Special Film Effects Using
Spatio-Temporal Volume Processing

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Department of Electrical & Electronic
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By Martin Gardner

E-mail: Martin.Gardner.98@bristol.ac.uk

Unless otherwise stated, all the work presented in this thesis is that of the author
Summary

This thesis describes a project to investigate the generation of novel special film effects using spatio-temporal volume processing. An algorithm for generating special effects was developed and implemented within a special toolkit, called S-TFX. This toolkit was used to successfully generate an extensive collection of novel special effects. Some of these effects include taking an arbitrary cross-section of the video sequence, forcing a particular object in the scene to stop moving and changing the direction that an object moves in without disturbing other objects in the scene.

The algorithm constructs a spatio-temporal volume from an input video sequence so that the video can be visualised as a single volume rather than a sequence of individual frames. The algorithm extracts the frames from the video and stacks them in order from front to back to create the spatio-temporal volume with time increasing along the Z-axis. The algorithm then defines two surfaces within the volume, the front surface and the back surface. The two surfaces can be defined in several different ways, parametrically, interactively or using volume segmentation. Using these surfaces the algorithm generates a set of N-2 intermediate surfaces between the front and back using interpolation or warping. This set of surfaces, including the front and back, are then used to sample the spatio-temporal volume to generate N new frames. The new frames can then be viewed as a new video sequence.

All the effects were discussed and explained on the basis of the interactions between the spatio-temporal objects in the scene and the sampling planes used to generate the effects. It was concluded that this work should be extended to consider both the scientific and artistic aspects of generating special film effects using spatio-temporal volume processing.
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Abbreviations

**STV: Spatio-Temporal Volume.**
Spatio-Temporal information is usually either a two dimensional field mapped through time or a three dimensional field. Multiple spatio-temporal volumes can map a three dimensional volume through time. Film or video sequences can be considered as spatio-temporal volumes, if all of the frames are stacked front to back.

**STO: Spatio-Temporal Object.**
A spatio-temporal object is an n-dimensional representation of an n-1 dimensional object within an STV. For example a stationary rectangle mapped through time is represented as a cuboid spatio-temporal object. STOs can be revealed within an STV by using volume segmentation algorithms. The S-TFX toolkit can show STOs by rendering isosurfaces within the volume or applying a threshold to the data within the volume.

**S-TFX: Spatio-Temporal Film Effects.**
This is the name of the toolkit the author has developed to generate special film effects using spatio-temporal volume rendering algorithms.
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1 Introduction

The aim of this project was to use non-linear spatio-temporal distortions to generate novel special film effects. The main concept was to use planar or non-planar cuts through spatio-temporal volumes (STV) to generate new video sequences where the shape and motion of video objects is changed and time is non-linear. A new interface for defining and manipulating 3D cuts through spatio-temporal volumes was also designed. This work was motivated by the desire to extend existing algorithms and systems for 3D visualisation to the interactive exploration of spatio-temporal volumes, with the aim of improved perception and understanding of spatio-temporal events and patterns. This innovative and exciting project has produced some curious and fascinating visual effects.

The thesis is divided into seven sections. Section 2 explores some of the technologies involved in generating special film effects and processing spatio-temporal volumes. In Section 3 the main algorithm for generating special effects using spatio-temporal volume processing is discussed. Section 4 explores a number of special effects that can be generated using the spatio-temporal film effect toolkit, which was developed to implement the algorithm. It also explains why some of the effects occur and how different effects affect each other. The functionality and limitations of the toolkit are discussed in detail in Section 5. Finally the thesis ends by drawing conclusions about the results and success of the project and discusses some areas that could be developed further.

2 The State of the Art

As part of the initial work on the project a survey of special film effects was undertaken. Attention was mainly paid to techniques that created similar effects to those expected from the non-linear deformation of cuts through spatio-temporal volumes.

2.1 Film and Digital Effects

Special effects have been used in films for many years; recently the use of digital special effects has become very popular. Almost every film shown in cinemas today has been through a computer for some sort of processing. Notable examples of films that have used cutting edge digital effects include: The Matrix [1], The Lord of the Rings: The Fellowship of the Ring [2], The Lord of the Rings: The Two Towers [3], Chicken Run [4], What Dreams May Come [5] and the television movie Band of Brothers [6]. Digital effects have also been used to great effect in advertisements and television programs, for example the BBC’s Walking with Dinosaurs [7] documentary or The Man from DelMonte [8] television advert.

2.1.1 Time Slicing

Time slicing involves filming a sequence from many different viewpoints and then interleaving the resulting frames in postproduction to produce effects that appear to manipulate the flow of time. There are many different ways of achieving control over the flow of time through a scene and several people have laid claim to the ‘invention’ of time slicing.
In America Dayton Taylor is credited with a 1994 patent for a ‘Virtual Camera Movement System’ [9]. He set up a company, Digital Air, to build a production service called *Timetrack* around his idea. The *Timetrack* virtual camera is shown in Figure 1. It is a very flexible system and can be used to generate many fascinating effects such as capturing motion blur or motion capture without markers in four dimensions including time.

![Timetrack Virtual Camera](image)

**Figure 1** The timetrack virtual camera.

Using an array of still cameras; the Timetrack device captures one subject from many different angles. (ABCNEWS.com)[10]

 Probably the most well known use of time slicing is in *The Matrix* [1] where it was used to emulate the dynamic movement control used in Anime [11] animated films. John Geata [12] from Manex Visual Effects [13] used a multi camera rig and a computer model of the sequence, to calculate the position and firing sequence of the cameras. The still images from the cameras were then scanned and combined with some computer-interpolated images to form the video sequence. An outline of this system is shown in Figure 2 and Figure 3.
Tim Macmillan [14] pioneered the use of time slicing in film and television during the 1980s initially as a form of video cubism. The methods used by Macmillan differ slightly from those used in *The Matrix* and by Dayton Taylor. Macmillan’s first method used a much simpler system based on a single length of film negative and corresponding apertures.

“The first motion-picture camera designed specifically around the technique by Macmillan involved a length of 16mm film negative held in a channel. Above the neg Macmillan placed clear perspex spacers to give the camera a focal length. Above the spacers was placed a length of opaque 16mm cine magnetic tape with a pinhole drilled into each frame (cine magnetic tape is opaque). A simple shutter over the magnetic tape then provided the means of exposure. The result was a perpendicular tracking shot through a space.” [15]

In developing his system Macmillan was investigating how cubism [16] could be transferred to the medium of photography and film. He was not alone in attempting
this; Camile Utterback developed a video cubism system that uses the participant’s motion to define the video sequence.

“Liquid Time is an interactive installation in which a participant’s physical motion in the installation space fragments time in a stored video clip. A participant’s movement in the space is tracked by an overhead video camera. As the participant moves closer to the projection screen they push deeper into time - but only in the area of the screen directly in front of them. As they move away the fragmented image heals in their wake - like a pond returning to stillness. In the Liquid Time installation, the interface of one’s body - which can only exist in one place, at one time - is the means to create a space in which multiple times and perspectives coexist. The resulting imagery can be described as video cubism” [17]

The effects generated by time slicing and other video cubism techniques can transcend our experience as they allow us to step outside of the boundaries of time to view events from multiple viewpoints at once.

2.1.2 Digital Compositing
Digital compositing produces the illusion of actors interacting seamlessly with an environment that has been generated artificially. Usually this involves one frame sequence for each element to be combined. The frame sequences are masked and segmented and then combined to make the final frame sequence. There are examples of this in *The Matrix* [1] (robots and the liquid mirror), *Gladiator* [18] (crowds and buildings) and *Moulin Rouge* [19] (the absinthe fairy and Paris flythrough).

2.1.3 3D Modelling
3D modelling can be used when constructing a life size set is too expensive. Instead the actors and the environment are separated either partially or fully. When only partially separated as in the Coliseum scenes in *Gladiator* the actors interact with a life size set that is incomplete, in this case only part of the Coliseum. The missing parts of the scene are generated by computer and then combined with the first sequence using digital compositing to produce the final scene.

3D models of the set textured and used in conjunction with compositing can ‘flesh’ out a scene and allow impossible camera motion like that of the Paris flythrough at the beginning of *Moulin Rouge*.

2.1.4 Virtual Extras
Along with the creation of virtual buildings and environments it is also possible to create virtual crowds of people. This technology has been used to great success in several films including:

- *Gladiator* [18] to show the crowds in Rome and the Coliseum.
- It was used to show flocking herds of dinosaurs and other animals in *Jurassic Park* [21] and *Walking with Dinosaurs* [7].
In *The Lord of the Rings: The Two Towers* [3] tens of thousands of warriors attack the Rohan stronghold Helm’s Deep. To show this event on screen the special effects company Weta Digital used the *Massive* software [22] developed by Stephen Regelous to model the warriors. The behaviour of each digital extra was controlled by a directed graph of fuzzy logic rules. Input to the graph came from a number of variables representing the environment surrounding the extra. The output of the graph was a probability distribution over the set of possible actions that the extra could perform. The set of possible actions was associated to motion capture data from human actors to ensure that the resulting virtual extra’s movement was as realistic as possible.

### 2.2 Volume Rendering and Interactive VR

#### 2.2.1 Volume Rendering

Volume rendering converts directly from the volumetric data to images without using geometric primitives. This is most suitable for data sets that are inherently volumetric such as biometric, sonar and seismic data. Image order and object order rendering are two methods for visualising volumetric images. Both methods attempt to allow for each point along the path of a ray to contribute to the corresponding pixel value on the image plane. Opacity can be varied with a transfer function to allow parts of a volume that are normally hidden to become visible.

##### 2.2.1.1 Image Order Rendering

This is sometimes known as ray casting, the ray is sent through the pixel into the scene according to the current camera parameters. The voxels in the path of the ray are sampled and are combined based on a specified function. The rays can be projected from a viewpoint, called a perspective projection, or parallel to each other, called an orthographic projection. Orthographic projections are quicker to generate but lack the depth cues found in perspective projections. The voxels along the ray path can either be sampled at uniform intervals or by traversal through the voxel space along the ray path using a 3D version of Bresenham’s method [23].

##### 2.2.1.2 Object Order Rendering

Object order rendering takes every point in the data set and projects it onto the final image. This generally uses the perspective projection and processes samples in the volume based on the organisation of the voxels and the current camera position. The discrete selection of the projected image points can cause serious artefacts, however object order rendering is fast and efficient. The artefacts introduced by this method can be overcome by using ‘splatting’ [24, 25, 26]. This involves projecting the energy of a voxel to the image plane one splat at a time. A splat is considered to have specified properties corresponding to its kernel. For example a typical kernel would be 3D Gaussian, which is spherically symmetrical, and therefore the evaluation of its footprint on the image plane is an efficient pre-processing task.

#### 2.2.2 Real-Time Volume Rendering

Without dedicated hardware volume rendering is usually performed offline as it is not possible to achieve an acceptable frame rate to allow real-time performance. The *VolumePro* 500 [27, 28] was the first commodity volume rendering hardware solution that could be used on a generic PC platform. Volume rendering software
built on the VLI API when used with the *VolumePro 500* can offer real time visualisation of medical data from CT and MRI scans at 30 frames per second. The *VolumePro* uses the Vox file format [29] specified by Mitsubishi to work with volumes up to $256^3$ voxels. The *VolumePro* card is a hardware implementation of ray-casting (see Section 2.2.1 Volume Rendering) with parallel slice by slice processing [27]. The second generation of this card, called the *VolumePro 1000* [30], is now available. It offers many improvements over the *VolumePro 500* including 2GB of memory, support for volumes up to $512^3$ voxels and perspective projection. Especially important is its support for the mixing of voxel and polygons in a volume. This will allow polygonal surfaces to be interactively defined within a spatio-temporal volume.

### 2.2.3 Volume Segmentation

Segmentation is the process of identifying and classifying data found in a digitally sampled representation. Typically the sampled representation is an image acquired from such medical instrumentation as CT or MRI scanners. Volume segmentation is often used in medical applications to identify tumours or regions of interest within a volume. When applied to spatio-temporal volumes, segmentation could allow the identification and extraction of specific spatio-temporal objects (STO) from a video sequence. The identification of an STO within an STV corresponds to finding an object common to several frames within a video sequence, a problem often faced by computer vision systems.

### 2.2.4 OpenGL

OpenGL [31,32] is a software interface to graphics hardware. It is designed to be streamlined and hardware independent, consequently, there are no commands for performing windowing tasks or obtaining user input included in it. OpenInventor [33] is a toolkit for OpenGL that provides a scene graph based interface to OpenGL primitives. OpenInventor is intended to make developing correct OpenGL programs easier.

### 2.2.5 The Visualisation Toolkit Vtk

The Visualisation Toolkit (*vtk*) [34, 35, 36, 37] was developed to provide a freely available software system for 3D computer graphic, image processing and visualisation. It consists of a C++ class library and several interpreted interface layers including *Tcl/Tk* [38], Java [39] and Python [40]. *Vtk* is widely used and it has a strong user community built around the *vtkusers* mailing list [41]. *Vtk* also contains an extensive class library and most importantly supports the *VolumePro* family of volume rendering hardware cards. This makes it an ideal candidate on which to build the toolkit for generating spatio-temporal film effects S-TFX.

### 2.2.6 The Insight Toolkit ITK

The National Library of Medicine Insight Segmentation and Registration Toolkit (*ITK*) [42] was developed as an open-source software system to support the Visible Human Project [43]. It can perform segmentation and registration in two or more dimensions. *ITK* could provide the functionality to segment spatio-temporal volumes and identify spatio-temporal objects.
2.3 Spatio-Temporal Information

Spatio-Temporal information is usually either a two dimensional field mapped through time or a three dimensional field. Multiple spatio-temporal volumes can map a three dimensional volume through time. Film or video sequences can be considered as spatio-temporal volumes, if all of the frames are stacked front to back, as in Figure 4, then we can visualise the film sequence as a single volume rather than a sequence of 2D images. The time axis of the spatio-temporal volume is always aligned with the Z-axis of the 3D space in which the volume resides. This volume can be manipulated in different ways to expose its internal structure [44]. Cutting the volume into a new set of frames can create a completely different film sequence, for example a sequence based on the cutting plane in Figure 5 would distort space-time in the clip. An example of a cut through an STV is shown in Figure 6. The volume can be viewed implicitly with the use of sampling planes as in Figure 6 or it can be rendered and viewed in its own right as a solid volume. Volume rendering, described in Section 2.2 can be used to view objects within the STV that cannot be seen using implicit methods. An example of a volume rendered STV is shown in Figure 7.

![Figure 4](image1.png)  
**Figure 4** A video or film spatio-temporal volume.  
Time increasing along the t axis

![Figure 5](image2.png)  
**Figure 5** A spatio-temporal Volume With a cutting Plane
A spatio-temporal object is an n-dimensional representation of an n-1 dimensional object within an STV. For example Figure 8 shows how a stationary rectangle mapped through time is represented as a cuboid spatio-temporal object. This simplification makes it is possible to define the central axis of the STO, as shown in Figure 9, which is useful in explaining how and why effects are generated when STVs are sampled with arbitrary surfaces. A more complicated STO is shown in Figure 7, and corresponds to a bird walking across the frame. STOs can be revealed within an STV by using volume segmentation algorithms or by modifying the transfer function used to render the volume.
2.4 Image and Video Warping Techniques

Many special effects involve the transformation of one object into another. An example of this occurs in The Matrix when an Agent transfers himself to a new host. The body of the host morphs into the Agent’s body. In order for the morph or warp to appear seamless the change from one body to another has to be padded with intermediate frames. The intermediate frames are a weighted combination of the start and target frames, the exact content of each intermediate frame is interpolated from the frames preceding and succeeding it.

Interpolation [45] provides methods for estimating missing values in datasets by taking an average of neighbouring points. Linear piecewise interpolation is the simplest method as it involves connecting each point in the data set by a straight-line segment. This produces an interpolation that agrees with the data but is discontinuous and difficult to generalise outside of range of the dataset. In a video sequence the transition would appear jerky with jagged edges. To be realistic the transition must be smooth. A more suitable interpolation method resulting in a smooth line connecting all of the data points can be achieved with a polynomial, quadratic or spline interpolation. The existing data points, in this case the start and end frames, are called knots and they are used to determine the shape of the interpolating curve. Each method gives a different curve for the same knot values. Polynomial interpolation is more sensitive to the positions of the knots than quadratic interpolation, which in turn is more sensitive than spline interpolation. This is due to the value of the derivative of the curve being discontinuous for polynomial and quadratic interpolation but continuous for spline interpolation.

Spline interpolation across a number of intermediate frames is applied to the pixel values of the start and end frames to produce a smooth transition between the two. Interpolation can also be applied to geometric shapes of any number of dimensions in order to warp one object into another. This is especially relevant when a video sequence has been segmented as it allows parts of it to be distorted without warping the whole scene.
3 Algorithm for Generating Special Effects from STV

The following algorithm has been designed to generate special effects from the spatio-temporal volumes. Each step of this algorithm is explained and discussed in detail.

1) Construct STV from film or video.
2) Define two surfaces inside the volume, the front surface \((F)\) and the back surface \((B)\).
   There are several different ways to define the surfaces;
   a. As planes using a parametric expression.
   b. As surfaces using analytical or parametric expressions.
   c. Interactive surface manipulation using NURBS
   d. Other definitions for example using 3D segmentation of the STV.
3) Generate \(N-2\) intermediate surfaces \(S\), between \(F \& B\), using interpolation or warping.
4) Generate \(N\) new frames \(E\) from the \(N\) surfaces \(S\) plus \(F \& B\).
5) View the new frames

3.1 Construct STV from Film or Video.

The film or video sequences can be input to the toolkit in one of a number of formats. The file formats supported by the toolkit are:
- The Standard QCIF video format.
- Separated QCIF files where each channel is stored in a separate file.
- Raw single channel in one file with accompanying *.id file to describe volume parameters such as image size and extent.
- A sequence of images in PNG format numbered according to a specified pattern.

Depending on the input file type the toolkit reads the data and generates the STV in several different ways.

For standard QCIF two readers read the source file, one extracts the luminance channel and the other extracts the chrominance channels. This results in three volumes being loaded into the toolkit. These files are read using two image file reader objects one with an extent of 176x(144+72) and the other 88x(288+72+72) as shown in Figure 11 and Figure 12. The toolkit reads in the file twice using these readers and then extracts a volume of interest from each one to get three objects containing the luminance and both chrominance channels.

For separated QCIF each channel is read separately from the appropriate file. Luminance is read from the file ending in .y, and the chrominance channels are read from the files ending .u and .v. The resulting three volumes are then loaded into the toolkit.

For the single channel files a single volume is created from the source file and loaded into the toolkit.
For PNG image sequences the user is asked to specify the details of the sequence. The toolkit uses this information to read all of the files in the sequence into a single multi-component volume. This volume contains all the channels in the input image sequence, so if the input images are in RGBA format all four channels are present in the loaded volume.

Once loaded the STV is displayed to the user. Because volume rendering currently only works on single component or greyscale data only the luminance channels of the input volumes are used. For the first three file types this is simple however for the PNG image sequence volume the luminance must be calculated and passed to the volume renderer. In order to view the volume in colour the renderer must be given a colour map to map back from the luminance values to RGB.

3.2 Define Two Surfaces Inside the Volume

3.2.1 As Planes Using a Parametric Expression

S-TFX allows the user to manipulate the sampling planes using the mouse. This implicit specification is complemented by the facility to specify the plane orientation explicitly. The toolkit can read and save text files that contain the specification of the planes. Figure 13 and Figure 14 illustrate the structure of the plane orientation files used by S-TFX.
num_planes <number of planes specified in this file>

Followed by num_planes repetitions of

start_plane <id of current plane>
normal <X Y Z vector for plane normal>
origin <X Y Z coordinates of the origin of the plane>
point1 <X Y Z coordinates of first point on the plane>
point2 <X Y Z coordinates of second point on the plane>
end_plane <id of current plane>

Figure 13 General Structure of a plane orientation file

Figure 14 A simple example of a plane orientation file.

3.2.2 As Surfaces Using Analytical or Parametric Expressions.

The toolkit does not currently provide this functionality, however it would not be difficult to extend the toolkit as *Vtk* itself supports implicitly defined surfaces. *Vtk* contains a class called *vtkSampleFunction* that allows the sampling of an implicit function over a structured point set. The user could be asked to enter the coefficients to an implicit quadratic surface. These coefficients can then be passed to the *Vtk* class *vtkQuadric*, which defines an implicit surface that is then sampled by *vtkSampleFunction*.

```tcl
# Quadric definition. This is a type of implicit function. Here the coefficients to the equations are set.
vtkQuadric quadric
  quadric SetCoefficients .5 1 .2 0 .1 0 0 .2 0 0

# The vtkSampleFunction uses the quadric function and evaluates function value over a regular lattice (i.e., a volume).
vtkSampleFunction sample
  sample SetSampleDimensions 30 30 30
  sample SetImplicitFunction quadric
  sample ComputeNormalsOff
```

Code Sample 1 A tcl code example of how implicit quadratic surfaces could be defined using *Vtk*.

This sample is from `/Examples/ImageProcessing/Tcl/Contours2D.tcl` in the *Vtk* source code package.

3.2.3 Interactive Surface Manipulation Using NURBS

The toolkit does not currently provide this functionality, as NURBS [46] [47] [48] [49] are not explicitly supported by *Vtk*. The openNURBS [50] initiative might provide a way of incorporating NURBS support into either S-TFX or *Vtk* itself. It is conceivable that since *Vtk* is constantly developing, support for NURBS will be
incorporated at some point in the future. With support for NURBS it should be possible to extend the toolkit such that the user can specify the sampling surfaces by picking points in the volume. These points will then be used to generate the NURBS surfaces as polygons within the volume, which in turn would be used to sample the volume.

### 3.2.4 Other Definitions

The sampling surfaces could be defined from a 3D segment of the volume. This would allow the surfaces to be defined by the outer surface of spatio-temporal objects in the scene. *ITK* could be used to provide the volume segmentation algorithms required for this functionality. Since *ITK* is closely related to *Vtk* combining the two toolkits within S-TFX should be quite simple.

### 3.3 Generate N-2 Intermediate Surfaces S, Between F & B, Using Interpolation.

Once the front and back sampling surfaces have been specified the next stage is to generate a new set of ‘frames’ from the STV. This involves sectioning the volume between the two sampling surfaces; the shape of each slice will be dependent on the front and back surfaces. If the clipping surfaces are strictly similar in shape, only differing by their position in space, then the intermediate surfaces will also be similar. If the clipping surfaces have different shapes then warping the front surface into the back surface will generate the intermediate sampling surfaces.

S-TFX provides two ways of generating the intermediate sampling surfaces. The simplest method involves taking the orientation of the front surface and assuming that the back surface is strictly similar. In the case where the sampling surfaces are planar it is assumed that the front and back surfaces are parallel. The user can specify the total number of surfaces to generate (*N*) and this is used with the distance between the front and back surfaces to specify the spacing between the intermediate surfaces. The toolkit uses the *Vtk* class *vtkImageReslice* to sample the STV based on these parameters. The *vtkImageReslice* class samples the STV and generates a new volume corresponding to the set of sampling surfaces. This volume can then be used to generate the new video frames.

The more complex method employed by S-TFX generates the intermediate surfaces by linearly interpolating between the front and back surfaces. Instead of generating a new volume S-TFX generates each sampling surface in turn. Before generating the next surface the current one is used to sample the volume and generate a corresponding frame that is saved as a PNG image. Code Sample 2 outlines how S-TFX implements this algorithm.
Code Sample 2 An outline of the algorithm used by S-TFX.
This code is used to generate sampling surfaces by linearly interpolating between the front and back surfaces.

3.4 Generate N New Frames E from the N Surfaces S plus F & B.
The STV is then sampled using the surfaces. Where a surface intersects a voxel the value of the surface at that point is interpolated from the value of the voxel in the STV. The type of interpolation used to determine the surface value can be nearest
neighbour, linear or cubic. This results in a set of images mapped across the surfaces.

When the volume is sampled using planes the shape of the images is dependent on the orientation of the planes. It was thought that in order to generate a useful frame sequence each image would need to be interpolated to fit onto a 2D planar-rectangular frame. However S-TFX does not do this, as doing so might affect the special effects generated by the toolkit. So in order to accurately investigate the effects of different sampling plane orientations it was necessary to leave the image slices unmodified.

If surfaces are used to sample the volume they have to be flattened before they can be converted into image frames. To convert the surfaces into planes will require an algorithm that can interpolate or warp from the surface to the plane whilst retaining the spatial coherence of the sampled data. A possible solution could be to use a variation of ray casting to generate a planar image of the surface that is dependent on the viewpoint from which the volume is viewed. This would allow the user of the algorithm to locate the viewpoint such that interesting features of the surface are visible in the planar image.

For efficiency S-TFX incorporates this part of the algorithm into generating the intermediate surfaces. When the simplest method of generating surfaces is used Vtk generates a new image data volume. The shape of this volume is defined by the orientation of the sampling plane and is not necessarily cuboid. However slices of the volume can be taken parallel to the XY plane and along the Z-axis of the volume. These slices correspond to the image frames of the generated sequence. If the slices of the volume are not rectangular they are zero-padded into a rectangular frame. When the intermediate surfaces are generated by interpolation S-TFX saves the frames as a sequence of PNG images. If the slices resulting from the surfaces are not rectangular they are zero padded before being saved as a PNG image.

3.5 View the New Frames.

The frames can be viewed in a number of ways depending on which method was used to generate the intermediate surfaces.

If the intermediate surfaces were generated from the orientation of the front plane alone:

- Video preview, the user can view the resulting video sequence immediately.
- The processed volume can be saved to the format of the original video. This volume can then be loaded back into S-TFX to be viewed or manipulated further.
- The processed volume can be saved as an image sequence and viewed frame-by-frame in a third party application or loaded into S-TFX and viewed as an STV.

If the intermediate surfaces were generated by interpolation the sampled frames were saved as a sequence of PNG images and so to view them as an STV they must be loaded into S-TFX. Alternatively the user can view the image sequence frame-by-frame in a third party application such as videoMach [51].

The use of arbitrary sampling surfaces allows for the generation of some very interesting special effects involving the manipulation of time flow through the
original sequence. Effects similar to those generated by time slicing and the video cubism of Camile Utterback [17] are possible.
4 Special Effects

The algorithm described in the previous section can be used to generate video sequences that contain novel special effects. In addition to this it can also be used to generate well-known effects such as motion blur and slow motion. The novel effects generated by S-TFX can be assigned to the following categories, *cross-section*, *standstill*, *swapping direction*, *leaning forwards* and *fluid motion*. However these categories are not mutually exclusive, one or several of them together may cause or contribute to an effect.

The video sequences and images referred to in this section can be found on the CD that accompanies the thesis. A summary of the contents of the CD can be found in Appendix B.

4.1 Cross-section

![Figure 15 Cross-sectional sampling planes.](image1.png)

This image shows how the sampling planes can be oriented to generate a cross-sectional sequence of the STV.

![Figure 16 A cross-section of a video sequence.](image2.png)

This image, taken from `cqueens_xsection.mpg`, shows a cross-section through the cqueens STV, generated by the plane arrangement shown in Figure 15.

If the sampling planes are parallel to any of the axes the resulting video frames will be cross-sections of the volume. This effect gives an interesting view of the time domain of the video sequence. Figure 15 and Figure 16 show the effect of a cross-section parallel to the YZ plane on the `cqueens_original.mpg` sequence. Taking a cross-sectional sequence from an STV often causes the background or stationary parts of the original scene to move while the previously mobile objects become stationary in the frame. This can be seen in `cqueens_xsection.mpg` where the traffic lights move from the left of the frame to the right and back again.

Using front and back planes that are not parallel to each other can generate more complicated effects. If the planes are perpendicular and the intermediate planes are interpolated between them effects such as those shown in Figure 17. In this case the front sampling plane was oriented to lay on the YZ plane at X=179 and the back sampling plane was oriented to lay on the XZ plane at Y=30. The exact orientations
of the sampling planes can be found in the file `elephant_convoy_perp_fb.plane` and Figure 18 shows the sampling planes in S-TFX.

The motion of the objects within the STV can dramatically affect the result of using a cross-sectional sampling. Comparing `cqueens_xsection.mpg` to `flocking_birds_xsection.mpg`, a frame from which is shown in Figure 19, confirms this. The motion of the birds is far more complex than the motion of the vehicles and people resulting in a sequence that is far more alien than `cqueens_xsection.mpg`.

Figure 17 An oblique cross-section of a video sequence.

This is a frame from `elephant_convoy_perp_fb.mpg`, which was generated using front and back sampling planes that were perpendicular to each other and parallel to the time axis. The intermediate planes were interpolated between the front and back planes.

Figure 18 The sampling plane orientation used to generate `elephant_convoy_perp_fb.mpg`.

Figure 19 A time-wise cross-section of a video sequence.

This frame, from `flocking_birds_xsection.mpg`, shows the cross-section effect when the sampling plane is parallel to the time axis.

### 4.2 Standstill

Standstill occurs when an object that was in motion in the original scene appears stationary in the processed sequence. To understand how and why this occurs consider how spatio-temporal objects are generated from images and how the sampling planes interact with them. Referring back to Section 2.3, Figure 8 and Figure 9 gives a representation of a STO as a cuboid with a central axis that is useful in explaining how and why standstill occurs.
Objects present in a scene are either stationary or in motion. The stationary objects correspond to tubes in the STV that have a central axis perpendicular to the image frame. The moving objects in a scene correspond to STOs in the STV that have a central axis that is not perpendicular to the image frame. Where the angle of the central axis of the STO to the image frame is between 0° and 90° the object moves across the frame at a speed inversely proportional to that angle. The object will appear stationary if the angle is 90°. Therefore setting the resample plane to be perpendicular to the central axis will result in making the object appear stationary in the sampled frame. Figure 20 is a frame from cqueens_stationary_van.mpg, which shows a van and single-decker bus appearing to be stationary in the scene as other objects move around them. The sampling plane for this sequence is shown in Figure 21, which confirms that the sampling plane is perpendicular to the STOs corresponding to the van and the bus.

4.3 Swapping Direction

The sequence cqueens_reverse_ddbus.mpg exhibits the effect whereby some objects in the scene move in the opposite direction to that which they move in the original sequence. However this behaviour is limited to only some of the objects in the scene: others move in the same direction as they did in the original sequence. In Section 4.2 STOs were modelled as three-dimensional tubes where the central axis of the STO was used as a reference against which to measure the cuts through the STO. As mentioned in Section 4.2 a moving object produces an STO with a central axis that is not perpendicular to the image frame. This can be exploited to generate sequences where the object appears to move in the reverse direction while other objects in the scene being undisturbed. This effect, seen in Figure 22 can be
explained by looking at the angles between the sampling plane, original image frame and the central axis of the STO. These angles have been defined for the cqueens_reverse_ddbus.mpg STV in Figure 23.

The angle between the original image frame plane and the perpendicular to the central axis of the STO is $\alpha$. The angle between the sampling plane and the perpendicular to the central axis of the STO is $\beta$. The final effect will depend on the relative positions of the original image frame plane and the sampling plane. If $\alpha$ is less than 90º and $\beta$ is greater than 90º the object in the sampled frame will appear to be reversed. It will also appear reversed if $\beta$ is less than 90º and $\alpha$ is greater than 90º.

Figure 22 A frame from cqueens_reverse_ddbus.mpg showing that the double-decker bus has reversed its direction.
This diagram shows the angles relevant to both reversing direction and motion blur. The angle between the original frame plane and the perpendicular to the central axis of the STO is $\alpha$. The angle between the sampling plane and the perpendicular to the central axis of the STO is $\beta$.

### 4.4 Motion Blur

When an object moves quickly enough past a camera the resulting image is blurred. Despite being a well-known special effect the way in which S-TFX generates motion blur warrants explanation. The motion blurring effect can be achieved for any object in an STV whether moving or stationary. Referring to Figure 23, as $\beta$ approaches $90^\circ$ the image of the object in the sampled frame will appear to streak across the frame as though it was too fast to be seen. This is illustrated by [cqueens_demo3.mpg](cqueens_demo3.mpg) where a pedestrian appears to streak across the frame very quickly. Figure 24 shows the STO of the pedestrian marked in green and Figure 25 shows how the pedestrian appears on one of the sampled frames. In this case the sampling plane cuts the pedestrian’s STO along its length parallel to its central axis giving a lengthwise cross-section of the pedestrian. This gives the effect of the pedestrian being spread across the frame in a way very similar to motion blur.
4.5 Leaning Forwards

Objects can be made to appear as though they are leaning towards their direction of travel. An example of this is shown in Figure 26 and Figure 27 where the double-decker bus is sheared in the direction in which it is travelling by an amount dependent on its velocity through the frame. This effect, which is key to more complex effects, can be seen in the video cqueens_dem01.mpg where the double-decker bus and white van are clearly leaning in their direction of travel.

To understand why this effect occurs consider the spatio-temporal objects involved. Figure 29 shows a representation of the original queens sequence as a spatio-temporal volume. This representation shows the STO that the double-decker bus makes as it passes through the frame. Consider the rectangular object in Figure 8 if this rectangle were moving from left to right across the frame the corresponding STO would be a cuboid whose central axis is not parallel to the Z-axis of the STV as illustrated in Figure 28. This is the sort of STO generated by the double-decker bus. Figure 29 shows the STO of the double-decker bus marked in red within the STV of the cqueens_orginal.mpg sequence. The sampling plane shown is the one used to generate cqueens_dem01.mpg. When the STO is cut using this plane, which is not coplanar to the original image frame, the cross-section is diamond shaped rather than rectangular. It is this that causes the bus to appear sheared in the sampled frame.
Figure 26 Double-Decker in *cqueens_original.mpg*

Figure 27 Double-Decker Bus in *cqueens_demo1.mpg*

Sequence of Images

Spatio-Temporal Object Corresponding to ‘A’

Y
Z
X

Central Axis of STO Not parallel to Z-axis

Two Dimensional Object ‘A’ Moving from the left to the right of the frame

Figure 28 Diagram showing the STO formed by a rectangle moving from left to right across a frame.
4.6 Fluid Motion

The shearing effect seen in Section 4.5 can also be applied to human or animal motion, however because humans rarely move in just one direction the result is motion that appears fluid and surreal. The sequence csalesman_demo1.mpg shows a salesman who waves his arms whilst holding a small box. Figure 30 contains a frame from the video showing the distortion of the salesman’s arms, which appear to be made of elastic as they move non-linearly. This effect can also be seen in elephants_fight_warped.mpg where a fast moving trunk has been smeared across space-time.

This effect produces video sequences that share surreal aspects in common with cubism and surrealism. However these effects are more fluid and natural than those generated by Camile Utterbeck in her Liquid Time [17] installation. Some of the sequences containing fluid motion bear a resemblance to the surreal work of Salvador Dali. An example of this is elephant_convoy_perp_fb.mpg, see Figure 17, where the elephants are stretched upwards as the sequence progresses, their legs becoming thin helices.
4.7 Well-known Effects

4.7.1 Slow Motion and Accelerated Motion
The well-known effect of slowing the apparent passage of time can be generated within S-TFX by re-sampling the STV with more slices than in the original. This will generate a longer sequence of frames which when viewed at the original frame rate will result in motion appearing slower than in the original. Conversely sampling the volume with fewer slices will give a sequence in which motion appears faster when replayed at the original frame rate. Examples of these effects can be seen in cqueens_slomo_x4.mpg and cqueens_hispeed_x4.mpg.

4.7.2 Playback Reversal
When the front sampling plane is placed behind the back sampling plane in the STV the resulting sequence will play in reverse when compared to the original sequence. This is because the STV is sliced by starting at the position of the front plane and then moving towards the back plane with no restriction on the relative positions of the two planes. A simple example of this effect can be seen in cqueens_playback_reversal.mpg, a more complicated example showing playback initially in reverse but then changing to forwards is cqueens_stretch_rev.mpg.
5 Spatio-Temporal Film Effects (S-TFX) Software Toolkit

This toolkit was built using the Visualisation Toolkit Vtk and the scripting language
Tickle with the TK windowing toolkit [38] (Tcl/Tk). Consequently it is platform
independent, as both Vtk and Tcl/Tk will work on a variety of platforms. The toolkit
implements the main algorithm described in Section 3, and was used to generate all
the special effects shown in the previous section.

5.1 Hardware Acceleration

The S-TFX toolkit supports but does not require the use of VolumePro volume
rendering hardware. Use of this hardware with the toolkit can dramatically improve
the performance of the toolkit when viewing volume rendered images. OpenGL
acceleration hardware can also be used with S-TFX.

5.2 Memory Requirements

The S-TFX toolkit requires that the video sequence to be loaded can fit into the
available system memory several times over due to the data caching employed by
Vtk, therefore a minimum of 1Gigabyte of system memory is recommended for
working with STVs larger than 172x144x300.

5.3 User Interface

S-TFX consists of four windows, the main window, video preview window, the
image sequence file parameter window and the background colour window.
Examples of these windows are show in Figure 32, Figure 33, Figure 34 and Figure
35.

5.3.1 Main Window

When S-TFX is initialised it will ask the user to specify a video sequence to open. If
the user selects an image sequence S-TFX uses the dialog in Figure 32 to ask the
user for further details of the sequence. S-TFX then loads the file and displays the
main window shown in Figure 33. The main window allows the user to interactively
define planes within the volume. The user can then use the main window to process
the volume according to those planes.

5.3.2 Video Preview Window

Once the volume has been processed a preview of the resulting video can be viewed
in the video preview window shown in Figure 34 by clicking the “Video” button in
the main window. This feature will only work if “Interpolate Intermediates” is
disabled. The video preview window allows the user to view the sequence forwards
and in reverse. The user can also step through the sequence one frame at a time or
skip to the start or end of the sequence.

5.3.3 Background Colour Window

The background colour window shown in Figure 35 allows the user to change the
background colour of the main window render view. This is useful if there is not
enough contrast between the rendered image and the background. This window
allows the user to specify a background colour that gives a suitable contrast to the
rendered image. The red, green and blue sliders define the RGB value of the background on a scale of 0-100.

Figure 32 S-TFX Image sequence file parameter window

Figure 33 S-TFX main window
5.4 S-TFX Functionality

5.4.1 Supported File Types
S-TFX supports the following file types.
- Standard QCIF Video Files
- Raw Single Component Volume Files
- Separate QCIF Video Files
- Image Sequences

5.4.1.1 Standard QCIF Video Files
Although S-TFX can read standard QCIF video files it cannot write sequences to standard QCIF video files. This is because it requires the luminance and chrominance channels to be interleaved, which is difficult to implement using Vtk. S-TFX uses Vtk’s image file writer classes to write STV’s to video files and these writers only write rectangular images whereas the standard QCIF image is L shaped, as shown in Figure 10. Consequently S-TFX extracts the luminance and chrominance channels of a QCIF video and stores them as separate volumes. Consequently standard QCIF files must be saved as separate QCIF or PNG image sequences.

5.4.1.2 Raw Single Component Volume Files
S-TFX can read and write raw single component volume files using an accompanying file to specify the file’s dimensions. The video file should contain binary unsigned char data with no header or footer. The accompanying file should share the same filename as the video file, including extension, with “id” appended to it. The format of the “id” file should conform to the specification in Figure 36 and Figure 37.
5.4.1.3 Separate QCIF Video Files
S-TFX can read QCIF video files that have been separated into three files, one for luminance, using the extension ‘.y’ and two for chrominance, using the extensions ‘.u’ and ‘.v’. Each channel is treated as a separate volume and sampling is performed each volume to ensure the resulting separate QCIF files are consistent.

5.4.1.4 Image Sequences
The most flexible input and output format that S-TFX supports consists of sequences of PNG images. The development of S-TFX has concentrated on using PNG image sequences for both input and output. This is because the PNG file format is royalty free and Vtk supports PNG file reading and writing natively.

5.4.2 Sampling the STV with Parallel Planes
S-TFX can be set to use only the front plane to sample the volume. All the intermediate sample planes will be parallel to the front plane. This setting is useful for generating arbitrary cross-sectional sequences of the STV.

5.4.3 Sampling the STV by Interpolating Between a Front and Back Plane
S-TFX can generate the intermediate sample planes by interpolating between the front and back planes. The software uses a naïve linear interpolation to calculate the current plane normal from the front and back plane normal. The sampling planes will be equally spaced between the front and back plane. This setting allows for greater freedom in sampling the STV and consequently the generation more complex effects than with parallel sampling planes.

5.4.4 Constrain Sampling Z-axis to the STV Z-axis
Normally the path of the sampling planes will either be defined by the front plane normal or interpolated between the front and back plane. However S-FTX can constrain the sampling plane Z-axis to follow the STV Z-axis. This means that the resulting frames will be constrained within the STV. A side effect of this is that each frame generated from sampling the STV will have the same dimensions. Because this setting forces the sampling planes to be offset from each other in the STV Z-axis direction rather than following their normal direction it can result in consecutive sampling planes being coplanar. Visually this corresponds to a single image moving through the frame where all the objects in the image are stationary with respect to each other.
5.4.5 View the STV Using Volume Rendering

S-TFX can be used to examine the volumetric structure of the video sequence. A volume rendering of the luminance component of the input STV can be displayed in the main window. S-TFX supports software or hardware volume rendering and defaults to using software volume rendering. S-TFX supports the VolumePro family of hardware volume rendering cards from Terarecon [52]. While software volume rendering can produce highly detailed renderings of the STV it also will require greater system resources than hardware rendering.

The rendering of the STV can be modified to reveal structures and objects that were previously occluded. S-TFX allows the user to modify the data visible in the rendering of the volume based on three types of threshold.

- A minimum threshold can be used to remove dark coloured objects from the volume rendering, as all voxels with a value below the threshold will be ignored.
- A maximum threshold can be used to remove light coloured objects, as all voxels with a value above the threshold will be ignored.
- A range threshold can restrict the contributory voxels to those with a value that lies within the range of ± 5 of the threshold.

S-TFX also supports the use of an isosurface to represent the data within the volume.

5.4.6 Save or Load Sampling Plane Orientations

To enable the same effect to be applied to different sequences it is possible to save the orientations of the sampling planes to plain text files. The general structure of the files is shown in Figure 13. This functionality can be used to apply effects to video sequences that are too large to fit into memory in one go. The user can load successive sections of the sequence and apply the same plane orientation to each one. This feature can also be used to apply the same sampling to different video sequences to investigate how resulting effect is dependent on both the content of a video sequence and the applied sampling.

5.4.7 Save Rendered Image

S-TFX allows the user to save a copy of the rendering as displayed on the screen to an image file in either TIFF or PNG format. This can be useful for recording interesting interactions between the sampling planes and the STV. This also allows S-TFX to be used as a general-purpose volume-rendering tool.

5.4.8 Save Front Plane Image

In addition to saving the rendered image the user may also save to PNG or TIFF the image shown on the front sampling plane. This can be useful for recording sections through an STV.

5.4.9 Save the Video in its Native Format

In some cases the user may be able to save the processed video sequence to be saved in the same format as the original video sequence.
5.4.10 Save the Video as a PNG Image Sequence
The processed video sequence can be saved as a sequence of frames in the PNG image format. The number of frames to be saved will be determined by the number of slices that were used to process the volume. This feature is useful for generating a sequence of images that can then be post-processed to generate an MPEG or AVI file of the video sequence.
6 Conclusions

This project has successfully generated an impressive collection of novel special film effects. The causes of the effects have been investigated and discussed, providing a basis for further development and study. The toolkit developed to generate the special effects has shown itself to be a very useful tool. It has been used to study and explain the spatio-temporal phenomena seen in the special effects in addition to its main function of generating the special effects. The novelty of the special effects has been testified by their resemblance to surrealist art. Indeed the toolkit for developing these effects could be used to explore this genre in three or four dimensions.

An initial study of the special effects revealed some useful information about how spatio-temporal objects interact with the sampling planes. This work provides a basis for a detailed systematic study into predicting which special effects will be generated from a given sampling. It can also be used to allow specific effects, such as standstill, to be applied to specific spatio-temporal objects within the spatio-temporal volume. In addition to studying the science of the effects it would be interesting to further explore how humans perceive and understand these spatio-temporal effects.

It is clear from this work that volume processing and rendering are very powerful tools for viewing and manipulating video sequences. The incorporation of the time domain in the representation allows the user to utilise their spatial awareness to explore in greater depth the time varying nature of the objects in the scene. The continued development of volume processing and rendering hardware and software will increase the flexibility of toolkits such as S-TFX and open new avenues of investigation in the study of spatio-temporal information.

I have found this to be a very enjoyable and exciting project; it has provided a new window of insight into the spatio-temporal interactions that one experiences everyday.
7 Future Work

- Scope for further extension/work
- Volume segmentation
- Systematic classification/investigation of effects

7.1 Additions and Modifications to S-TFX

7.1.1 View Volume Rendered STVs in Colour
A minor improvement to S-TFX this would allow the user to use colour as a tool for identifying STOs within the volume. To view the STVs in colour a colour lookup table or colour mapping would be used to transform luminance scalar data back to the RGB vector data. S-TFX would need to calculate the colour map from the input data and then pass it to the volume rendering software, which would then apply the colour map to the scalar data. The issues with converting between YUV and RGB, discussed in Appendix B, would also need to be addressed

7.1.2 Allow definition of a Sampling Surface
S-TFX samples the STV using planes; if it were to use surfaces as well it would be possible to generate a much larger range of special effects. S-TFX could be extended to provide this feature using NURBS as discussed in Section 3.2.3.

7.1.3 Four-Dimensional Spatio-Temporal Volumes
It would be interesting to extend S-TFX to deal with four-dimensional STVs and there are two ways in which this could be interpreted. It could be that the video consists of a sequence of image volumes, so there are three spatial dimensions and one temporal dimension. An example of this would be a beating heart captured as a volumetric image. Alternatively there could be several videos of a scene taken from different viewpoints using a multi-camera rig. These multi-view STVs would therefore consist of a collection of volumes each with two spatial dimensions and one temporal dimension, the fourth dimension would then be defined by the camera number.

The introduction of a fourth dimension brings with it another degree of freedom. Where this project has interpolated two-dimensional planes through a third dimension this extension would involve interpolating three-dimensional objects through a fourth dimension. The computational and conceptual challenges of this are both intimidating and tempting. Some research will be needed in order to establish if Vtk will support this natively or whether it might be necessary to modify Vtk to support this feature.

7.1.4 Support for Long Sequences and High Definition Video Files
There are two challenges when attempting to visualise and manipulate large data sets. The first is that of devising an efficient paging algorithm to minimise the amount of data that must be loaded at anyone time. The second is that of balancing the amount of data loaded with the corresponding interaction performance. Since system resources are always limited a large amount of loaded data will slow the system down and make it less responsive to the user.
There are two situations when a sequence will be too large to be loaded in one go. The sequence could be very long or of a high resolution. The high definition video files could produce sequences satisfy both these criteria. Currently S-TFX can deal with very long sequences by allowing the user to apply the same sampling to different STVs. In effect S-TFX lets the user deal with the paging problem in order to simplify the sampling. The user breaks the sequence down into manageable sections, which can then be used by S-TFX.

Dealing with the second situation is more complex. When loading a high-resolution sequence the user cannot solve the problem by reducing the number of frames they load at any one time. Instead S-TFX will have to solve the problem itself. One way of doing this would be for S-TFX to sub-sample the input sequence in two or three dimensions so that it can fit into memory. The user could then work on the sub-sampled volume. Once the user has finished working on the sub-sampled volume S-TFX could apply the sampling to the larger original sequence offline. In this way the responsiveness of the system will be maintained while the user is interacting with the data.

7.1.5 Support for Native Output of Video Sequences to Standard Formats
In order to produce the demonstration videos presented with this thesis it was necessary to post-process the output of S-TFX. A useful extension to either S-TFX or Vtk would be to allow the user to write video files in standard formats directly from volumes of image data or image sequences.

7.1.6 Support for All Image Sequence Formats Supported by Vtk
Currently S-TFX only reads and writes image sequences in the PNG format. However Vtk supports a range of other image formats. It would be sensible to extend S-TFX to support all the image formats supported by Vtk, and ensure that adding support for future image formats is straightforward.

7.1.7 Volume Segmentation
The analysis of STOs within STVs using S-TFX is limited by the lack of volume segmentation. S-TFX compensates for this using isosurfaces and applying thresholds to the volume rendering transfer function. The utility of S-TFX could be greatly improved by using ITK [42] to provide volume segmentation algorithms within S-TFX.

7.2 Systematic Study of Special Effects Generated by S-TFX
This thesis contains a brief study of the special effects generated by S-TFX. It would be sensible to extend this study to systematically and exhaustively examine the effects and the underlying science. Initially the study could concentrate on the simplest effects: the ones generated by parallel sampling planes would be a suitable place to start.

The study should look at the variables involved in generating the effects. When using parallel sampling planes the variables are the normal and origin of the front sampling plane, the origin of the back sampling plane and the number of slices between the front and back planes. Exploring this relatively simple case should
provide insight into how to study the more complicated effects. Identifying the variables most critical to the special effects will be very important in keeping the study tractable.

7.3 Artistic Aspect

This thesis has concentrated on the technical and scientific issues associated with the generating the special effects. It would be very interesting to explore the artistic possibilities of S-TFX and the effects it can generate. To do so would require some artistic inspiration so an artist could be commissioned to produce some artwork with S-TFX. Hopefully the exposure of S-TFX to an artistic mind will reveal further uses and effects.

7.4 Commercialisation

The purpose of developing S-TFX was to develop a toolkit for generating special effects using spatio-temporal volume processing. Since this has been successful and has generated some very novel effects it is likely that companies who are involved in applying special effects to film might find S-TFX useful. Therefore S-TFX could be exploited commercially by selling or licensing its technology to interested companies. Achieving this would involve some research into the current toolkits used by these companies and how S-TFX could be incorporated into them. However before approaching any prospective companies it will be necessary to decide whether or not any aspect of S-TFX could be patented and if so whether this would be worthwhile.
8 References


http://www.aardman.com/chickenrun/, IMDb entry:


http://us.imdb.com/Title?0120889


http://www.framestore-cfc.com/

[8] Tim Macmillan. The time slicing effects in *The Man from DelMonte*


[10] Jack Valko. *Frozen in Time Virtual Camera Pans Still Image*. Figure 1 from ABCNEWS.com article


[11] Anime is a genre of cell animation originating from Japan. Further information can be found from the following locations: http://www.anime-expo.org/index2.html

http://www.google.com/search?q=Anime+&start=0&start=0


http://whatisthematrix.warnerbros.com/cmp/sfx_index.html


[34] The Visualisation Toolkit vtk project homepage: http://www.vtk.org/ products and services for vtk are provided by Kitware Inc http://www.kitware.com/


[40] Python is an open source interpreted programming language and is available from http://www.python.org/. For an introduction to Python see How to Think Like a Computer Scientist: Learning with Python. Allen Downey, Jeff Elkner and Chris Meyers, Green Tea Press. A free version of this book is available at http://www.greenteapress.com/thinkpython/

[41] The vtkusers mailing list vtkusers@public.kitware.com for more information and the list archives see http://public.kitware.com/mailman/listinfo/vtkusers.

[42] For further information on the National Library of Medicine Insight Segmentation and Registration Toolkit (ITK) see http://www.itk.org/.

[43] The Visible Human Project http://www.nlm.nih.gov/research/visible/visible_humand.html was established to produce a system of knowledge structures that will transparently link visual knowledge forms to symbolic knowledge formats such as the names of body parts.


[50] The openNURBS initiative http://www.opennurbs.com provides tools to accurately transfer 3-D geometry between applications.

[51] videoMach is a software toolkit for building and converting audio/video files. It can be used to construct video clips from still images, enhance recorded material or convert video, audio and image files between many supported formats. Available from http://gromada.com/

[52] The VolumePro family of hardware volume rendering cards can be purchased from Terarecon whose web page is http://www.rtviz.com/products/volumepro_prod.html.