl
    m2ele 5 .01 fsqp_bu

    # set lower and upper bounds on zoom between 45 and 50 degrees
    m2ele 6 [D2R 45] fsqp_bl
    m2ele 6 [D2R 50] fsqp_bu

    # load in an initial position
    m2load {-3 4 4 2.44 -0.68 0 0.7854} fsqp_state
```

```
    # turn on display at each iteration
    fsqp_display 1
    set iteration 0
    set q [m2dump fsqp_state]
    visualize $q
    render
}


############################################################
#                                                          #
# routine to call to perform minimization                  #
#                                                          #
############################################################
proc doit {} {
    # call fsqp with 7 parameters in state,
    #    2 nonlinear inequality constraint
    #    0 nonlinear equality constraints
    #    0 linear inequality constraints
    #    0 linear equality constraints
    #    3 functions to minimize
    fsqp 7 2 2 0 0 -nf 3

    # dump out the end state
    set q [m2dump fsqp_state]

    # set view parameters based on state
    visualize $q

    # render the scene
    render
}

############################################################
#                                                          #
# routine called at each iteration of minimization         #
#    this version increments an iteration counter and      #
#    displays the results                                  #
#                                                          #
############################################################
```

```
proc fsqp_display_tcl {{val 0}} {
    global iteration

    echo iteration: $iteration
    incr iteration

# render the state at each iteration
    visualize [m2dump fsqp_display]
    render
}

############################################################
#                                                          #
# object function(s) for minimization                      #
#                                                          #
############################################################
proc fsqp_obj_tcl {{func -1}} {
    global obj1 obj2
    global w1 w2 w3


    set val {}
    set q [m2dump fsqp_state]

    switch $func {
       {1} {
           # project object1 to left third line of screen
           set p1 [compute_px $q [centroid $obj1]]
           set desp1 {-.33 0}
           set val [mult $w1 [sc_dist $p1 $desp1]]
       }
       {2} {
           # project object2 to right third line of screen
           set p2 [compute_px $q [centroid $obj2]]
           set desp2 {.33 0}
           set val [mult $w2 [sc_dist $p2 $desp2]]
       }
       {3} {
           # try to look into gaze vector of obj1 as much
           # as possible.  Assume that obj1 is looking at obj2
           set gaze [minus [centroid $obj2] [centroid $obj1]]
```

```
            set gaze [div $gaze [enorm $gaze]]
            set cosP [cos [R2D [pitch $q]]]
            set sinP [sin [R2D [pitch $q]]]
            set cosA [cos [R2D [azimuth $q]]]
            set sinA [sin [R2D [azimuth $q]]]
            set vn [list [mult $sinA $cosP] [mult $cosA $cosP] $sinP]
            set sval [plus [dot $vn $gaze] 1]
            set val [mult $w3 [mult $sval $sval]]
        }
    }

    return $val
}

#############################################################
#                                                           #
# constraint function(s) for minimization                   #
#                                                           #
#############################################################
proc fsqp_cntr_tcl {{n 0}} {
    global obj1 obj2

    set q [m2dump fsqp_state]
    set val 0
    switch $n {
       {1} {
           #
           # constraint to make sure that viewnormal is not
           # pointed AWAY from object1 -- object is projected correctly, but
           # behind the viewer
           set cosP [cos [R2D [pitch $q]]]
           set sinP [sin [R2D [pitch $q]]]
           set cosA [cos [R2D [azimuth $q]]]
           set sinA [sin [R2D [azimuth $q]]]
           set vn [list [mult $sinA $cosP] [mult $cosA $cosP] $sinP]
           set vp [list [tx $q] [ty $q] [tz $q]]
           set ovp [minus [centroid $obj1] $vp]
           set val [mult -1 [dot $ovp $vn]]
       }
       {2} {
           #
```

```
            # constraint to make sure that viewnormal is not
            # pointed AWAY from object2 -- object is projected correctly, but
            # behind the viewer
            set cosP [cos [R2D [pitch $q]]]
            set sinP [sin [R2D [pitch $q]]]
            set cosA [cos [R2D [azimuth $q]]]
            set sinA [sin [R2D [azimuth $q]]]
            set vn [list [mult $sinA $cosP] [mult $cosA $cosP] $sinP]
            set vp [list [tx $q] [ty $q] [tz $q]]
            set ovp [minus [centroid $obj2] $vp]
            set val [mult -1 [dot $ovp $vn]]
        }
    }
    return $val
}


############################################################
#                                                          #
# routine to convert state vector into the current view    #
#                                                          #
############################################################
proc visualize {q} {
#
# tx,ty,tz, azimuth, pitch, roll, and acfov retrieve the
# 1st through 7th elements of the vector respectively
#
    set camx [tx $q]
    set camy [ty $q]
    set camz [tz $q]
    set cama [R2D [azimuth $q]]
    set camp [R2D [pitch $q]]
    set camr [R2D [roll $q]]
    set camfov  [R2D [acfov $q]]

# set the view based on the state vector
    fullview $camx $camy $camz $cama $camp $camr
# set the field of view based on the state vector
    fov $camfov
}
```

```
#############################################################
#                                                           #
# routine to calculate the screen space distance between #
# two points                                                #
#                                                           #
#############################################################
proc sc_dist {x1 x2} {
    set diff [minus $x1 $x2]
# make sure just use the x and y coordinates (ignore z)
    set proj [lrange $diff 0 1]
# use euclidean norm
    return [enorm $proj]
}


#############################################################
#                                                           #
# routine to calculate the screen space projection based #
# on the camera parameters of q                             #
# a c version of this function exists and is called      #
#   project q wsp                                           #
#                                                           #
#############################################################
proc compute_px {q x} {
    vsave
    fullview [tx $q] [ty $q] [tz $q] \
       [R2D [azimuth $q]] [R2D [pitch $q]] [R2D [roll $q]]
    set savefov [fov]
    fov [R2D [acfov $q]]
    Mident
    persp_M
    view_M
    vrestore
    fov $savefov
    set val [Mxform $x]
    return $val
}
```

A4.5 C-Code to implement over the shoulder constraint

```
/*************************************************************************/
/*  fsqp_over.c                                                          */
/*    c-code example for implementing over the shoulder shot             */
/*                                                                       */
/*  this assumes that the following has been done from the “tcl side”    */
/*                                                                       */
/*      fsqp_init 7                                                      */
/*      # values loaded into vectors fsqp_bl, and fsqp_bu                */
/*      # and initial state                                              */
/*      m2load {-1E+10 -1E+10 -1E+10 -1E+10 -1E+10 -0.01 0.785} fsqp_bl  */
/*      m2load {1E+10   1E+10  1E+10  1E+10  1E+10  0.01 0.872} fsqp_bu  */
/*      m2load {-3.24 4.58 4.16 2.44 -0.68 0.00 0.7854} fsqp_state       */
/*      # and routine is called as:                                      */
/*      fsqp_over [centroid obj1] [centroid obj2] {-.3 0} {.3 0} 1       */
/*                                                                       */
/*    Steven M. Drucker                                 4/29/94          */
/*************************************************************************/
#include <stdio.h>
#include <math.h>
#include <local/3d.h>
#include <local/matrix2.h>
#include <local/command.h>
#include <local/commandtypes.h>
#include <tcl.h>

#define TRUE 1
#define FALSE 0

#define ERROR \
       return((sprintf(interp->result, “%s”, ((Command_3d *)(clientData))->help), \
       TCL_ERROR))

static float wsp1[3], wsp2[3], sp1[3], sp2[3], flag;
static double init_val[7];

/* relative weights for objective functions */
static float w1 = 1.0;
static float w2 = 1.0;
```

```
static float w3 = 1.0;
extern double  objeps;
extern double  epsneq;
extern double  udelta;


void over_obj();
void over_cntr();
extern void    grobfd(int,int,double *,double *,void (*)(int,int,
               double *,double *));
extern void    grcnfd(int,int,double *,double *,void (*)(int,int,
               double *,double *));
VectorN_D *open_sl_as_vn();
fsqp_over( clientData, interp, argc, argv )
char *clientData;
Tcl_Interp *interp;
int argc;
char **argv;
{
  /* takes wsp1, wsp2, screenpos1, screenpos2, and */
  /* flag (direction of normal) 1, 0, or -1 */
  /* assumes dividing line at 0 right now */
  void (*gradfcn)();  /* gradiant of objective function */
  void (*gradcnt)();  /* gradiant of constraint function */
  char *q, *objfunction, *constrfunction, *gradobj, *gradconstr;
  int i,nparam,nf,nineq,neq,mode,iprint,miter,neqn,nineqn,inform,r;
  int ncsipl,ncsipn,nfsip,mesh_pts[1];
  char buf[1024];
  double bigbnd,eps,epsneq,udelta;
  double *x,*bl,*bu,*f,*g,*lambda;
  VectorN_D *vnd;

  if (argc < 6) ERROR;
  if (sscanf( argv[1], "%f %f %f", &wsp1[0], &wsp1[1], &wsp1[2] ) != 3)
      ERROR;
  if (sscanf( argv[2], "%f %f %f", &wsp2[0], &wsp2[1], &wsp2[2] ) != 3)
      ERROR;
  sp1[2] = sp2[2] = 0.0;
  if (sscanf( argv[3], "%f %f", &sp1[0], &sp1[1]) != 2)
      ERROR;
  if (sscanf( argv[4], "%f %f", &sp2[0], &sp2[1]) != 2)
```

```
    ERROR;

  flag = atof(argv[5]);
  if (argc == 9) {
    w1 = atof(argv[6]);
    w2 = atof(argv[7]);
    w3 = atof(argv[8]);
  }

  /* see the fsqp handbook for a thorough explanation of these parameters */
  mode = 100;
  miter = 200;
  bigbnd=1.e10;
  eps = 1.e-5;
  objeps = 1.e-5;
  epsneq=1.e-5;
  udelta=1.e-5;
  gradobj = 0;
  gradconstr = 0;
  iprint = 0;
  nparam = 7;
  nf = 3;
  nineqn = 2;
  nineq = 2;
  neq = 0;
  neqn = 0;
  gradfcn = grobfd;
  gradcnt = grcnfd;

  bl=(double *)calloc(nparam,sizeof(double));
  bu=(double *)calloc(nparam,sizeof(double));
  x=(double *)calloc(nparam,sizeof(double));
  f=(double *)calloc(nf+1,sizeof(double));
  g=(double *)calloc(nineq+neq+1,sizeof(double));
  lambda=(double *)calloc(nineq+neq+nf+nparam,sizeof(double));

  /* set up bl and bu based on fsqp_bl and fsqp_bu */
  /* set up bl */
  strcpy(buf, "fsqp_bl");
  if ((vnd = open_sl_as_vn(buf, argv[0], interp)) != NULL) {
  } else ERROR;
```

```
r = vnd_get_n(vnd);
if (r != nparam) {
 sprintf(interp->result, “fsqp: lower bounds is not equal to number of params”);
  return(TCL_ERROR);
}
for (i=0; i < nparam; i++) {
  bl[i] = vnd_get(vnd, i);
}

/* set up bu */
strcpy(buf, “fsqp_bu”);
if ((vnd = open_sl_as_vn(buf, argv[0], interp)) != NULL) {
} else ERROR;
r = vnd_get_n(vnd);
if (r != nparam) {
 sprintf(interp->result, “fsqp: upper bounds is not equal to number of params”);
  return(TCL_ERROR);
}
for (i=0; i < nparam; i++) {
  bu[i] = vnd_get(vnd, i);
}

/* set up state */
strcpy(buf, “fsqp_state”);
if ((vnd = open_sl_as_vn(buf, argv[0], interp)) != NULL) {
} else ERROR;
r = vnd_get_n(vnd);
if (r != nparam) {
  sprintf(interp->result, “fsqp: state has wrong number of params”);
  return(TCL_ERROR);
}

for (i=0; i < nparam; i++) {
  x[i] = vnd_get(vnd, i);
}

ncsipl=ncsipn=nfsip=mesh_pts[0]=0;


cfsqp(nparam,nf,nfsip,nineqn,nineq,neqn,neq,ncsipl,ncsipn,mesh_pts,
     mode,iprint,miter,&inform,bigbnd,eps,epsneq,udelta,bl,bu,x,f,g, lambda,
```

```
      over_obj,over_cntr,gradfcn,gradcnt);

  strcpy(buf, "fsqp_state");
  if ((vnd = open_sl_as_vn(buf, "obj_tcl", interp)) != NULL) {
  } else {
    sprintf(interp->result,"state not found from objtcl");
    return;
  }

  r = vnd_get_n(vnd);
  if (r != nparam) {
    sprintf(interp->result, "fsqp: state has wrong number of params");
    return;
  }

  for (i=0; i < nparam; i++) {
    vnd_set(vnd, i, x[i]);
  }

  free(bl);
  free(bu);
  free(x);
  free(f);
  free(g);
  free(lambda);
  return(TCL_OK);
}

/*************************************************/
/* objective function for over the shoulder shot */
/*************************************************/
void
over_obj(nparam, j,x,fj)
int nparam, j;
double *x, *fj;
{
  Vector p1,p2;
  Vector dist;
  Vector gaze, vn;
  float len;
  float cosP, sinP, cosA, sinA, sval;
```

```
  double val;

  switch(j) {
  case 1:
    compute_px(x,wsp1,p1);
    p1[2] = 0;
    VVminus(p1, sp1, dist);
    len = VVlength(dist);
    val = (double) (w1 * len);
    break;
  case 2:
    compute_px(x,wsp2,p2);
    p2[2] = 0;
    VVminus(p2, sp2, dist);
    len = VVlength(dist);
    val = (double)(w2 * len);
    break;
  case 3:
    VVminus(wsp2, wsp1, gaze);
    VVAnormalize(gaze);
    cosP = cos(x[4]);
    sinP = sin(x[4]);
    cosA = cos(x[3]);
    sinA = sin(x[3]);
    vn[0] = sinA * cosP; vn[1] = cosA * cosP; vn[2] = sinP;
    sval =  flag * (VVdot(vn, gaze) + 1.0);
    val = (double) (w3 * (sval * sval));
  }
  *fj = val;
}

/************************************************/
/* constraint function for over the shoulder shot */
/&************************************************/
void
over_cntr(nparam,j,x,gj)
int nparam,j;
double *x,*gj;
{
  float cosp, sinp, cosa, sina, val;
  Vector vn, vp;
```

```
  Vector ovp;

  switch(j) {
    /* make sure that object 1 is not projected behind view */
  case 1:
    cosp = (float)cos(x[4]);
    sinp = (float)sin(x[4]);
    cosa = (float)cos(x[3]);
    sina = (float)sin(x[3]);
    vn[0] = sina*cosp; vn[1] = cosa*cosp; vn[2] = sinp;
    vp[0] = (float)x[0]; vp[1] = (float)x[1]; vp[2] = (float)x[2];
    VVminus(wsp1, vp, ovp);
    val = -1 * VVdot(vn, ovp);
    *gj = (double)val;
    break;
  case 2:
    /* make sure that object 2 is not projected behind view */
    cosp = (float)cos(x[4]);
    sinp = (float)sin(x[4]);
    cosa = (float)cos(x[3]);
    sina = (float)sin(x[3]);
    vn[0] = sina*cosp; vn[1] = cosa*cosp; vn[2] = sinp;
    vp[0] = (float)x[0]; vp[1] = (float)x[1]; vp[2] = (float)x[2];
    VVminus(wsp2, vp, ovp);
    val = -1 * VVdot(vn, ovp);
    *gj = (double)val;
    break;
  }
}

compute_px(x,wsp,sp)
double x[7];
Vector wsp;
Vector sp;
{
  float fov;
  Matrix perspM, viewM, finalM;

  ViewSave();
  GetFieldOfView( &fov );
   FullView( (float)x[0], (float)x[1], (float)x[2], RtoD * (float)x[3], RtoD *
```

```
(float)x[4],  RtoD * (float)x[5]);
  SetFieldOfView( RtoD * x[6] );
  GetPerspXformMatrix( perspM );
  GetViewMatrix( viewM );
  Mmult(viewM, perspM, finalM);
  VVtransform(wsp, finalM, 1, sp);
  ViewRestore();
  SetFieldOfView( fov );
}

project( clientData, interp, argc, argv )
char *clientData;
Tcl_Interp *interp;
int argc;
char **argv;
{
  double x[7];
  Vector wsp, sp;

  if (argc != 3) ERROR;
  if (sscanf( argv[1], "%lf %lf %lf %lf %lf %lf %lf",
           &x[0], &x[1], &x[2], &x[3], &x[4], &x[5],&x[6]  ) != 7)  ERROR;
  if (sscanf(argv[2], "%f %f %f", &wsp[0], &wsp[1], &wsp[2]) != 3) ERROR;
  compute_px(x,wsp,sp);

  sprintf(interp->result,"%f %f %f",sp[0],sp[1],sp[2]);
  return(TCL_OK);
}


static Command_3d fsqphard_cmds[] =
{
{ "_COM3D_", NULL, 0, 0, "" },
{ "_COM3D_", NULL, 0, 0, "#" },
{ "_COM3D_", NULL, 0, 0, "# 3d fsqphard Commands" },
{ "_COM3D_", NULL, 0, 0, "#" },
{     "fsqp_over", fsqp_over, 8, 8,
       "fsqp_over wsp1 wsp2 sp1 sp2 flag [w1 w2 w3] (over the shoulder shot)"
},
{     "project", project, 8, 8,
       "project q wsp1 (calculate screenspace projection of wsp1)"
```

```
},
{      NULL }
};

CommandList_3d_Add_fsqphard( command_root )
CommandList_3d *command_root;
{
       if (!CommandList_3d_Add_Commands( command_root, fsqphard_cmds ))
       {fprintf( stderr, "CommandList_3d_Add_fsqp: failed\n");
       return( FALSE );
       }
       return( TRUE );
}
```

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