Dynamosaics: Video Mosaics with Non-Chronological Time *

Alex Rav-Acha Yael Pritch Dani Lischinski Shmuel Peleg
School of Computer Science and Engineering
The Hebrew University of Jerusalem
91904 Jerusalem, Israel
E-Mail: {alexis,yaelpri,danix,peleg}@cs.huji.ac.il

Abstract

With the limited field of view of human vision, our perception of most scenes is built over time while our eyes are scanning the scene. In the case of static scenes this process can be modeled by panoramic mosaicing: stitching together images into a panoramic view. Can a dynamic scene, scanned by a video camera, be represented with a dynamic panoramic video even though different regions were visible at different times?

In this paper we explore time flow manipulation in video, such as the creation of new videos in which events that occurred at different times are displayed simultaneously. More general changes in the time flow are also possible, which enable re-scheduling the order of dynamic events in the video, for example.

We generate dynamic mosaics by sweeping the aligned space-time volume of the input video by a time front *surface and generating a sequence of* time slices *in the process. Various sweeping strategies and different time front evolutions manipulate the time flow in the video, enabling many unexplored and powerful effects, such as panoramic movies.*

1 Introduction

Imagine a person standing in the middle of a crowded square looking around. When requested to describe his dynamic surroundings, he will usually describe ongoing actions. For example: "some people are talking in the southern corner, others are eating in the north", etc. This kind of description ignores the chronological time when each activity was observed. Due to the limited field of view of the human eye, people can not view an entire panoramic scene in a single time instance. Instead, we examine the scene over time as our eyes are scanning it. Nevertheless, this does not prevent us from obtaining a realistic impression of our dynamic surroundings and describing it.

When a video camera is scanning a dynamic scene, the absolute "chronological time" at which a region becomes visible in the input video, is not part of the scene dynamics. The "local time" during the visibility period of each region is more relevant for the description of the dynamics in the scene, and should be preserved when constructing dynamic mosaics. The distinction between chronological time and local time for describing dynamic scenes inspired this work. No true panoramic video can be constructed, as different parts of the scene are seen in different times. Yet, panoramic videos giving a realistic impression of the dynamic environment can be generated by relaxing the chronological consistency, and maintaining only the local time (see Fig. 1).

We use the *space-time volume* [3] to mosaic panoramic videos as well as new videos having other time manipulations. The space-time volume is constructed from the input sequence of images by aligning and sequentially stacking them along the time axis. We show how new movies can be produced by sweeping the space-time volume with a *time front* surface and generating a sequence of *time slices*. Mosaicing using strips, similar to those used in ordinary mosaicing [10], obtains seamless images from time slices of the space time volume, giving the name "Dynamic Mosaics" ("Dynamosaics").

Various strategies for sweeping the time front through the space-time volume result in different manipulations of the original chronological time. For example, when a camera is scanning the scene, it can be played in different speeds, even backwards, while preserving the local time characteristics of the original video. Sweeping the space-time volume with a non-planar evolving time front surface results in dynamic mosaics with a spatially varying time flow. For example, it becomes possible to modify a competition video to produce a number of new videos, each having a different winner (see Fig. 8).

*This research was supported (in part) by the EU under the Presence Initiative through contract IST-2001-39184 BENOGO, and by a grant from the Israel Science Foundation.

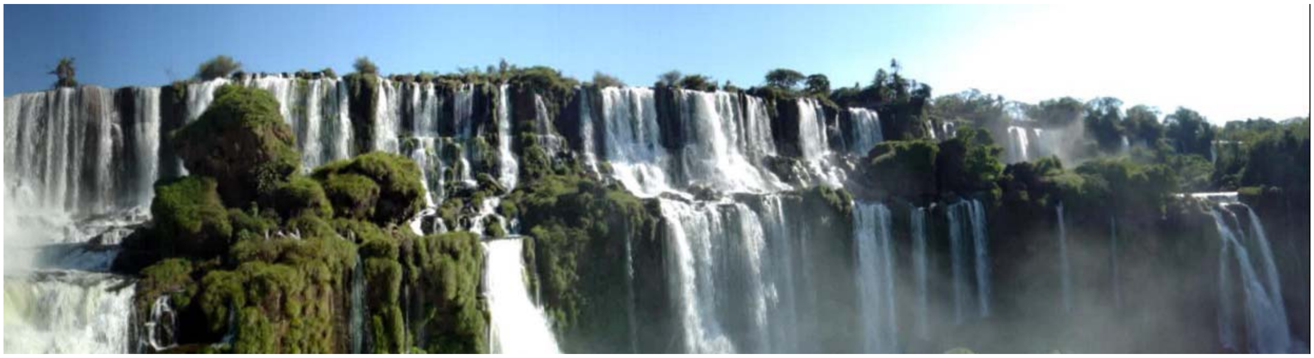


Figure 1. Dynamosaicing can create dynamic panoramic movies of a scene. This figure is only a single frame in a panoramic movie, generated from a video taken by a panning camera (420 frames). When the movie is played (see *www.vision.huji.ac.il/dynmos*), the entire scene comes to life, and all water flows down simultaneously.

1.1 Related work

The most popular approach for the mosaicing of dynamic scenes is to compress all the scene information into a single static mosaic image. There is a variety of methods for describing the scene dynamics in the static mosaic. Some approaches eliminate all dynamic information from the scene, as dynamic changes between images are undesired [19]. Other methods encapsulate the dynamics of the scene by overlaying several appearances of the moving objects into the static mosaic, resulting in a "stroboscopic" effect [5, 4, 1]. In contrast to these methods that generate a single mosaic image, we use mosaicing to generate a new video having a desired time manipulation.

The creation of dynamic panoramic movies can alternatively be done with panoramic video cameras [8, 16] or with multiple video cameras covering the scene [17, 14]. An attempt to incorporate the panoramic view with the dynamic scene using a single video camera was proposed in [5]. The original video frames were played on top of the panoramic static mosaic, registered into their locations in the mosaic. The resulting video is mostly stationary, and motion is visible only at the location of the current frame.

Klein et al. [6] also utilize the space-time volume representation of a video sequence, and explore the use of arbitrary-shaped slices through this volume. This was done in the context of developing new non-photorealistic rendering tools for video, inspired by the Cubist and Futurist art movements. In the "digital photomontage" system [1] non-planar slices through a stack of images (which is essentially a space-time volume) are used to combine different parts from images captured at different times to form a single still image. However, the goal of that system is to produce a single composite still image, and the possibilities of generating dynamic movies from such 3D image stacks were not discussed.

Slicing through space-time volumes has also been used in panoramic stereo [9] and X-slits rendering [21]. Unlike these methods which assume a static camera, dynamosaics are generated by coupling the scene dynamics, the motion of the camera, and the shape and the motion of the time front.

It should always be remembered that a preliminary task before any mosaicing is motion analysis for the alignment of the input video frames. Many motion analysis methods exist, some offer robust motion computation that overcomes the presence of moving objects in the scene [2, 18]. A method is described in [13] to compute image motion even when a large portion of the image consists of dynamic texture and moving objects. While for clarity of presentation most figures in this paper show the case of constant camera motion, all examples of panoramic dynamosaicing were made with a hand held camera whose motion was non-uniform.

2 Dynamosaicing

2.1 The Space-Time Volume

Given a sequence of input video frames, they are first registered and aligned to a global spatial coordinate system (u, v). Stacking the aligned video frames along the time axis results in a 3D space-time volume (u, v, t). Fig. 2 shows two examples of 2D space-time volumes. For a static camera the volume is a rectangular box, while a moving camera defines a more general swept volume. In either case, planar slices perpendicular to the t axis correspond to the original video frames. A static scene point traces a line parallel to the t axis (for a static or panning camera), while a moving point traces a more general trajectory.

2.2 Mosaicing by an Evolving Time Front

Image mosaicing can be described by a function that maps each pixel in a synthesized mosaic image to the input frame from which this pixel is taken and its location in that frame. When only strips are used, the mapping determines for each column (row) of a mosaic image the source

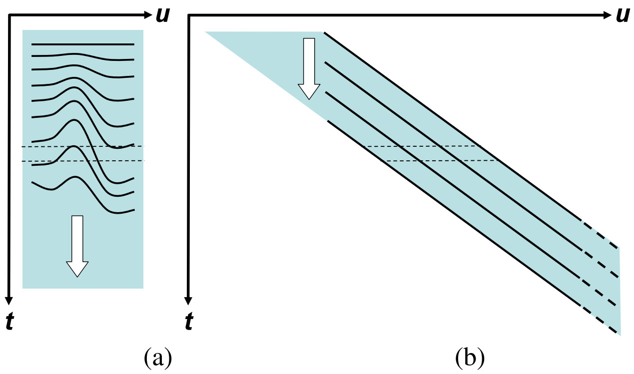


Figure 2. 2D space-time volumes: Each frame is represented by a 1D row, and the frames are aligned along the global u axis. A static camera defines a rectangular space-time region (a), while a moving camera defines a more general swept volume (b). Snapshots of an evolving time front surface produce a sequence of time slices; each time slice is mapped to produce a single output video frame. Time flow for generating dynamic mosaics from a panning camera is shown in (b).

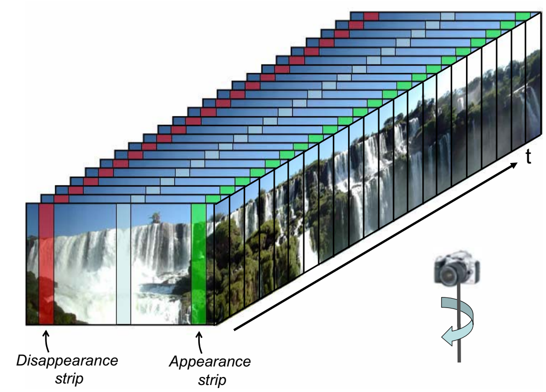


Figure 3. Input frames are stacked along the time axis to form a space-time volume. Given frames captured with a video camera panning clockwise, panoramic mosaics can be obtained by pasting together vertical strips taken from each image. Pasting together strips from the right side of the images will generate a panoramic image where all regions appear as they first enter the sequence, regardless of their chronological time.

column (row) in the input sequence. This function can be represented by a continuous slice (*time slice*) in the space-time (u-t) volume, as shown in Fig. 2. Each time slice determines the mosaic strips by its intersection with the frames of the original sequence at the original discrete time values (shown as dashed lines in Fig. 2).

To get a desired time manipulation we specify an *evolving time front*: a free-form surface that deforms as it sweeps through the space-time volume. Taking snapshots of this surface at different times results in a sequence of time slices (Figure 2). It should be noted that mosaicing with general time slices cannot be done with strips, and more general 2D mosaicing methods should be used.

2.3 Panoramic Dynamosaicing

Panoramic dynamosaics may be generated using the approach described above with the time slices shown in Fig. 2b. Assuming that the camera is scanning the scene left-to-right, the first mosaic in the sequence will be constructed from strips taken from the right side of each input frame, showing regions as they first appear in the field of view (see Fig. 3). The last mosaic in the resulting sequence will be the mosaic image generated from the strips on the left, just before a region disappears from the field of view. Between these two extreme slices of the space-time volume we use intermediate panoramic images that are represented by time slices moving smoothly from the first slice to the last slice. These slices are panoramic images, advancing along the local time from the appearance slice to the disappearance slice, where the local dynamics of each region is preserved. Fig. 1 shows a single panorama from such a movie.

Panoramic dynamosaics represent the elimination of the chronological time of the scanning camera. Instead, all regions appear simultaneously according to the local time of their visibility period: from their first appearance to their disappearance. But there is more to time manipulation than eliminating the chronological time. The next section will describe the relationships between time manipulations and various slicing schemes.

Figures 1 and 4 show examples of panoramic dynamosaics for different scenes. To generate the panoramic movies corresponding to Fig. 1 and Fig. 4, simple planar slices were used. Since it is impossible to demonstrate the dynamics effects in these static images, we urge the reader to examine the video clips at *www.vision.huji.ac.il/dynmos*.

3 Manipulation of Chronological Time

In this section we describe the manipulation of chronological time vs. local time using dynamosaicing. The dynamic panoramas described in the previous section are a simple example of this concept where the chronological time has been eliminated. Chronological time manipulation can be useful for any application where a video should be edited in a way that changes the chronological order of objects in the scene. The realistic appearance of the movie is kept by preserving the local time, even when the chronological time is changed.

3.1 Advancing Backwards in Time

This effect is best demonstrated with the water falls sequence, which was scanned from left to right by a video camera. If we want to reverse the scanning direction, we can simply play the movie backwards. However, playing

1063-6919/05 $20.00 © 2005 IEEE

Figure 4. A dynamic panorama of a tree whose leaves are blowing in the wind. Left: three frames from the sequence (out of 300 frames), scanning the tree from the bottom up. Right: a single frame from the resulting dynamosaic movie.

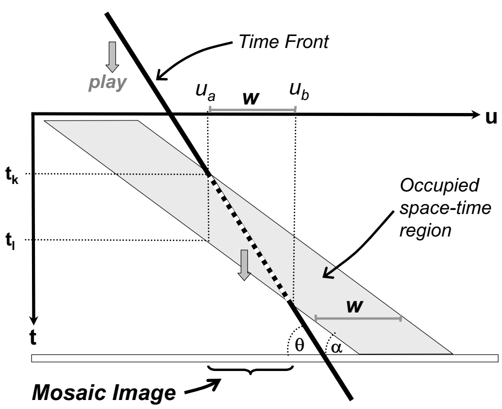


Figure 5. A slicing scheme that reverses the scanning direction using a time front whose slope is twice the slope of the occupied space-time region ($\tan\theta = 2\tan\alpha$). The width of the generated mosaic image is w, the same as that of the original image. Sweeping this time front in the positive time direction (down) moves the mosaic image to the left, in the opposite direction to the original scan. However, each region appears in the same relative order as in the original sequence: u_a first appears in time t_k, and ends in time t_l.

the movie backwards will result in the water flowing upwards.

At first glance, it seems impossible to play a movie backwards without reversing its dynamics. Yet, this can also be achieved by manipulating the chronological time, while preserving the local dynamics. Looking at panoramic dynamosaics, one can claim that all objects are moving simultaneously, and the scanning direction does not have any role. Thus, there must be some kind of symmetry, which

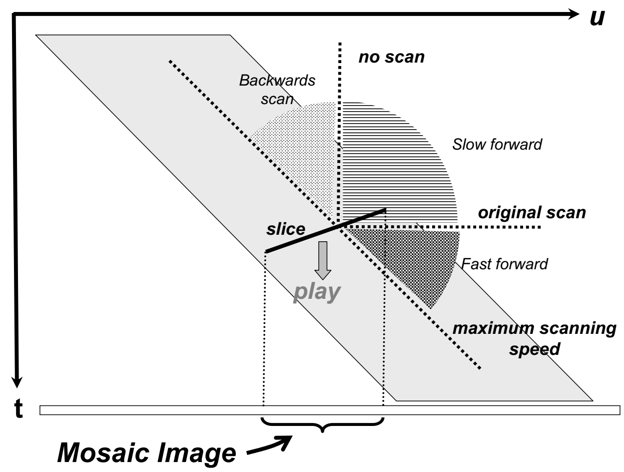


Figure 6. The effects of various planar time fronts. While the time front always sweeps in a constant speed in the positive time direction, various time front angles will have different effects on the resulting video.

enables to convert the panoramic movie into a scanning sequence in which the scanning is at any desired direction and speed.

Indeed, the simple slicing scheme shown in Fig. 5 reverses the scanning direction while keeping the dynamics of the objects in the scene. In the water falls example, the scanning direction is reversed, but the water continues to flow down! This is nicely shown in the video at *www.vision.huji.ac.il/dynmos*.

3.2 Time Manipulations with Planar Time Fronts

The different types of time manipulations that can be obtained with planar time fronts are described in Fig. 6. The time fronts always sweep "downwards" in the direction of positive time at the original speed to preserve the original local time.

The different time fronts, as shown in Fig. 6, can vary both in their angles relative to the u axis and in their lengths. Different angles result in different scanning speeds of the scene. For example, maximum scanning speed is achieved with the panoramic slices. Indeed, in this case the resulting movie is very short, as all regions are played simultaneously. (The scanning speed should not be confused with the dynamics of each object, which preserve the original speed and direction).

The field of view of the resulting dynamosaic frames may be controlled by cropping each time slice as necessary. This can be useful, for example, when icreasing the scanning speed of the scene while preserving the original field of view.

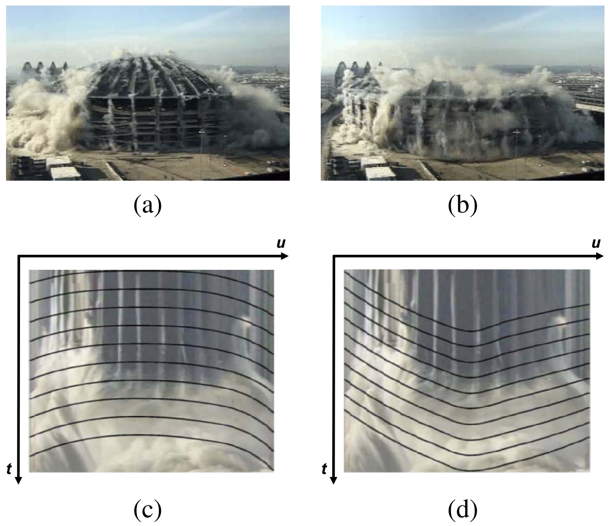


Figure 7. (a) and (b) are frames from two video clips, generated from the same original video sequence with different time flow patterns. (c) and (d) show several time slices superimposed over a u-t slice passing through the center of the space-time volume. The full video clips are available at *www.vision.huji.ac.il/dynmos*.

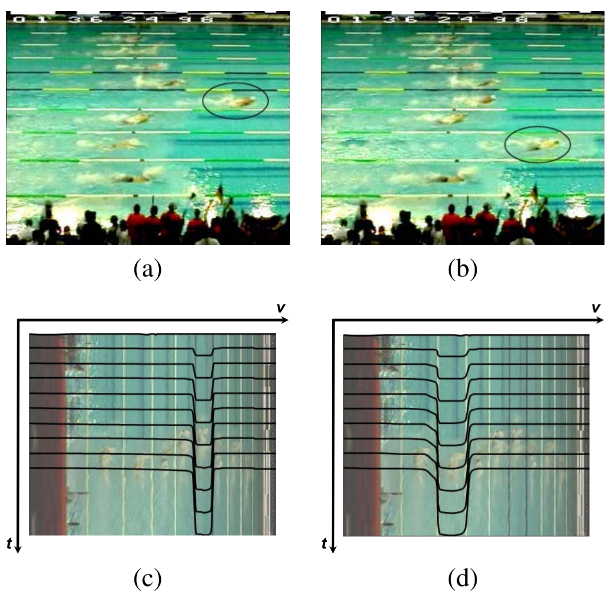


Figure 8. Who is the winner of this swimming competition? Temporal editing enables time to flow differently at different locations in the video, creating new videos with any desired winner, as shown in (a) and (b). (c) and (d) show several time slices superimposed over a v-t slice passing through the center of the space-time volume. In each case the time front is offset forward over a different lane, resulting in two different "winners".

3.3 Temporal Video Editing

Consider a space-time volume generated from a video of a dynamic scene captured by a static camera (as in Figure 2a). The original video may be reconstructed from this volume by sweeping forward in time with a planar time front perpendicular to the time axis. We can manipulate dynamic events in the video by varying the shape and speed of the time front as it sweeps through the space-time volume.

Figure 7 demonstrates two different manipulations of a video clip capturing the demolition of a stadium. In the original clip the entire stadium collapses almost uniformly. By sweeping the time front as shown in Figure 7c the output frames use points ahead in time towards the sides of the frame, causing the sides of the stadium to collapse before the center (Figure 7a). Using the time front evolution in Figure 7d produces a clip where the collapse begins at the dome and spreads outward, as points in the center of the frame are taken ahead in time. It should be noted that Agarwala et al. [1] used the very same input clip to produce still *time-lapse mosaic* images where time appears to flow in different directions (e.g., left-to-right or top-to-bottom). This was done using graph-cut optimization in conjunction with a suitable image objective function. In contrast, our approach generates entire new dynamic video clips.

Another example is shown in Figure 8. Here the input is a video clip of a swimming competition, taken by a stationary camera. By offsetting the time front at regions of the space-time volume corresponding to a particular lane one can speed up or slow down the corresponding swimmer, thus altering the outcome of the competition at will. The shape of the time slices used to produce this effect is shown as well.

In this example we took advantage of the fact that the trajectories of the swimmers are parallel. In general, it is not necessary for the trajectories to be parallel, or even linear, but it is important that the tube-like swept volumes that correspond to the moving objects in space-time do not intersect. If they do, various anomalies, such as duplication of objects, may arise.

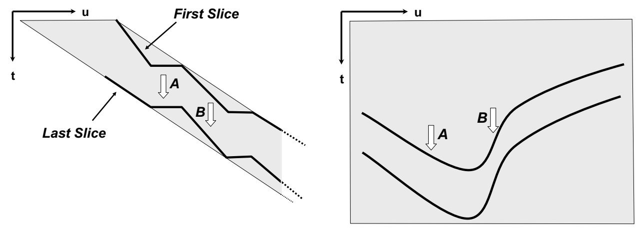
4 Distortion Control

4.1 The "Doppler" effect

For simplicity we present the distortion analysis in the one dimensional case, when the objects are moving in the u-t plane. In our experiments, we found that the distortions caused by the motion component perpendicular to this plane were less noticable. For example, in the panoramic dynamosaics most distortions are due to image features moving in the direction parallel to that of the scanning camera.

Consider the space-time region where a time slice intersects the path of a moving object. Let α_s be the angle between the time slice (in that region) and the t axis. When $\alpha_s = \pi/2$ there is no distortion as the entire object is taken from the same frame. Let α_o be the angle between the path of the object and the t axis. When $\alpha_o = 0$ the object is stationary and again there is no distortion. In other cases,

Figure 9. With the input video panning from right to left, the frequency of the waves in the original image (left) becomes higher in the dynamosaic image (right) due to the Doppler effect.



(a) (b)

Figure 10. Reducing visual distortions of moving objects.
(a) In this non-planar time front the slope in region A was reduced to zero, while the slope in region B was increased. As a result, moving objects in A will not be distorted.
(b) The shape of the time front may be adjusted in a continuous manner to fit the dynamics in the scene. Lower slopes (Region A) should be used for regions with moving objects that are more sensitive to distortions.

the width of the object will shrink or expand. The ratio between the resulting and the original width is easily shown to be $|\frac{\tan\alpha_s}{\tan\alpha_s - \tan\alpha_o}|$.

In the particular case of panoramic dynamosaics, the effect of linear slicing of the space time volume on moving objects can be understood by imagining a virtual "slit" camera that scans the scene, as done in [20]. Similar to the general case, the width w^{new} in the panoramic movie will be:

$$w^{new} = \left|\frac{v_c}{v_c - v_o}\right| \cdot w^{original},$$

where v_c and v_o are the velocities of the scanning slit and the object correspondingly.

Objects moving opposite to the scanning direction have negative velocity ($v_o < 0$). This implies that such objects will shrink, while objects moving in the camera direction will expand, as long as they move slower than the camera. The chronological order of very fast objects may be reversed. Notice also that when the camera motion v_c is large, w^{new} approaches $w^{original}$, which means that when the camera is scanning fast enough relative to the objects in the scene, these distortions become insignificant.

The shrinking and expansion effects just described have some interesting resemblance to the well known Doppler effect, where the frequencies of an approaching signal become higher, while the frequencies of a receding signal become lower (See Fig 9).

4.2 Slope-Adjusted Time Fronts

It is possible to minimize the distortions in selected areas (e.g. containing objects of interest), while increasing the potential distortions in other regions by adjusting the slope of the time front according to the dynamics of objects in the scene. This concept is demonstrated in Fig. 10. The visual distortions are reduced by setting the slope of the time slice to be smaller in regions where the distortion should be minimized, and larger in regions where the distortion is less noticeable or less important (such as the static regions, where no distortion can occur). In the extreme case, a few regions can have a slope of zero, meaning that the objects in those regions will be displayed exactly as they were in the original video.

Determining the structure of the time slices is in general a user dependent task, as it depends on the subjective appearance of the scene. Nevertheless, some automatic processing may be incorporated:

- Define an objective cost function, and minimize it using schemes such as graph-cuts [7]. The existence of an appropriate cost function is not obvious, since subjective criteria are involved. For example, human observers are more sensitive to distortions in rigid objects than in dynamic textures.

- Tracking of moving objects, taking care to always select a moving object from a single frame, or from a small number of adjacent frames.

An example of distorions due to a moving object is shown in Fig. 11. These distortions are caused by the street performer, swaying quickly forward and backward. We have therefore used a slope-adjusted time front to generate the movie corresponding to Fig. 12. In this case, the shape of the time slice was determined by manually selecting regions that should have a smaller distortion.

5 Discussion

Given an input video sequence, new video sequences with a variety of interesting, and sometimes even surprising, effects may be generated by sweeping various evolving time fronts through its aligned space-time volume.

In particular, we have shown that when a dynamic scene is scanned by a video camera, the chronological time is of-

Proceedings of the 2005 IEEE Computer Society Conference on Computer Vision and Pattern Recognition (CVPR'05)
1063-6919/05 $20.00 © 2005 IEEE

Figure 12. A frame from a panoramic dynamosaic of a crowd looking at a street performer.

Figure 11. The street performer (also shown in Fig. 12) is moving very quickly forward and backward. Therefore, the planar slicing scheme of Fig. 2b results in distorted images (left). With the adjusted time slices shown in Fig 10a, the distortions of the performer are reduced with no significant influence on its surroundings (right).

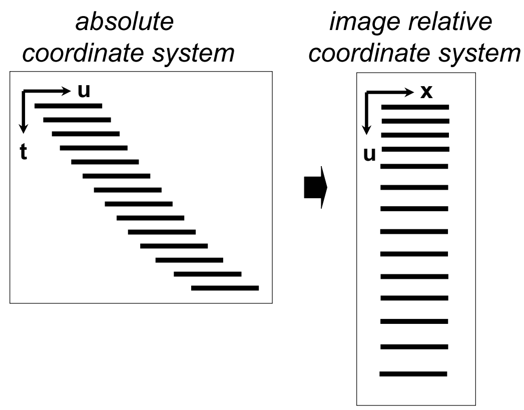


Figure 13. The (u-t) space-time volume can be transformed to the (x-u) space-time volume for easier implementation.

ten not essential to obtain a realistic impression of the dynamic scene. Local time, describing the individual dynamic properties of each object or region in the scene, is more important than the chronological time. We have exploited this observation to manipulate such sequences in ways that are otherwise impossible. In particular, we have demonstrated the use of this concept to create dynamic panoramas, and to reverse the scanning direction of the camera, without affecting the local dynamic properties of the scene.

Besides their impressive appearance, dynamic panoramas can be used as a temporally compact representation of scenes, for the use of applications like video summary or video editing.

We have also demonstrated that the use of non-planar time fronts makes it possible to introduce local changes in the time flow of the video, thus enabling speeding up or slowing down selected events. The time flow manipulations presented in this paper may be viewed as instances of the more general spatio-temporal video warping framework described more fully in [12].

The possible distortions of moving objects may be handled with traditional motion segmentation methods [15] and non-planar slicing schemes [7]. First, independently moving objects should be segmented. Then, the rest of the scene, including dynamic textures and other temporal changes will be addressed with the proposed method.

6 Appendix: Alternative Coordinate System

Sometimes it is more convenient to use an alternative representation of the space-time volume as used in Fig. 13. In this representation, the world coordinates (u, v) are replaced with the image coordinates (x, y). The camera motion is represented by re-spacing the space time volume according to the location of the camera along the u axis [11]. Although the first representation is technically more correct, the latter one might be easier to implement, especially when the velocity of the camera varies from frame to frame. In the image coordinate system, for example, dynamosaic panoramic movies correspond to parallel vertical slices of the (x, y, u) space-time volume.

References

[1] A. Agarwala, M. Dontcheva, M. Agrawala, S. Drucker, A. Colburn, B. Curless, D. Salesin, and M. Cohen. Interactive digital photomontage. In *ACM Transactions on Graphics (Proceedings of SIGGRAPH 2004)*, pages 294–302, 2004.

[2] J.R. Bergen, P. Anandan, K.J. Hanna, and R. Hingorani. Hierarchical model-based motion estimation. In *European Conference on Computer Vision (ECCV'92)*, pages 237–252, Santa Margherita Ligure, Italy, May 1992.

[3] R.C. Bolles, H.H. Baker, and D.H. Marimont. Epipolar-plane image analysis: An approach to determining structure from motion. *International Journal of Computer Vision (IJCV'87)*, 1(1):7–56, 1987.

[4] W.T. Freeman and H. Zhang. Shape-time photography. In *IEEE Computer Society Conference on Computer Vision and Pattern Recognition (CVPR'03)*, volume II, pages 151–157, 2003.

[5] M. Irani, P. Anandan, J. Bergen, R. Kumar, and S. Hsu. Mosaic representations of video sequences and their applications. *Signal Processing: Image Communication*, 8(4):327–351, May 1996.

[6] A. Klein, P. Sloan, A. Colburn, A. Finkelstein, and M. Cohen. Video cubism. Technical Report MSR-TR-2001-45, Microsoft Research, 2001.

[7] V. Kwatra, A. Schödl, I. Essa, G. Turk, and A. Bobick. Graphcut textures: image and video synthesis using graph cuts. In *ACM Transactions on Graphics (Proceedings of SIGGRAPH 2003)*, pages 277–286, July 2003.

[8] Shree K. Nayar. Catadioptric omnidirectional camera. In *IEEE Computer Society Conference on Computer Vision and Pattern Recognition (CVPR'97)*, pages 482–488, Peurto Rico, June 1997.

[9] S. Peleg, M. Ben-Ezra, and Y. Pritch. Omnistereo: Panoramic stereo imaging. *IEEE Trans. on Pattern Analysis and Machine Intelligence*, 23(3):279–290, March 2001.

[10] S. Peleg, B. Rousso, A. Rav-Acha, and A. Zomet. Mosaicing on adaptive manifolds. *IEEE Trans. on Pattern Analysis and Machine Intelligence (PAMI'00)*, 22(10):1144–1154, October 2000.

[11] A. Rav-Acha and S. Peleg. A unified approach for motion analysis and view synthesis. In *Second IEEE International Symposium on 3D Data Processing, Visualization, and Transmission (3DPVT)*, Thessaloniki, Greece, September 2004.

[12] A. Rav-Acha, Y. Pritch, D. Lischinski, and S. Peleg. Evolving time fronts: Spatio-temporal video warping. Technical Report 2005-10, The Hebrew University of Jerusalem, 2005.

[13] A. Rav-Acha, Y. Pritch, and S. Peleg. Online video registration of dynamic scenes using frame prediction. Technical report, The Hebrew University of Jerusalem, June 2005.

[14] P. Sand and S. Teller. Video matching. In *ACM Transactions on Graphics (Proceedings of SIGGRAPH 2004)*, pages 592–599, 2004.

[15] J. Shi and J. Malik. Motion segmentation and tracking using normalized cuts. In *ICCV98*, pages 1154–1160, 1998.

[16] T. Svoboda and T. Pajdla. Epipolar geometry for central catadioptric cameras. *International Journal of Computer Vision (IJCV'02)*, 49(1):23–37, August 2002.

[17] K. Tan, H. Hua, and N. Ahuja. Multiview panoramic cameras using mirror pyramids. *IEEE Trans. on Pattern Analysis and Machine Intelligence (PAMI'04)*, 26(7):941–946, April 2004.

[18] P.H.S. Torr and A. Zisserman. MLESAC: A new robust estimator with application to estimating image geometry. *Journal of Computer Vision and Image Understanding (CVIU'00)*, 78(1):138–156, 2000.

[19] M. Uyttendaele, A. Eden, and R. Szeliski. Eliminating ghosting and exposure artifacts in image mosaics. In *IEEE Computer Society Conference on Computer Vision and Pattern Recognition (CVPR'01)*, volume II, pages 509–516, Kauai, Hawaii, December 2001.

[20] J.Y. Zheng and S. Tsuji. Generating dynamic projection images for scene representation and understanding. *Journal of Computer Vision and Image Understanding (CVIU'98)*, 72(3):237–256, December 1998.

[21] A. Zomet, D. Feldman, S. Peleg, and D. Weinshall. Mosaicing new views: The crossed-slits projection. *IEEE Trans. on Pattern Analysis and Machine Intelligence*, 25(6):741–754, June 2003.

Proceedings of the 2005 IEEE Computer Society Conference on Computer Vision and Pattern Recognition (CVPR'05)
1063-6919/05 $20.00 © 2005 **IEEE**