

Trajectory Mapper: Interactive Widgets and Artist-Designed Encodings for Visualizing Multivariate Trajectory Data

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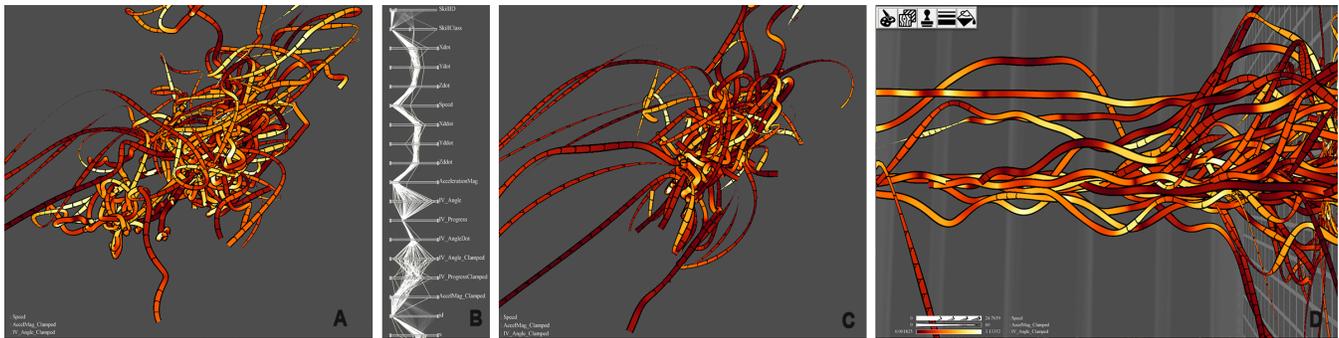


Figure 1: Multivariate trajectory visualization applied to tool trace data for laparoscopic surgical training exercises. The color map encodes a measure of progress toward the goal with deeper red indicating good progress. The width and stamped lines encode additional data variables. (A) 100 tool traces from surgeons at the novice skill level. (B) Filtering is adjusted interactively via a parallel coordinates widget. (C) Now, 100 tool traces from expert surgeons are displayed. (D) Projected and extended in time, the novice trajectories are longer.

Abstract

We present *Trajectory Mapper*, a system of novel interactive widgets and artist-designed visual encodings to support exploratory multivariate visualization of spatial trajectories. Trajectories are rendered using a three-way multi-texturing algorithm so that the color, texture, and shape of each mark can be manipulated separately in response to data. Visual encodings designed by artists and arranged in categories (e.g., divergent, linear, structured) are utilized as strong starting points for visual exploration. Interactive widgets including linked parallel coordinates plots, 3D camera controls, and projection to arbitrary 3D planes facilitate data exploration. An innovative visual mapper menu enables rapid experimentation with alternative data mappings using the artist-designed or custom encodings that can be created with no programming using image editing software. In addition to system design details and insights, two applications with collaborating domain science users are presented. The first requires analyzing 2D crowd simulations and the second 3D tool traces from laparoscopic surgery training exercises.

1. Introduction

Trajectory data are fundamental to the study of robotics, biomechanics, climate, population shifts, fluid flows, and even economic trends. For visualization researchers, trajectories also serve as a specific case of motion (time-varying) data visualization, which is a longstanding area of research and even debate (e.g., [WAPW06, TMB02, CKE*12, SKK*14, RFF*08, WBM*16]). Trajectories are especially challenging to understand when include not just spatial changes over time but also additional data variables (e.g., changes in acceleration, pressure, or density). This is what we mean by multivariate trajectory data.

Our approach to visualizing multivariate trajectories builds upon several current themes in data visualization research and results in a system we call *Trajectory Mapper*. *Trajectory Mapper* extends the use of multiple interactive coordinated views to mix traditional 3D scientific visualization displays with 2D information visualization techniques, such as parallel coordinates (e.g., [PKH04, KERC09]). We also join a tradition of visualization researchers who call for additional work on facilitating *visual design* in data visualizations [Cox08]. Recently, this effort has focused on new tools aimed specifically to support artistic involvement in the scientific data visualization design process [KAM*08, SK16]. Our interdisciplinary

team and co-authors (computer scientists, domain scientists, and a traditionally trained artist) embody this approach. In the Trajectory Mapper interface, we advance this line of research by exploring the potential for domain science users to create their own data-to-visual mappings from strong starting points designed and optimized specifically for trajectory visualization by artists.

2. Related Work

We build upon lessons from a variety of visualization tools that have been developed to better analyze trajectories, trends over time, and other 2D and 3D data-driven paths (e.g., streamlines in fluid flow visualization). The utility of animation for supporting *visual analysis* (as opposed to presentation) has been questioned in general data visualization settings [TMB02,RFF*08]; however, animation has been shown to be useful for the specific case of flow visualization [SFL*04,WBM*16]. Thus, our approach is to support both animated and static trajectories. Our time expansion widget implements a feature similar to the “time drawer” of Lopez-Hernandez et al. [LHGMB10]; however, our widget is designed for more general use where trajectories cannot necessarily be aligned to a common time axis. We are not aware of prior work that, like our approach, supports time expansion as a two-step process for 3D data. In our approach, trajectories are first projected via an interactive widget onto an arbitrary plane in space, and then these projected data are expanded back into 3D space using time as a *new* third dimension extending perpendicularly from the plane.

Multivariate visualization has been a consistent research challenge. Creative use of textures [Int00]; glyphs inspired by oil painting techniques [KML99]; and multiple layers of color, particles, and contextual cues [SK16,WKP14,MWK09] have all led to successful multivariate visualizations. Our approach renders data-driven color and texture on a surface, similar to Decal Maps [RASS17], and the specific surface utilized is a line that can also change width in response to data, similar to Stylized Line Primitives [SGS05] and the 3D ribbons of Ware et al. [WAPW06].

We hypothesize that expert artists can assist in designing similarly successful, perceptually optimized, visual encodings. This is supported by lessons learned from scientist-artist-technologist renaissance teams [Cox08], the finding that artistic critique of scientific visualizations can mirror the results of quantitative user studies of these visualizations [AJDL08], and the compelling visual results that come from a string of interactive tools designed to more closely engage artists in the visualization design process [KAM*08,SK16,BG,BG07,MWK09].

3. Trajectory Mapper Widgets and Visual Encodings

Trajectory Mapper works with a set of trajectories – 2D or 3D paths through space that can be parameterized by time and exist in a common coordinate space. Each trajectory is represented as a mark in the visualization that follows at least a portion of its space-time path, and the visual channels of color, texture, and shape are used to adjust its appearance in response to data. This visual language can be used to produce visualizations in the style of Figure 1, which has an aesthetic similar to Ware’s multivariate tracks of humpback

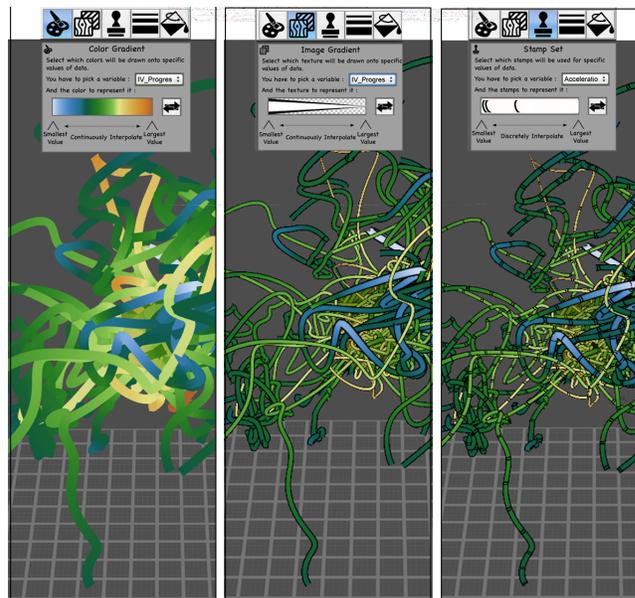


Figure 2: A series of three applications of the visual mapper widget to link a color gradient (left), texture gradient (middle), and stamp (right) to specific variables in the dataset.

whale behavior [WAPW06]. The key advantage of Trajectory Mapper is that the visual mapping can be rapidly adjusted and extended in the same system where trajectories can be explored interactively. The system functions as both an exploratory visualization framework and a multivariate visualization design tool.

A typical use case begins with loading a new dataset. A text-based comma-separated-value (CSV) file format is used to make the tool broadly applicable and easily adoptable. The first line of the file must list text labels for each column of data, and we require that the file contain four unique columns: *id* – unique trajectory id, *time* – a floating point timestamp, *x* – the x coordinate of the trajectory at this timestamp, and *y* – the y coordinate of the trajectory at this timestamp. A *z* data column can optionally be included for 3D trajectories. Any number of other variables (e.g., speed, temperature, pressure) may be included as additional columns.

The display is divided into linked “windows”, with the left devoted to a spatial display of each trajectory and the right an interactive 2D parallel coordinate plot with one axis for each column in the data file. A legend describing the current data-to-visual mapping is displayed in the bottom left corner.

3.1. Visual Mapper Widget and Trajectory Rendering

The Visual Mapper widget is a tabbed dialog window. Figure 2 illustrates how it may be used to map up to three data variables to different visual channels of the trajectories. The first step is to select a visual channel from the top list of icons. Color is the most prominent channel, so it is listed first; see Figure 2 (left). The interface is presented so as to be accessible to novice users, guiding the user through each step with textual instructions. First, the data

variable is selected from a drop down menu. Then, the particular mapping to apply is selected from a second drop down menu that is displayed as a gallery of examples. The gallery approach (visible in the accompanying video) is a deliberate design choice. As compared to sliders or other gradient editing interfaces, the gallery of examples immediately shows the user the full range of possible color mappings. In Figure 2 (left) a blue to orange color gradient has been selected. There is also a button to the right for reversing the mapping (i.e., to run from orange to blue).

Figure 2 (middle) demonstrates the impact of applying a texture gradient. Similar to a color gradient, we define a texture gradient as a continuously varying visual element that is mapped onto the trajectory as the data values increase or decrease. Texture gradients are stored in image files; the leftmost column of pixels in the image will be mapped onto the trajectory when the data value reaches a minimum, the rightmost column when the data value is maximum, the center column when the data value is half way between the minimum and maximum, and so on. The texture gradient in Figure 2 serves two purposes; the dark border helps to disambiguate depth when multiple trajectories overlap, and the change in width is tied to a specific data variable. Stamps also apply texture to the trajectory, but in a discrete way as shown in Figure 2 (right). The visual mapper widget also includes global controls for the maximum width of trajectories and for the visualization background color.

The initial choices for visual mappings have been designed and optimized by an artist and are organized conceptually as diagrammed in Figure 3. The colors, texture gradients, and stamps are designed to be able to work together in any combination. The key guidance to users is to select the appropriate mapping based upon the pattern (linear, divergent, structured) that fits the data. All of the visual options can be set via config files and example images. Stamp image files contain a distinct set of one or more stamps spaced equally apart across the image. Stamps are defined in grayscale with the alpha either completely opaque or completely transparent.

Trajectories are rendered using a custom GLSL shader that creates 2D or 3D thick polylines from filmpplane-aligned billboards. Values for the data variables selected in the visual mapper are passed into the shader, which uses these as texture lookups to map color and texture gradients onto the geometry. For stamps, a single stamp is selected and stretched over each rectangle in the billboarded polyline. The stamp's gray value is combined with gradient color by a multiplication. As a result white values in the glyph will not alter the trajectory appearance, gray values will darken the color, and black values appear black.

3.2. Parallel Coordinates Widget and Animation

A parallel coordinates plot with interactive filtering via sliders is shown on the right side of the screen, and this real-time filtering is linked to the 3D view. *Time* is a required variable in our datasets, and it appears in the parallel coordinates plot along with all other variables listed in the data file. It is useful to manually filter on the time variable during data exploration, but it can also be useful to setup automatic filtering based on time in order to view an animation. This is accomplished via an animate button in the top toolbar that drops down a small interface to control the size of the sliding time window to display and the speed of the animation.

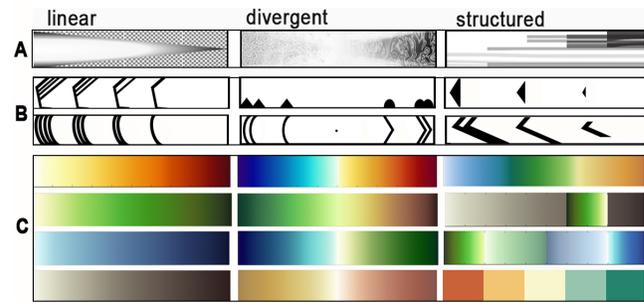


Figure 3: Artist-designed sets for the visual mapper interface. *A* = texture gradients; *B* = stamps; *C* = color gradients.

3.3. Projection and Time Expansion Widget

Figure 4 illustrates a time expansion feature. For 2D datasets, this feature enables the scientist to interactively expand the data using the *z* spatial dimension to depict time. For 3D datasets, the trajectories already exist in a 3D spatial context, so the time expansion functions a bit differently. Here, the trajectory data are first projected, like a shadow, onto a plane, then the projected data are expanded in time away from this plane. The accompanying video demonstrates an example of analyzing a golf swing using this feature. The most useful and novel aspect of the approach is the ability to interactively define the projection plane to be any arbitrary plane in space, for example, the plane formed by the rotation of the arms in a golf swing, which is not parallel to the ground.

4. Results

We have applied Trajectory Mapper to two serious data analysis problems with our domain science collaborators and co-authors. This section reports on these two applications. Feedback comes from multiple critique sessions that occurred over more than one year of development, a culminating recorded hour-long data analysis session, and follow-on conversations. The hour-long analysis sessions were semi-structured and used a talk out loud protocol. The sessions began with 10 minutes of training on the most recent version of the tool with a simple example dataset. Then, the scientists' data were loaded, and a first prompt was provided: Use the tool to verify something you already know about your data. After making several observations, the discussion naturally turned to searching for new patterns and forming new hypotheses. This was encouraged with a second prompt: Now, use the tool to gain as many new insights about the data as you can.

4.1. Application 1: Laparoscopic Surgical Training

Two scientists collaborated to explore the first application area, data-driven evaluation of surgical skill. The datasets were collected using an instrumented laparoscopic surgical trainer and include as many as 21 variables of potential interest. Novice, intermediate, and expert surgeons participated in the studies, and the high-level goal was to characterize differences across these three groups (e.g., see Figure 1). In the recorded analysis session, the pair began by

verifying that less skilled surgeons have more spread-out trajectories. This was accomplished by applying a binned color map to the skill level variable and filtering by skill level in the parallel coordinates plot.

These surgical data cluster around a small space of repeated action, so occlusion can be an issue. Time expansion helped to overcome this. When projected onto a ground plane and then extended into space, the movements of the surgical tools in depth (the most difficult dimension to control) can still be observed but differences in time are more apparent, as experts are generally able to complete the tasks faster.

Much of the time during the recorded analysis session was spent investigating hypotheses of motion differences between novices and experts. Of particular interest were outlier regions where experts and novices unexpectedly overlapped. Understanding these outliers helped illuminate rationale for improved metrics. The linked parallel coordinates plot was used to filter the data to elucidate outliers. This view helped to identify a new theory that might explain the false positives in an approach called Intent Vectors [DLSK17]. The collaborators were able to confirm known trends, gain new insights, and generate a new hypothesis within about an hour.

4.2. Application 2: Crowd Simulation

The second application is with scientists studying crowds. Multiple datasets were explored, including bottleneck and crossing scenarios (e.g., Figure 4). Each trajectory corresponds to the path that one person followed in a real-world scenario. The variables of interest along each trajectory are entropy scores designed to measure how closely various crowd simulation techniques match these real world data [GVDBL*12]. There are five such scores, corresponding to the five simulation techniques investigated: Social forces [HFV00], T-Model [POO*09], Vision-Based Model [MHT11], ORCA [vdBGLM11], and TTC forces [GK15].

In the recorded analysis session, the pair of researchers began by animating the data. They mapped color to the time variable and then switched the mapping to id to better distinguish between individuals. They confirmed lane following behavior. Next, they confirmed (by adjusting color mappings) that TTC forces performs better than social forces according to the entropy scores; the reason is that the former model accounts for anticipation as compared to the social force model which is purely reactive.

Much of the time during the recorded analysis session was spent exploring spatial variance with respect to errors. Social forces showed errors that are roughly the same everywhere, but this is not true of ORCA (generally better, but struggles with turning corners) or PAM (similar to ORCA but better at the beginning of trajectories). Parallel coordinates were used to display only slow movements, and several dual encodings were applied (color maps plus line width changes) in order to search for moments where two metrics differed significantly. In this preliminary evaluation, there were many examples of confirming expected trends. New insights that resulted from the exploration were based on identifying and isolating moments in the crowd crossing scenario where several of the newer methods outperform the older simulation methods.

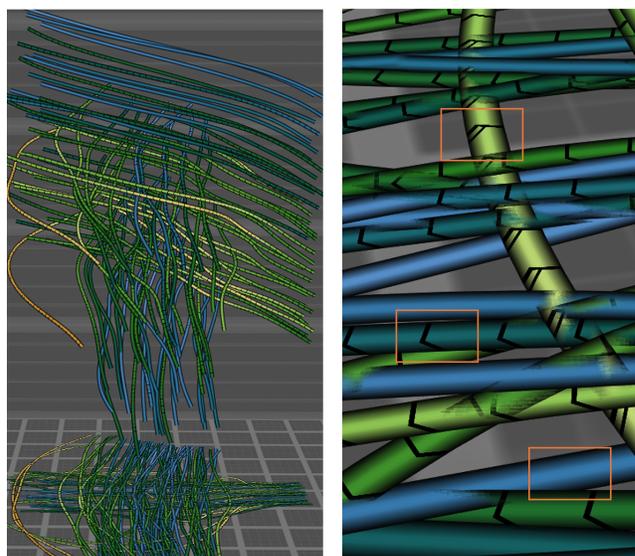
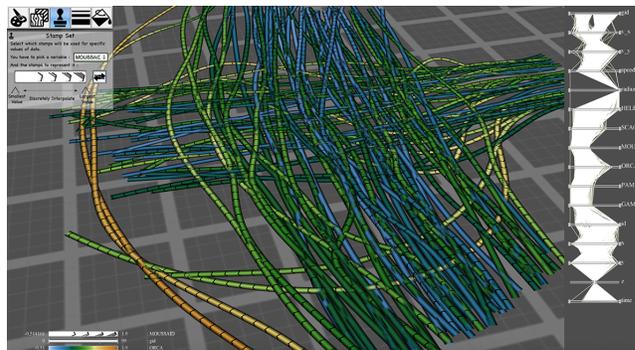


Figure 4: A crowd crossing scenario. The data are 2D; 3D trajectories are generated via time expansion. Highlighted regions in bottom right show how stamps vary in response to data.

5. Conclusion and Future Work

Trajectory Mapper supports an important specific type of motion analysis that has been an ongoing challenge in visualization. This paper introduces the core concepts (artist-designed visuals, rapid manipulation of data-to-visual mappings, coordinated linked views, and projection and time expansion) that make this possible and demonstrates impact through two real-world applications. Future work includes auto-generating derived data fields, such as density metrics and aggregate statistics for each trajectory.

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