

Motion Planning for Camera Movements

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Abstract—Moving a camera through a (virtual or real) environment is a complicated task. Often a user is given direct control of the camera. Such direct control is difficult for inexperienced users and results in rather ugly camera motions that easily lead to motion sickness. In this paper we describe a new technique for automatic generation of camera motion using motion planning techniques from robotics. We focus here on motion in virtual environments. In our approach the user simply specifies a required goal position (and orientation) using e.g. a map, and the system automatically computes a smooth, collision free motion from the current position and orientation to the required position (and orientation) that can be used by the camera. As preprocessing, the approach uses the probabilistic roadmap method to compute a roadmap through the environment. When a motion is required, a path is obtained from the roadmap which is then improved by various smoothing techniques to satisfy constraints from cinematography.

I. INTRODUCTION

In many virtual environment applications, like games, architectural walkthroughs, urban planning systems, CAD model inspection systems, and training systems, the user must navigate through the environment to inspect it and perform certain tasks. Navigation means: steering a camera through the environment. In most of today’s systems this is done using a joystick or arrow keys on the keyboard in combination with a mouse. Such direct control has a number of disadvantages. It is difficult for inexperienced users, it results in rather ugly motions that easily lead to motion sickness, and it requires a lot of attention while the user should preferably concentrate on more higher-level tasks at hand.

In this paper we describe a new navigation technique. In this approach the user simply specifies a required goal position (and orientation) using e.g. a map, and the system automatically computes a smooth motion from the current position and orientation to the required position (and orientation), avoiding collisions with obstacles in the scene. This motion results in a smooth path for the camera that is much more pleasant to watch and enables the user to concentrate on other tasks. The approach is applicable both in virtual environments and in steering robotic cameras.

We base ourselves on motion planning techniques from robotics, in particular the probabilistic roadmap method (PRM) [1], [4], [12], [13], [22], [25] that has been successfully applied in many motion planning problems, ranging from robot arms to the folding of proteins. This technique is combined with theory for cinematography to obtain smooth camera motions.

The method is fast (after little preprocessing camera motions are computed instantaneously) and experiments show that the resulting motions are indeed pleasant to watch. The method has successfully been integrated in a system for walkthroughs in architectural designs and urban planning.

Previous Work

In the past decade a lot of research has been done on supporting camera motion. In this section we briefly review some of the work. We can distinguish three types of results.

A number of authors have studied techniques to support the motion by the user. For example, the user is kept on a constraint subspace [10], the “guide manifold”, which can be seen as a virtual side walk, or the speed of motion is automatically adapted to rapidly cover distance [19]. These methods do not assist the user in the actual navigation to a particular goal. In [18] a path planner is used to help users avoid unnecessary maneuvers due to collisions with the environment. In [23] PRM’s are used to create a path for an avatar while still allowing for local user-steered exploration.

Another collection of papers studies the computation of effective fixed camera positions to assist the user in performing certain (manipulation) tasks, the so-called “shot systems” [3], [6], [9]. To achieve this a collection of constraints is often derived which is then solved. These systems do not plan obstacle-avoiding motions.

Most previous work on planning camera motions is directed toward systems in which the camera must follow an object (like in third-person games). A distinction can be made in systems where the motion of the object is known beforehand [17] and systems where this motion is not known [2], [5], [8]. Similar problems have been studied in robotics where a robot with a camera must track targets [7], [16].

Our problem setting is rather different from the ones studied before. It requires motion planning rather than reactive behavior. Also, with camera motions smoothness of the motion is much more critical than in third-person views (where the camera motion does not even have to be continuous).

Paper Structure

In the next section we will more precisely define the notion of camera motion, the requirements, and the problem we want to solve. In Section III we describe the preprocessing we do on the scene to create a roadmap of possible motions. In Section IV we propose a number of techniques to improve the quality

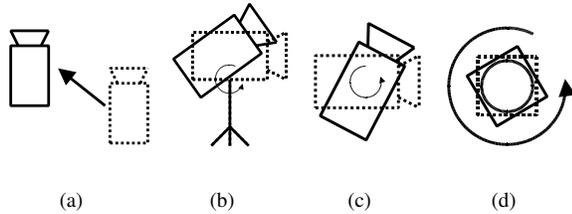


Fig. 1. Possible camera motions. (a) Translation. (b) Pan (side view). (c) Tilt (top view). (d) Roll (front view).

of the path. For a camera motion also the viewing direction and the up vector play an important role. In Section V we show how these can be incorporated in the motion. Finally in Section VI we describe the CAVE system that we built which incorporates the automated camera motion approach in an application for architectural walkthroughs.

II. CAMERA MOVEMENT

In this section we will define what we mean by a good camera motion. A camera can be described with a position, an orientation, and a zoom-factor. (There are some other parameters, like the type of projection used, shear, etc. but for natural camera motions we obviously want a perspective projection and no shear). The configuration (position and orientation) of a camera can be described in a few different ways. Throughout this paper we will use three parameters to describe the position of the camera, another three to describe the point the camera looks at (which represents the viewing direction) and one parameter that describes the rotation of the camera around the axis spanned by the two positions, also called the twist or roll. This makes a total of seven parameters to describe a camera configuration, although one is redundant (the viewing direction can also be specified by two parameters).

The camera can move in four different ways (often combined), as depicted in Fig. 1: the camera can translate, that is, move to a new position, it can rotate horizontally, it can rotate vertically, and it can roll around its main axis.

Using literature from cinematography [20], [29] some general guidelines on the best motions can be distilled.

- The camera should preferably not pass too close to obstacles. Otherwise too big a part of the screen will be filled with the obstacle and this would give the viewer a feeling of (almost) a collision. So we need some clearance for the camera. Exactly how much depends on the application.
- The horizon of the camera should be kept as horizontal as possible to prevent a “drunk” feeling by the viewer. This means that we should preferably not roll the camera.
- When the camera makes a sharp turn, its speed should be lowered. Otherwise objects will move too fast through the view.
- To prevent long dull shots, the speed of the camera should always be as high as possible, bounded by some speed

that depends on the application (e.g., are we walking or flying through an environment).

- The viewer should get cues about where the camera is going. In particular, the viewer should be able to anticipate a rotation. As we will see, this can be achieved by letting the camera not look in the direction of motion but into the turns, that is, toward the position were it will be some short time in the future.

The goal in this paper is to compute camera motions that satisfy these guidelines. More precisely, we can formulate the problem as follows: Given an environment consisting of a set of obstacles O , a start configuration s , and a goal configuration g , compute a short, natural looking camera motion from s to g avoiding collisions with all $o \in O$.

III. CREATING A ROADMAP

To enable immediate response to motion requests we need to preprocess the scene. The result of this preprocessing will be a roadmap consisting of collision-free motions. For a camera roadmap, only the position is stored in the roadmap. The viewing direction will be computed when the actual camera path is required.

It is way too time and storage consuming to compute all possible motions. Hence, we will only compute a coarse roadmap. This roadmap will consist of straight-line motions. When the actual path is required, the roadmap will be locally extended and a smooth path will be computed, using the roadmap as a guideline.

To compute the roadmap we will use the so-called *Probabilistic Roadmap Method (PRM)* [1], [4], [12], [13], [22], [25]. It constructs a roadmap of possible motions in a probabilistic way. Free robot configurations are created randomly and form the nodes of the roadmap graph. For nearby nodes we check whether the straight-line connection between them is collision-free and, if so, add a corresponding edge to the graph. It can be shown that, once the graph gets dense enough, all nodes will get connected.

A big advantage of PRM is that its complexity tends to be dependent on the difficulty of the path, and much less on the global complexity of the scene. In the past few years the method has been successfully applied in many motion planning problems dealing with robot arms [14], car-like robots [26], [28], multiple robots [27], manipulation tasks [24] and even flexible objects [11], [15].

A number of important choices have to be made to be able to use PRM’s to create camera motions. To guarantee that the camera keeps a minimal clearance to the objects in the scene, we don’t consider the camera as a point but as a sphere $S_\delta(c)$ of radius δ around camera position c . Here δ is the minimal clearance required. If we allow arbitrary camera motion through the scene we can pick random positions for the configurations. If we require the camera to stay on a fixed height we pick random configurations on that height. If particular positions are important or should preferably be avoided we can also take that into account here. Many PRM implementations do not allow cycles in the roadmap graph.

For planning camera motions though we need cycles to make sure the camera takes a logical short path to the goal (see [21] for a treatment of this issue).

A. Adding the Start and Goal

We will first only plan the motion for the position of the camera. Later we will incorporate the orientation. Our first step is to compute an initial path. To this end we need to add the start and goal position of the camera to the roadmap and compute a good path in the graph, taking into account the guidelines from Section II.

Adding the start position s and goal position g to the roadmap is done in exactly the same way as the random positions were added. We create two nodes for them and try to connect these nodes to a set of neighbor nodes. If such connections are successful and s and g end up in the same connected component of the graph, then a path exists.

If s or g cannot be connected to the graph we expand the graph by adding a number of additional random positions in the vicinity of s and g . This is in particular important if s or g lies in a very confined region in the environment. This local expansion can be done very fast (normally just a few nodes suffice).

If s and g can be connected to the graph but are not in the same connected component, there either does not exist a path, which can be reported, or the initial roadmap was not dense enough. We can either spend some more time on the roadmap construction or use techniques to expand the roadmap at critical places [14].

B. Computing the Shortest Path

In order to find the shortest path between s and g in the roadmap graph, Dijkstra's shortest path algorithm can be applied. This would, however, lead to a path that is short in length, but does not take any of the guidelines for a natural motion into account. It will also not necessarily lead to the fastest path because the camera has to slow down when approaching a sharp turn and after the turn it has to accelerate again. Wider turns are preferred over short sharp turns as long as the path length does not increase too much. It can be beneficial to make a small detour, thus avoiding sharp turns. The overall camera speed will be higher, because it has to slow down less, see Fig. 2.

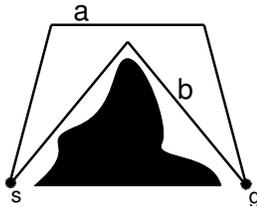


Fig. 2. Path b is shorter than path a but a is preferred because the overall speed is higher.

To find a balance between a good and a short path, we use a penalty function. As we will see in Section IV-A we will

replace turns in the path by circle arcs. As the speed with which such an arc can be traversed depends on the radius we need to take the angle between successive edges of the path into account when computing the cost of a path. The penalty value for an edge e when arriving from edge e' is $p(e, e')$. The length of edge e , $l(e)$ also needs to be taken into account. This results in a total distance measure $d(e)$ for e arriving from e' of $p(e, e') + l(e)$. For our experiments we had the best results by calculating p as $\frac{1}{\alpha^2} \cdot m$, where α is the angle between e' and e and m is a multiplication factor depending on the scene.

To compute the shortest path according to this distance measure we need to use an edge-based version of Dijkstra's shortest path algorithm rather than the usual node-based version. For each edge in the graph we compute the shortest path from the start position, until we reach the best edge leading to the goal position. This is an easy modification. Let $\text{deg}(c)$ denote the degree of node c in the roadmap and let $\text{DEG} = \sum_{c \in V} \text{deg}(c)$. Then the algorithm will take time $O(\text{DEG} \log \text{DEG})$. Fortunately, we connect each node c with at most $|N_c|$ other nodes, the size of the neighbor set for c and we pick only a constant number of neighbors. So the total number of edges is linear in the size of V . We can also avoid that too many edges connect to the same node. As a result $\text{DEG} = O(|V|)$. This means that a path between s and g can be computed in time $O(|V| \log |V|)$. We can rather easily extend the algorithm to avoid all kinds of "unwanted" routes. For example an edge that travels over flat terrain can be preferred over an edge that goes over bumpy terrain.

IV. IMPROVING THE PATH

We have now found a path between the start and goal configurations that avoids obstacles. However, the path consists of straight line segments and, hence, is only C^0 continuous. In order to create a smooth robot motion, the path must be at least C^1 continuous. In this section we will describe how to make the path C^1 continuous using circular blends and how to compute a continuous speed function for traversing the path.

A. Adding Circular Blends

The path produced so far consists of edges that correspond to straight-line motions that meet at nodes. These nodes introduce first-order discontinuities in the motion. To remove these discontinuities, we use circular blends between the edges that meet at a node. We could also use parabolic blends, clothoids or Béziers to get a higher degree of continuity. The problem with parabolic blends and Béziers however is that they do not have a constant curvature. This means that a single segment can vary in curvature which is unwanted because camera speed will be dependent on the curvature. Also taking uniform steps on the curve (for collision checks) is not easy. The curvature of clothoids varies linearly along its arc length. The approach is quite complicated and offers much more options than needed for camera motions.

Let e and e' be two consecutive edges in the final path that meet at a node v . Let p_m be the midpoint of e and let p'_m be the midpoint of e' (see Fig. 3(a)). We replace part of the path

between p_m and p'_m by a circular arc that lies in the plane spanned by the two edges. This arc will have its center on the bisecting line of e and e' , will touch e and e' and have either p_m or p'_m on its boundary, depending on which one lies closer to the node v . Because the arc touches the two edges it will remove the first-order discontinuity at node v . Since the arc will only remove at most half of the edges e and e' we can repeat this for each node on the path. The resulting path will be C^1 continuous.

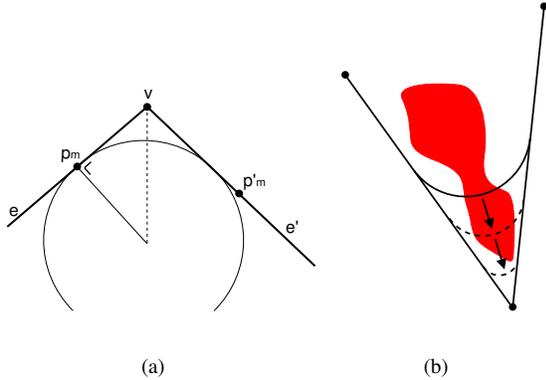


Fig. 3. (a) Replacing a node by a circle arc. (b) Moving a circle arc to avoid an obstacle.

There is a problem though. Replacing a part of the edges with an arc might introduce collisions between the camera sphere S_δ and the obstacles when it moves along the circle arc. If this is the case we use a smaller arc instead by reducing the distance between v and the touching points on the edges (see Fig. 3(b)). Assuming the initial path does not touch any obstacles, there exists a radius for the circle arc for which the motion along the arc is collision free. We use a binary search on the radius to find the largest possible radius for which the motion is collision free. Note that computing collision checks between the circular blends and the obstacles is the most time-consuming part of the algorithm (after the preprocessing). Most collision checkers do not allow such checks directly. Here, we approximate the arc by a number of short cylinders (with the same radius as the camera sphere) and check these instead.

B. Speed Diagram

Smoothness of the path itself is not sufficient for a smooth robot motion. Also the speed along the path should change in a continuous way. To this end we need to compute a speed diagram that indicates the speed $s(c)$ at each location c along the path. The maximum speed $s_{\max}(c)$ allowed must depend on the curvature of the path. We experimentally determined an appropriate function $s_{\max}(r)$ that depends on the radius r of the circular arc to ensure that the motion looks as natural as possible for every radius (in our experiments we used $\left(\frac{r}{r+1}\right)^2$, but this depends on the scene and the user preferences). For the straight parts of the path there will also be a maximum

speed, depending on the type of motion we want. Using this information we can create a maximal speed diagram. Because our path consists of straight line segments and circle arcs, the maximal speed diagram will be a step function (Fig. 4).

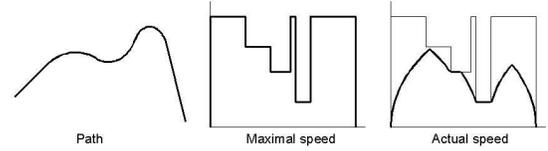


Fig. 4. A smoothed path, the maximal speed diagram, and the speed diagram.

To turn this maximum speed function $s_{\max}(c)$ into a continuous speed function $s(c)$ we need to take the maximal allowed acceleration and deceleration into account. We will briefly indicate how this process can be done in time linear in the number of pieces of the path, using a greedy algorithm. $s_{\max}(c)$ consists of a number of steps, each with a constant speed. The i 'th step of $s_{\max}(c)$ is denoted with step_i . We look at successive steps of $s_{\max}(c)$, starting with the first segment. step_i has a begin position b_i and an end position e_i . We can distinguish the following two cases:

- 1) If the maximum speed of step_i is higher than the current speed in $s(b_i)$, then we add an acceleration curve that starts at b_i and ends at the position where the maximum speed is reached or at e_i otherwise. This curve is a root function, depending on the maximal acceleration.
- 2) If the maximum speed of step_i is lower than the current speed in $s(b_i)$, we need to find a position p where to start the deceleration in $s(p)$ that makes sure that the speed reached at b_i is equal to the maximum speed of step_i . For this, we follow a deceleration curve backwards from b_i , removing pieces of $s(c)$ until the curve intersects $s(c)$ at a position p (see Fig. 5). We charge the time this takes to the pieces of $s(c)$ that we remove. As each part is added and removed at most once, the total time required for adding deceleration curves is linear.

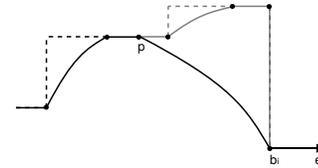


Fig. 5. Finding the place to start the deceleration.

C. Shortening the Path

The method described so far does result in smooth paths. There is a problem though. Because the roadmap graph is rather coarse the shortest path in the graph might not really be short. The default approach used with the PRM method is to shorten the path by making shortcuts. Repeatedly, two random configurations c and c' on the path are chosen and

we verify whether the cylinder $C_\delta(c, c')$ between them is collision-free. If so, we replace the path between c and c' by a straight line. We cannot directly apply this approach because a shorter path might actually not be faster. Instead we need to evaluate whether the new path is indeed faster. To this end we compute the total time by adding circle blends and computing a speed diagram as indicated above. (To speed up the processing we do not test the circle arcs for collision in this stage but experiments show that this is not crucial. We still obtain a reasonable approximation of the traversal time.) Only when the new total time is lower than the previous total time we replace the piece of the path.

The resulting path is shorter and faster but usually consists of many short line segments. This has as a disadvantage that the speed needs to change often. Paths with less, larger edges and arcs look nicer. So we add another step that removes nodes on the path that lie near to each other, checking whether no sharp turns are introduced. The result of the two improvements is demonstrated in Fig. 6. At the left you see the path without shortening. In the middle figure the path is improved by making shortcuts. And in the right figure unnecessary nodes are removed.

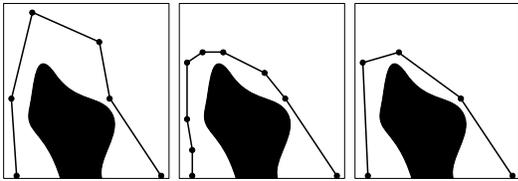


Fig. 6. Optimizing the path using shortening.

V. OTHER CAMERA PARAMETERS

In the previous sections we concentrated on creating a smooth motion. But when this motion is used to steer a camera we also need to take the the viewing direction and twist into account. In this section we will include these in the motion.

A. Smoothing the Viewing Direction

For a smooth camera motion, intuitively one might think that the viewing direction should be equal to the direction of motion. This though is not true. As indicated in Section II it is important to give the viewer cues about where the motion is going. This can be achieved by looking at the position on the path where the camera will be in a short time (experiments show that about 1 second is the right amount). See Fig. 7. Note that, as we fix the time we look ahead, the distance we look ahead changes depending on the speed. This is exactly what we want to achieve as in sharp turns we want to look at a nearer point than in wide turns.

This has a second important effect. If we would look along the direction of motion and we reach a circle arc, there is a discontinuity in the speed with which the viewing direction changes. Stated differently the viewing direction is only C^0 continuous. For a smooth motion the viewing direction must

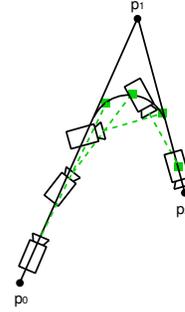


Fig. 7. Making a turn with the camera. The dotted line is the viewing direction. At the end of the turn, the camera has nearly completed its tilt.

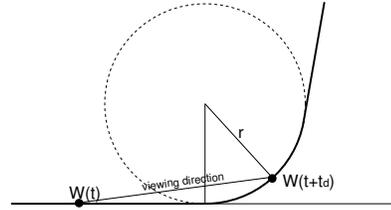


Fig. 8. The viewing direction.

be C^1 continuous. As we will show, looking at a position ahead will achieve this.

Let us formalize this approach. Let $W(t)$ denote the position of the camera in the world at time t . At time t we will look at position $W(t+t_d)$ where t_d is the time we look ahead (as stated above a good value for t_d is 1 second). The viewing direction $D(t)$ is along the line from $W(t)$ to $W(t+t_d)$ (see Fig. 8). We want to prove that $D(t)$ is C^1 continuous.

The path is represented by a function $P(i) : [0..l] \rightarrow \mathbb{R}^3$, where l is the length of the path. The speed function is represented by $V(i) : [0..l] \rightarrow \mathbb{R}$. (In terms of the previous section, $V(i) = s(P(i))$.) We first need a function $U(t)$, which, given a time t , returns a position i . (We assume that the motion starts at time 0.) Then $W(t) = P(U(t))$.

It is easy to see that the time to reach a certain position i on the path is

$$T(i) = \int_0^i \frac{1}{V(x)} dx \quad (1)$$

This function is defined since $V(i)$ is always positive, except for the start and end positions which we need to treat separately anyway (see Section V-C). The function $U(t)$ we are interested in is the inverse of $T(i)$:

$$U(t) = T^{-1}(t) \quad (2)$$

From the previous section we know that $P(i)$ is C^1 continuous (see Section IV-A) and that $V(i)$ is C^0 continuous (see Section IV-B). It follows that $1/V(i)$ is also C^0 continuous because $V(i)$ is positive. Because the derivative of $T(i)$ is $1/V(i)$, $T(i)$ is C^1 continuous. $T(i)$ is a one-to-one function. So for every i there is exactly one value for $T(i)$ and vice versa. As a result we can indeed take the inverse of $T(i)$. Taking the inverse of

a one-to-one function does not change the continuity. So $U(t)$ is also C^1 continuous.

Remember that $W(t) = P(U(t))$. Since both $P(i)$ and $U(t)$ are C^1 continuous, $W(t)$ is also C^1 continuous. The viewing direction $D(t)$ equals:

$$D(t) = \frac{W(t + t_d) - W(t)}{|W(t + t_d) - W(t)|} \quad (3)$$

The function of the difference of two C^1 continuous functions divided by a positive number is also C^1 continuous. So $D(t)$ is a C^1 continuous function as we wanted to prove.

Experiments with a number of test persons show that the above method is very effective. Setting d_t very close to 0, that is, looking in the direction of motion quickly caused motion sickness and the motion was unpleasant to look at. Setting d_t to about 1 second removed the motion sickness and gave the best result.

B. Up Vector

We have now smoothed the camera motion and the viewing direction. This leaves us with one more parameter to deal with: the roll of the camera around its longitudinal axis. This roll is often indicated by the up vector. The preferred direction of the up vector is parallel to the y -axis, since then the horizon of the camera is equal to the horizon in the normal world (see Section II). When the up vector changes too much, the user feels the effect of being in a roller coaster.

A straightforward solution would be to always let the up vector point in the direction of the y -axis. But this can lead to problems. When the camera makes a looping-like motion, the up vector normally points down halfway the motion. If we force it to point upwards, it rotates the camera 180° about the viewing direction in a very short period of time. This sudden rotation is called a twist and should be avoided.

We have investigated a number of solutions to deal with the twist. Experiments show that the best solution was to try to avoid situations where a twist can occur. There is a high chance of twists when the plane spanned by two consecutive edges in the path makes a small angle with the y -axis. We cannot forbid such pairs of edges altogether because they might constitute the only possible path. But we can discourage them by including this angle in the penalty function for finding shortest paths in Section III-B. Experiments showed that an exponential penalty function works best, so that a path with a twist is only selected if there is really no alternative. If a twist still occurs we adapt the speed of motion locally to make it less dramatic. This combination of techniques gave satisfying results.

C. Start and Goal

Up to now we assumed that the camera starts with a viewing direction along the first edge of the path and ends with a direction along the final edge. This is of course not the case. In particular at the start of the path the camera is most likely pointing in a different direction. At the goal it depends whether the user also specifies the final orientation or only the final

position. In the latter case no addition processing is required there.

After experimenting with a number of different approaches we found that the most natural solution is to start with a rotation from the start direction to the direction of the first edge before starting to move the camera. The rotation is performed using Euler angles, because this more naturally corresponds to our own way of turning (we move our head up or down and rotate around our vertical axis). We compute a speed function for this rotational part of the motion. We blend the last part of the rotation with the start of the camera path to make it look more natural. The goal position can be treated in a similar way.

VI. THE CAVE SYSTEM

The approach to generating camera movements as described above has been implemented in the form of a C++ library called CAVE (Cameras in Virtual Environments). The library has a very simple API, allowing for easy integration in different virtual environment systems. CAVE does not require a description of the scene in any format. It only requires a pointer to the collision checker of the VE system in which it is used. It uses this collision checking to determine whether camera paths are collision free (it can be downloaded at <http://www.give.nl/cave>).

To test the effectiveness of the approach we incorporated the library into some architectural walkthrough applications by the company LetsLook (<http://www.letslook.com/>). The applications have been created within the development environment Quest3D (<http://www.quest3d.com/>). Incorporating the CAVE library in Quest3D was just a few hours of work. Next we adapted the walkthroughs by adding a clickable map and some additional position feedback. In Fig. 9(a) you find an image of the interface.

Preprocessing the scene of part of Rotterdam in Fig. 9(a) to create an adequate roadmap using PRM took about 5 seconds (on a Pentium 4, 2.4 GHz). After this preprocessing smooth motions can be computed between any pair of positions in less than half a second. This feels like immediate response. Experiments show that the technique is very robust; even when the user places the camera almost against a wall, the method successfully finds a motion. Different users confirmed that the resulting motions were pleasant to look at.

The walkthrough of Rotterdam uses a two-dimensional roadmap at a fixed height. To test our approach in a full three-dimensional environment we also incorporated CAVE in a model of a building (Fig. 9(b)), again provided by LetsLook. Using the same setup, building a roadmap took about 8 seconds. Motions can again be created in less than half a second. This scene is a good environment to test our solution to deal with the up vector when going from a low to a high position in the scene. Again, we showed the resulting motions to a number of people that confirmed the quality of the results.



Fig. 9. Two examples of implementations of CAVE (scenes created by LetsLook). (a) The interface for the walkthrough of a part of Rotterdam in CAVE. (b) A 3D implementation of CAVE.

VII. CONCLUSIONS

In this paper we have describe a new approach to automatically planning camera motions. The technique is based on a novel application of the Probabilistic Roadmap Planning approach. Combining the approach with theory for cinematography and applying various smoothing techniques we obtained a generic system that can easily be integrated in various virtual environment applications. The method is fast and versatile. Experiments with architectural walkthroughs verified the quality of the resulting motions.

The technique can easily be extended to suite specific needs. For example, the view direction can be controlled by the user instead of the algorithm during a motion to gain more insight in an environment.

The approach is also applicable to robotic camera's in the real world, where the same constraints apply. The presented techniques are useful in other applications as well. For example the path an avatar walks in a virtual environment can be made more natural by using a speed diagram and the path of a robot can be made more efficient by using circular blends.

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