Making Space for Time in Time-Lapse Photography

Michael Terry Gabriel J. Brostow Grace Ou Jaroslav Tyman Diane Gromala
mterry@cc .gatech.edu
GVU Center / College of Computing
Georgia Institute of Technology

ABSTRACT
This paper presents a visualization technique that transforms regular time-lapse footage into composite images, accentuating periodic and long-term events. Traditional time-lapse techniques convey only an accelerated view of the local passage of time, making them most appropriate for studying events coincident in time. Our approach provides a controlled means of trading in the spatial resolution of the output image to gain temporal expressiveness. The input material is sampled – not necessarily linearly – and combined to produce summary visualization of events. Long-term trends, as well as periodic events, become apparent using this technique, making it an effective aid for educational settings (e.g., demonstrating how seasonal phenomena unfold), summarization tasks, and browsing and searching large stores of time-lapse video. We demonstrate this visualization technique on a data set captured over a four month period.

Keywords: Educational Visualization, Time-lapse Photography, Scientific Visualization, Animating Photos, Video Summary, Video Indexing

1 INTRODUCTION

Traditional time-lapse techniques accelerate motion picture footage to offer a view of events that is otherwise difficult to experience. By playing footage at rates hundreds or thousands of times beyond a real-time rate, viewers can gain an appreciation and understanding of contiguous events that unfold over minutes, hours, or days. This unique vantage point has numerous practical applications, from scientific inquiry (e.g., [20]) to the documentation of long-term social events [21].

While traditional time-lapse is particularly adept at revealing near-term, coincident events, it is less effective at exposing phenomena that occur periodically or over very long periods of time. For example, differences in the lengths of days throughout the year are not easily noticed in traditional linear time-lapse renderings, since changes in day length are gradual. Similarly, the time and location at which the moon rises varies slightly every day. However, it is difficult to detect this pattern with traditional time-lapse video since one cannot directly compare the moon’s trajectory across days.

Previous work has recognized a general lack of visualization techniques that highlight periodic events embedded within serial data [3], though some examples exist. For example, [3, 22] make use of spirals to lay out time-series data. These visualizations have been applied to data ranging from movie release dates to chimpanzee eating habits. Plaisant et al. [17], on the other hand, use linear representations to visualize personal histories, such as medical records. In each of these cases, trends and patterns embedded within time series becomes more apparent through the particular visualization technique.

We are similarly motivated to create visualizations that highlight long-term and periodic events, but for photographic data. Like traditional time-lapse photography, we seek representations that increase the ease with which an individual can experience spans of time beyond normal human scales. However, we wish to push beyond this simple technique so that even greater expanses of time can be experienced at once. Additionally, like existing efforts, we pursue visualizations that aid in discovering and identifying periodic events, specifically those contained within time-lapse data.

To meet these goals, we introduce the concept of a Time Map, a visualization technique that explicitly trades space for time to display different moments of time within the same image (Figure 1). Time Maps take, as input, images captured from the same vantage point, and output visualizations that emphasize coincident or periodic events. These visualizations have applications in educational settings, and can support analyzing, browsing, or searching large stores of time-lapse imagery. For example, Time Maps can be used to illustrate natural phenomena, such as lunar and solar cycles, or as a tool to sift through long stretches of time-lapse data.

Time Maps are constructed by mapping single points in the output image to unique moments in time. For example, given three snapshots taken at morning, noon, and night, a Time Map can be
produced that divides the destination frame into three regions, each corresponding to the three times of day (see Figure 1). This type of rendering of time-lapse data sacrifices spatial continuity, while rearranging temporal continuity to display multiple moments within the same scene. We call this style of Time Map a tree ring.

Using the same underlying algorithm, this technique can also create visualizations that tile images sampled from disparate moments in time. For example, several days from the same scene can be tiled to reveal long-term trends, as in Figure 2. In this rendering, the same time of day is displayed for four days sampled from a four month period. Though basic, this Time Map makes clear long-term differences in day length due to the changing orientation of the Earth relative to the sun. These types of Time Maps are called tiled views.

Tree rings and tiled views comprise the two basic styles of Time Maps. However, these styles can also be combined. Furthermore, Time Maps can be generated at sizes larger than the input images in cases when the number of temporal samples to be summarized exceeds the original image width or height. Such an example can be seen in Figure 4.

The rest of this paper is divided into the following sections. First, we discuss applications for this visualization technique. Next, we present Time Maps’ formulation and outline the space of possible parameters for their construction. This section also includes a discussion of our implementation and how we deal with incomplete or missing data. We then contextualize this work with regard to previous efforts. We conclude with a discussion of possibilities for future work.

2 Uses and Applications

The two styles of Time Maps, tree rings and tiled views, each provide their own unique set of affordances. Tree rings provide summaries of spans of time in a single, static snapshot. For example, Figure 3 displays a summary of the weather over a 12 hour period. Tree rings are most suited for situations requiring a compressed view of a contiguous span of time.

Figure 2: This Time Map, a tiled view, shows the same time of day (late afternoon) for four days sampled over a four month period. Changes in the Earth’s orientation to the sun are clearly visible by noting the position (or absence) of the sun in the sky.

Tiled views, on the other hand, are particularly well-suited for revealing periodic events. For example, some human activity is dependent on the day of the week (e.g., weekly meetings). These patterns can be easily recognized when time-lapse data is tiled to match the calendar month in which it was captured. For example, in the source material for the Time Map in Figure 5, a reflection of the interior of the room is visible when the occupant turns on a lamp (the brown/orange colors in some of the individual images in the center). This characteristic helps reveal the occupant’s tendency to turn the light on at approximately the same time every morning, but only on weekdays.

2.1 Application Domains

Our experiences developing and using Time Maps suggest three primary domains of use: educational applications, summarization and analysis tasks, and browsing and searching tasks. We discuss each in turn.

Tiled view Time Maps are particularly effective at demonstrating natural phenomena in a visually engaging manner. For example, a tiled view for a month of data accentuates the pattern of the moon rises: Each day, the moon rises and sets slightly later than the previous day, and in a different location. The ability to directly compare adjacent days makes these patterns obvious. These relationships would be lost in serial presentations of the same data.

In a similar fashion, tiled views simultaneously displaying several months of data demonstrate trends in seasonal differences of day length. Additional insights are possible by comparing different geographical locations side-by-side. For example, synchronized tiled views for data captured from Hong Kong and Alaska reveal much greater variance in the overall amount of change in day length between these locations: Alaska’s days vary from being very short to very long, while day length in Hong Kong remains relatively stable. This variance is due to differences in latitude, but is particularly striking when viewing the two tiled views side-by-side. Though we have not used these visualizations in an actual classroom setting, it is not hard to imagine how they could fruitfully complement curricula for general science classes.

Time Maps, especially tree rings, can be used for summarization tasks. As mentioned previously, Figure 3 serves as a static summary of a 12 hour period at Cornell University. Creating a tiled view of
Figure 4: 48 hour Time Map expressing passage of time in proportion to radial distance from \((1, \frac{v_{max}}{2})\). Output is 4x size of input frames, though each ring of time represents a unique time sample. Artifacts in the Time Map (i.e., aliasing) indicate activity within a particular region.

Figure 5: Time Map of January mornings. This Time Map uncovers a pattern in the occupant's daily routine: internal reflection in the window (the brown hues visible in some images) shows the occupant regularly active in the morning, but only during weekdays.
these tree ring summaries for every day of the month provides a single image to represent that month’s weather conditions.

These summaries also serve to reveal sequential activity: Changes in the scene are visible via the visual discontinuities in the output image. Because Time Maps sample portions of a source image when constructing an output image, a person or object wholly visible in an original image is represented as a slice of color in the output image. For example, in Figure 3, the pre-dawn trajectory of the moon is visible on the left side of the image. Human activity later in the day is noticeable in the center of the image over areas of sidewalk. While such aliasing has traditionally been eschewed, these artifacts serve as markers of activity in the data set.

Finally, Time Maps can be used to both browse and search a large set of time-lapse data. At its conception, this project set out to explore novel ways of experiencing months or years of time-lapse data holistically. In support of this work, we collected snapshots from over 25 publicly available webcams, sampling the webcams every 2-5 minutes (depending on their individual refresh rates), producing dozens and dozens of hours of video to analyze.

To browse and scan this data for interesting phenomena, we relied heavily on tiled, month views. These synopses increased the ease with which we could quickly locate exceptional and repeating events. Automated, algorithmic analysis could assist in this process, but Time Maps provide a general method that allows viewers to apply their own interpretation of the data to suit their particular task.

3 Formulation

The general framework for creating Time Maps provides the following control parameters:
- the range of time to be summarized in the output image,
- layout of tiles, if a tiled view is desired,
- distance function and anchor point(s) if tree rings are desired,
- scale factor if output should be larger than input.

By varying the parameters in this framework, a range of Time Map renderings is possible, each offering its unique summary of time.

The time-lapse footage serving as source data can be treated as a stack of images: a 3D block of image samples with dimensions $x_{\text{max}}, y_{\text{max}},$ and $t_{\text{max}}$ [16]. To access a specific color value, the function $I(x,y;t)$ indexes into the volume of samples, interpolating as necessary. A traditional time-lapse sequence is synthesized by rendering each 2D image $J(u,v)$:

$$J(u,v)_{\Delta t} = I(x,y;t_0 + \Delta t).$$

Here, the individual only has control over the time-lapse $\Delta t,$ while the output pixel coordinates $(u,v)$ are simply reused as inputs: $x = u$ and $y = v.$ Each image resulting from this regular sampling of the $\mathbb{R}^3$ space of pixels only represents one moment at a time. We propose an alternative sampling framework that presents temporal events spatially. This is achieved through a more versatile $\mathbb{R}^3 \rightarrow \mathbb{R}^2$ mapping:

$$K(u,v)_T = I(A(u),B(v),C(u,v,T)).$$

where $T = [t_{\text{min}},t_{\text{max}}]$ now specifies a range of time. Combined, the $A,$ $B,$ and $C$ functions return the 3D coordinate for $I$ to look up a color value. The functions $A$ and $B$ are fully specified given the scaling parameter $s,$ which allows output images whose size differs from the input, typically set to $\frac{t_{\text{max}}}{t_{\text{min}}}$:

$$A(u) = \frac{u}{s} \mod x_{\text{max}},$$

$$B(v) = \frac{v}{s} \mod y_{\text{max}}.$$  \hspace{1cm} (3, 4)

The function $C$ trades off spatial resolution for temporal resolution by making use of all the user-specified parameters, $s, T, r, c,$ and distance function $D.$ $C$ computes a time offset into the data according to the requested visualization layout:

$$C(u,v,T) = t_{\text{min}} + \alpha(t_{\text{max}} - t_{\text{min}}) + D(u,v,T),$$

$$\alpha = \min \left(1, \frac{v/r - 1}{y_{\text{max}}} \frac{c + u/s}{x_{\text{max}}}, \frac{t_{\text{max}}}{max(1,rc - 1)} \right).$$

and where $r$ and $c$ are the desired numbers of rows and columns for rendering an output image as tiled versions of the input data base (see Figure 5). For such tiling, $\alpha$ switches each subwindow to index into range $T$ in row-major order; Eq. 6 is altered slightly for column-major ordering. For a single tile, function $D$ maps temporal distance between $t_{\text{min}}$ and $t_{\text{max}}$ onto spatial distance $d_{\text{max}}$ as measured from $(u_p,v_p), a user-selected point in the output. Artists may design simple or complex versions of $D,$ but a typical formula that creates concentric time rings about the image center has $D(u,v,T) = t_{\text{min}} + \frac{[(t_{\text{max}}/2,x_{\text{max}}/2) - (u,v)]}{d_{\text{max}}} t_{\text{max}}.$ To instead render time as horizontal or vertical subdivisions of space, $D$ can ignore the $u$ or $v$ coordinates, respectively. Note that bounds checking on the $t$ returned by Eq. 5 is necessary if a non-zero $D$ is used in combination with tiling.

With the technique in place, we now describe its application to several example data sets. The Time Map shown in Figure 3 was created using a $T$ spanning 12 hours, a distance function $D$ that only measures distance along the $u$ axis, and $s = r = c = 1.$ Time progresses from left to right along the $x$ axis because $(u_p,v_p)$ was selected to be at $u = 1.$

Figure 5 displays a Time Map of the same time in the morning for every day in January. To create this Time Map, the following parameters were used: $T$ spanning 35 days (some masked out afterward), $r = 5, c = 7, s = 1,$ and $D = 0.$

An interesting result of our formulation is the decoupling of output frame size from that of the input footage. Figure 4 is an example of a two day Time Map, with $D(u,v,T)$ being a radial distance function centered on the left of the frame. Especially noteworthy is that here $s = 4.2125,$ allowing the rendering of the 320x240 input as a 1348x1011 output. Time progresses from left to right through the concentric circles. Increasing $s$ while holding $T$ constant would add spatial resolution. Alternately, increasing $t_{\text{max}}$ and $y_{\text{max}}$ improves temporal resolution.

3.1 Implementation Details and Known Limitations

While the implementation of Eq. 2 is fairly straightforward, several performance-related matters bear explaining. Most importantly, access to a large $xvt$ volume of time-lapse footage is slowest when a
new image file is read from disk. It is desirable to ensure that each
image in the input is read at most once, especially when interac-
tively manipulating the Time Map or when rendering an animation.
To this end, the $t$ values returned by first computing Eq. 5 for the
whole output space are used to cache frame numbers in a hash table.
By also sorting the requisite frame numbers, the cache can better
support resampling between images. Even when rendering a sin-
gle frame, precomputing $C$ is beneficial when parameters go un-
changed for multiple input sequences. By utilizing these caching
schemes, one can achieve real-time, interactive production of many
Time Maps.

When assembling a Time Map, the space-to-time mapping may re-
quest a missing source frame. This may be due to insufficient sam-
ping frequency, the camera being obscured, or as is often the case,
a temporary data-capture malfunction. The latter two instances are
detected automatically when consecutive frames have a significant
(or zero) $L_2$ distance. Ideally, we can reconstruct the missing data
through interpolation [2].

However, when the gap is greater than one frame, simply locating
nearest neighbors may not be sufficient. For example, if hours of
data are missing in a tiled composition, then the nearest neighbor
of a daylight frame could be a night frame, creating a visually dis-
tracting element. For applications emphasizing accuracy, missing
data should be rendered as such. For aesthetic purposes, the fol-
lowing steps can be used: 1) check for a nearest neighbor within a
maximum amount of time, else 2) “jitter” [6] samples from compa-
rable images. For example, if entire hours of data are missing, then
sample several days forward and backward.

While Time Maps can produce valuable, alternative renderings of
time-lapse data, it is important to note two known limitations of
this technique. First, since Time Maps sample from multiple points
in time for the same scene, the best results occur when the camera
view is completely fixed. If aspects of the view change (for exam-
ple, its orientation, zoom, etc.), then the resultant Time Maps may
not have any descriptive value because spatial continuity has been
lost. Tree ring renderings are especially vulnerable to this problem.
Second, some Time Maps may result in visually unappealing com-
positions if there is great variance (high frequencies) in the hue and
luminosity of the scene over the time period sampled. For exam-
ple, if a tree ring Time Map is produced for a scene with stormy
weather, strong colored striations may result. This phenomenon is
partially visible in Figure 3. While these striations accurately de-
pict the events of a period, they may be undesirable for aesthetic
applications of this technique.

4 Related Work

Work related to ours occurs in several domains. Past work in in-
formation visualization has presented techniques for exposing peri-
odic events in serial data by laying data points along a spiral [3, 22].
These visualizations serve some of the same purposes as ours, but
do so with abstract representations of data. A hybrid of these tech-
niques is easily imagined: While we have used grids to lay out tiled
views of our data, one could just as easily lay out images along a
spiral.

Video summarization techniques, such as those demonstrated by
Wittenburg et al. [23], build on Rapid Serial Visual Presentation
(RSVP) concepts [7] to display multiple frames of source video
within the same output image. Our tiled views extend these con-
cepts by allowing non-sequential frames of data to be simultane-
ously summarized (e.g., the four month period depicted in Fig-
ure 2).

Other techniques render time-series data using graphs and
charts [17, 14]. Among the more related uses are previews of an-
nual light intensity variations for interior daylighting, plotted as
2D graphs [9], or pictured as CAD modeled comparison stills and
QuicktimeVRs [4]. In the graphics community, [11] and [10] auto-
mate the task of placing tiled versions of videos and image patches,
respectively, in order to achieve an aesthetic effect, rivaled by the
heavily stylized approach for video of [12].

Vision researchers are also very interested in summarizing image
data [13], especially when developing recognition and indexing
schemes for video libraries. Our approach allows for non-linear
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The interest of [15] in time-lapse photography as a data source aids
in studies of appearance variance – even in weather patterns. Recent
techniques, such as Image Fusion [18] or video cube sampling [5],
offer summarization methods that reconstruct a scene from multi-
ple moments in time. For example, an image taken at night can be
enriched by intelligently blending in details from an image of the
same scene taken during the day. While these techniques offer val-
uable methods for understanding temporal events, they are generally
limited to exposing near-term, coincident events. Phenomena that
occur periodically, or over very long periods of time, are not easily
identifiable.

5 Conclusion and Future Work

Time Maps provide a controlled means of trading in the spatial res-
olution of an output image to gain temporal expressiveness. The
result is a visualization composed from multiple images taken over
a period of time. Static images, interactive sessions, and real-time
animations are all possible.

Given this basic architecture, further improvements are possible.
One potential area for improvement is the treatment of aliasing.
Depending on the application, Time Maps have the limitation that
they faithfully sample the input footage. High frequency events,
like people running through a scene, can result in visible aliasing
in tree ring Time Maps. While this form of aliasing has value (i.e.,
it shows change in the data set), it may be desirable to show more
context. For example, when an artifact is detected, more of the sur-
rrounding context could be blended into the final image.

Another area that could be improved is the manner in which Time
Maps interpolate when sampling “between” pixels in the $x y t$ space.
While we present a method for dealing with large data gaps, re-
cent work like that of [19] could allow Time Mapping of otherwise
unusable time-lapse footage.

Finally, our current modes of interactive control only allow specifi-
cation of the Time Map. When used to browse or search time-lapse
data sets, it would be useful to be able to point and click on a region
of the Time Map to directly access that video clip.
REFERENCES