様　式　C－１９、F－１９－１、Z－１９　(共通)

科学研究費助成事業　　研究成果報告書

平成 ２９ 年　 ６ 月　 ２ 日現在

機関番号：３２６１２
研究種目：若手研究(B)
研究期間：2014～2016
課題番号：２６７３００６１

研究課題名（和文）地図メタファーを用いた高次元データ可視化手法の研究

研究課題名（英文）Visualizing High-dimensional Data by Introducing Map Metaphors

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交付決定額（研究期間全体）：（直接経費）　　2,700,000円

研究成果の概要（和文）：本研究計画では，(1) 数値データを地形データに変換するアルゴリズムの構築，(2) わかりやすい構図や注釈配置による地図表現の可読性の向上，(3) ユーザの好みや興味の対象によるカスタマイズの機構の導入の3 つの課題を，3 年間において取り組んだ．高次元数値データから地形データへの変換及び可読性の高い地図画像表現の生成までの一連の可視化処理について，手法の定式化を図る．その後，データ変換および可視化画像生成のそれぞれの段階における最適性を表す指標を定義し，対話処理を通じてユーザの興味の対象に応じ結果に変更を加えることに着手した．その効果を，注視点計測装置を用いた実験を通して評価・検証を行った．

研究成果の概要（英文）：In this research, (1) a construction of algorithms for transforming numerical data to geographical data, (2) an improvement in readability of map expressions by introducing intuitive map compositions and annotation placement, (3) a framework of map customization according to user preference. The three challenges of the project were conducted step-by-step within the three years. We formulate the problem as a series of visualization processes from the transformation of high dimensional numerical data to geographical data, and generation of intuitive map representation. Furthermore, we define aesthetic criteria for representing optimality at each stage of data conversion and visualization. The presentation results are also changed according to the users' preferences through several intervention processes. The effectiveness of the approach was evaluated and verified through several experiments using an eye-tracking system.

研究分野：情報可視化

キーワード：高次元データ　視覚メタファー　地図

１．研究開始当初の背景

Due to the development of measurement equipment, data has been captured in higher resolution and more frequently, which increase the difficulty of visual analysis on such bug datasets. Nonetheless, in classical multivariate data visualization (Fig. 1(a)), conventional visual metaphors usually composed various patterns using a simple point and line representation. Users are required to learn and get used to such abstract design in order to understand the information behind the visual representation.

２．研究の目的

In this project, we aim to introduce antique maps (Fig. 1(b)), a well-known visual metaphor, to represent multivariate datasets so that users can intuitively interact with our system to explore and analyze their interested datasets. More specifically, several mathematical models will be developed to automatically transform information embedded in the dataset using antique map representation (Fig. 1(c)).

(a) (b) (c)

Figure 1: Integrating (a) conventional visualization and (b) hand-drawn antique maps to compose (c) map-based visualization on multivariate datasets.

As shown in (Fig. 1 (a)), Parallel Coordinates Plots (PCP) is one of typical multivariate data visualization techniques. However, it is composed of various points and polylines, which strongly influences the data comprehension of analyzers. On the contrary, maps are well-known visual metaphor being used for decades. Introducing such well-known metaphors to visualization also become a boom in the recent year [1]. Maps have been used for long because its geometry patterns provide intuition on the geographical information, while the current application is limited on visualizing data associated with geographical information such as longitude and latitude [2].
Therefore, for general multivariate data visualization as shown in Fig. 1 (c), several techniques need be developed to accomplish this visualization pipeline. The entire framework includes (1) a transformation algorithm to transform numerical data into geographical data [3], (2) an advanced map composition design to layout geographical information and annotation labels to improve the readability of the visualization, (3) an interface that allows users to interactively communicate with the customized layout, which is especially an important factor to process a Visual Analytics (VA) process.

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３．研究の方法

As mentioned in Section 2, the entire project has been decomposed into 3 Tasks and was conducted in the past three years. The three tasks include (1) a novel algorithm to transform numerical datasets to geographical datasets, (2) an intuitive map decomposition together with appropriate text label annotation to improve the map readability, and (3) a development of interactive user interface to customize map layout according to user preferences.

First, we design our visualization framework as series of visualization processes integrated from Tasks (1) and (2), that is, a transformation process from high dimensional numerical data to geographical data together with a design of image representation with high readability. After that, we define several aesthetic criteria that show the optimality at each stage of data conversion and image generation. In task (3), to interactively update and improve visualization results generated by our systems according to the user preferences and points of interest (POIs) through user intervention process. Finally, we demonstrate several experiment results, and evaluate the effectiveness and efficiency of our visualization methods that is designed by introducing several map metaphors for constructing high-dimensional data. This is achieved by studying eye gazes of users using an eye-tracking system.

４．研究成果

As described previously, three tasks are conducted in this project. These include T(1) a novel algorithm to transform numerical datasets to geographical datasets, T(2) an intuitive map decomposition together with appropriate text label annotation to improve the map readability, and T(3) a development of interactive user interface to customize map layout according to user preferences.

In T(1), first to formulate the problem, we extracted the underlying manifold connectivity over the data samples in the high-dimensional space, and then compute geodesic distances between every pair of samples. Finally, we project the data samples onto a low-dimensional space. To achieve this as a dimensionality reduction process, we incorporate landmark MDS in this study because this allows us to project a large number of high-dimensional data samples by emphasizing and selecting a small number of representative data samples.

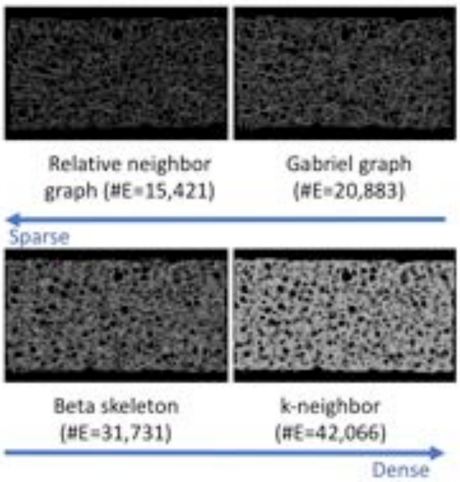

Figure 2: Proximity graphs of the Swiss roll data projected on 2D space. (#E: the number of edges.)

Our main problem here is to properly choose the type of proximity graphs in order to compute the connectivity of the target manifolds. In the example in Figure 2, suppose that we demonstrate the classical Swiss roll data as a demonstration example. Multiple types of graphs are tested for constructing the proximity of data samples. Based on our experience, we have learned that we can employ beta-skeletons if the dimension is relatively low, while we should use sparse graphs such as Gabriel graphs instead when the dimension increases. In our system, we allow users to select appropriate types of proximity graphs such as beta-skeleton graph and thus project the corresponding data samples onto 2D space (see Figure 2).

In T(2), in the second task, we aim to optimize the layout to generate sufficient space around target stations to place labels that represent either landmarks or additional information. Figure 3 illustrates the flowchart of our system design. We first give network data with the geographical position of stations and their corresponding transfer information as input (green rectangle in Figure 3). With this geographical map, the users are allowed to assign a point of interest and the magnification range and scale around the assigned POI. Users can also indicate their interest in landmarks near stations within the focus region. Once this setting is accomplished, the system will automatically compute a relative neighboring graph for controlling the geometry of the magnified metro lines, smoothing the layout for seeking possible space for the thumbnail labels, and therefore rearranging each edge orientation to its closest octilinear direction to compose a focus+context layout (blue rectangle in Figure 3). To achieve this, a linear programming formulation is introduced to minimize the distortion of the map so that we can embed annotation labels in the focus region while still preserving the octilinearity of the layout (red rectangle in Figure 3).

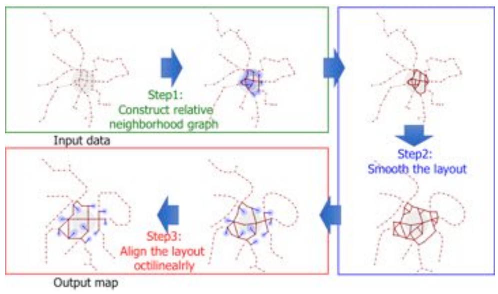

Figure 3: An example of map decomposition together with appropriate text and image labels.

In this task, we observed the aesthetic criteria from the design of illustrators and summarized them as follows:

(S1) Focus edge length: Edges at the center of a focus should be magnified; however, the ones close to the focus boundary should be as uniform as the ones in the context area.

(S2) Context edge length: Edges in the context area should preserve uniform length as conventional metro maps.
(S3) Maximal angles of incident edges: Maximize the angles between incident edges that are connected to the same stations.
(S4) Relative positioning: Preserve the vertex embeddings of a planar network.
(S5) Edge octilinearity: Align all line features (metro lines and label leaders) along octilinear directions.
(S6) Overlap-free layout: Avoid intersections and overlaps among line features and area features (annotation labels).

Moreover, as shown in Figure 4, the idea has been further improved by integrating the construction of a proximity graph showing the manifold structure of data sample points in a high dimensional space, to a contour tree representation (with branches as shown in the middle image of Figure 4) from the constructed proximity graph. Finally, a terrain representation from the contour tree is used as a tool to interact with the dataset. In the conventional work, researchers usually consider the minimum and maximum of a single scalar value. In this research, we extend these methods and introduce a new framework to construct a contour tree for multiple scalar values using both maxima and minima as feature points.

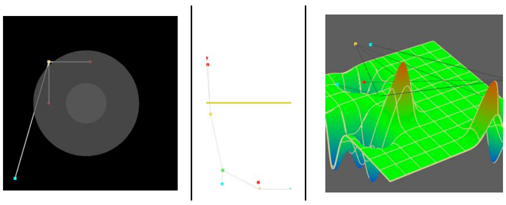

Figure 4: Proximity graphs to terrain representation.

Finally, in T(3), we evaluate the effectiveness of our approach by introducing several on-line questionnaires and analyzing eye gaze of map readers using an eye-tracking system. Illustration maps often direct our visual attention to the specific route with geographic symbols and annotation labels associated with important landmarks. This inspires us to evaluate the quality of such maps by analyzing the spatial distribution of visual attention over the map domain. In this task, we introduce kernel density estimation in order to identify important routes that are implicitly designated by the map designers. Our algorithm begins by composing the density field as a combination of Gaussian kernels centered on the landmarks. The algorithm then allows us to extract an important route on the map as the trajectory of a ball running along the valley of the density field. We conducted a user study where we compared the routes reconstructed from the sequence of landmarks specified by the participants and their originally intended routes, and report some insight into possible aesthetic criteria in illustrating such maps.

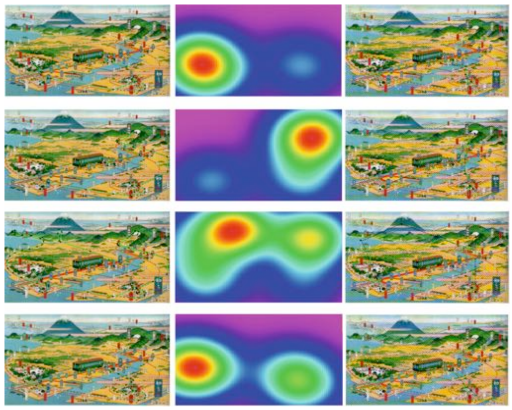

Figure 5: Eye gazes of users from our eye-tracking experiment.

In summary, we have investigated the visual representation of high-dimensional datasets by introducing several map visual metaphors. Based on our experimental results, maps can be considered as a good candidate for the selection of visual representation.

５．主な発表論文等
（研究代表者、研究分担者及び連携研究者には下線）

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(すべての論文は査読有り論文である．)

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