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CONTENTS

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Surveys on line drawing simplification for Chinese cultural computing

Chen Jiazhou[1] (✉), Amal Ahmed Hasan Mohammed[1], Huang Keyu[1], Miao Yongwei[2]

1. School of Computer Science and Technology, Zhejiang University of Technology, Hangzhou 310023, China
2. School of Information Science and Technology, Hangzhou Normal University, Hangzhou 311121, China

Abstract

In the recent decade, many approaches of rough line drawing simplification were proposed, but they are not well summarized yet, especially from the perspective of Chinese cultural computing. In this paper, a comprehensive review of existing line drawing simplification methods was presented, including their algorithms, advantages/disadvantages, inputs/outputs, datasets and source codes, etc. For raster line drawings, related simplification work was discussed according to four main categories: fitting-based methods, tracing-based methods, field-based methods, and learning-based methods. For vector line drawings, a deep investigation was introduced for two major steps of simplification: stroke grouping and stroke merging. Finally, conclusions were given, key challenges and future directions of line drawing simplification for Chinese traditional art were thoroughly discussed.

Keywords line drawing, sketch, simplification, cultural computing

1 Introduction

Chinese traditional art emphasizes shapes more than colors, such as Chinese calligraphy, papercut, elaborate-style painting, thus lines are one of the most essential tools in Chinese traditional art. Taking Chinese craftsmanship as an example, craftsmen usually draw lines to design the structure of the artwork before making crafts. Satisfied line drawings are well preserved by craftsmen, they can be either re-used to make more crafts later or passed to inheritors to follow and study.

Fig. 1 shows two craftsmanship examples based on line drawings. In Figs. 1(a) and 1(b), a Qinghai piled embroidery is shown, silk fabrics are first pasted to hard papers which are only parts of the picture, and then pasted together in a particular order. Therefore, lines represent not only the object silhouettes but also the pasting order. In Figs. 1(c) and 1(d), a papercut is shown, which is cut using red papers. To guarantee the connectivity of the paper, lines are exhibited in different manners, including Yang carving and Yin carving.

(a) Lotus drawing (b) Piled embroidery (c) Courtyard drawing (d) Papercut

Fig. 1 Two craftsmanship examples

Lines in Chinese traditional art show three very important characteristics. One is that the cultural meaning can only be revealed by the integrality of lines, not individual ones. The other is that lines are highly abstract, they show great simplicities. The third is that lines always have big exaggeration for cultural

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Corresponding author: Chen Jiazhou, E-mail: cjz@ zjut. edu. cn
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expression purposes.

These characteristics bring many challenges for using line drawings. Firstly, lines should be grouped according to their usages or meanings. Secondly, lines should be simplified to clean and smooth ones, as lines drawn by sketching or extracted from images are very redundant and rough. Finally, it is also important to investigate the way to exaggerate line drawings, to decouple the artistic expression and shape description. Among these challenges, simplification is one of the most important tasks, as it requires grouping and is a prerequisite for shape exaggeration. For this reason, it is very necessary and urgent to do a comprehensive review of line drawing simplification methods, including their algorithms, advantages/disadvantages, inputs/outputs, datasets, key challenges, and future directions for Chinese traditional art applications.

In this review, the existing line drawing simplification methods according to the format of input data are divided into raster line drawings and vector line drawings. Raster line drawings are discrete images that are scanned or shot from real drawing artworks. Lines in raster images are mixed in image pixels and are difficult to separate. The output of the simplification of raster line drawings can be either vector graphics or raster images. Vector line drawings consist of separable strokes, which are mostly recorded by digital pens or generated by drawing software. Since the input is in vector format, the output of simplification is normally in vector format too.

2 Simplification of raster line drawings

Thousands of line drawings on the papers or silks for Chinese traditional art are preserved by folk craftsmen all over the country. Many of them were collected into museums by digital scanning. Re-using them into modern design art is a very important way to further inherit and spread them, which requires simplifying and converting line drawings into a vector format in the meantime.

Since most of line drawings in Chinese traditional art are intermediate forms, not final artworks, they are usually drawn roughly. And papers or silks may fade, be corroded, and even be broken due to centuries of preservation, which makes the simplification more challenging. On one hand, lines are not as clear as people expected. They may have different widths, even gaps, messy strokes. These variations have to be carefully handled during the simplification. On the other hand, lines in raster images may have a very complex topological structure, which should be preserved in the process of simplification. For instance, the intersection of different lines could produce various junction types, such as T-junctions or Y-junctions. Besides, the final simplification result is not unique. Therefore, it brings more challenges to simplify strokes in raster line drawings.

The existing simplification methods for raster line drawings are generally divided into four categories, fitting-based methods, tracing-based methods, field-based methods, and learning-based methods. The three categories ahead can also be referred to as the non-learning methods, compared with the learning-based methods. Table 1 shows the statistics of representative non-learning simplification methods, including their algorithms, the roughness of line drawings they can deal, the format of the input and output, and whether their source codes are available. If vector graphics are required as a product, stroke vectorization is also unavoidable during stroke simplification.

Table 1 Statistics of non-learning simplification methods for raster line drawings

Category	Method	Structure-aware	Roughness	Input	Output	Code
Fitting-based	Method in Ref. [1]	×	Clean	Raster	Vector (P)	×
	Method in Ref. [2]	Topology	Middle	Raster	Vector (P + B)	Binary
Tracing-based	Method in Ref. [3]	Topology	Clean	Raster	Vector (P)	×
	Method in Ref. [4]	Topology	Middle	Raster	Vector (P + B)	×
	Method in Ref. [5]	Junction	Middle	Raster	Vector (P)	×
	Method in Ref. [6]	Junction	Clean	Raster	Vector (P)	×
Field-based	Method in Ref. [7]	Topology	Middle	Raster	Vector (P + B)	√
	Method in Ref. [8]	Topology	Middle	Raster	Vector (B)	√
	Method in Ref. [9]	Junction	Middle	Raster	Vector (P)	×

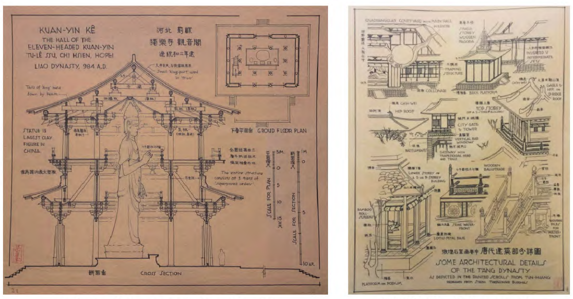
In Table 1, P represents that polygon is supported, B represents that Bézier curve is supported, and P + B represents that both are supported.

If vector graphics are not required, it may be also possible to achieve simplification by directly converting the raster line drawing image into an image that looks cleaner. In this case, most existing methods are based on end-to-end deep learning techniques.

2.1 Fitting-based method

Fitting-based methods achieve line simplification and vectorization simultaneously. It stems from converting scanned engineering drawings to electric diagrams, thus has simplification capability as well. Early vectorization methods focus on geometric primitive fitting, such as straight lines, ellipses, Bézier curves, and even B-splines. These methods can produce compact parametric curves, but the robustness is barely guaranteed. Special adjustments have to be complemented against over-fitting or style variations, like multiple layers proposed [1].

One major limitation of fitting-based methods is to specify the number and the type of geometric primitives, it is extremely difficult for complex line drawings that contain multiple geometric primitive types. Fig. 2 shows two architectural line drawings drawn by Liang Sicheng, both of them use different geometric primitive types. Fitting all these geometric primitives simultaneously is extremely challenging. A hybrid fitting method is thus more suitable for such complex line drawings.



(a) Architectural details of Tang Dynasty (b) Hall of Kuan-yin from Liao Dynasty

Fig. 2 Two line drawings of architectures

To release this challenge, Favreau et al. employed a hybrid approach that fits both straight lines and Bézier curves with a global optimization [2]. A topological graph is constructed, and successive edges in this graph are merged to form hyperedges, which is the core of the proposed method. Three operators were proposed: hyperedge merge and split, Bézier degree switch, and hyperedge overlap and dissociation. The second operator modifies the degree of Bézier curves from one (straight line) to three (cubic Bézier). Both fidelity to the input bitmap and simplicity of the output are explicitly balanced in global optimization, thus the number of curves and their degrees are considered to achieve the best trade-off.

2.2 Tracing-based method

The fitting-based simplification method still cannot provide free-form curves, as supported geometric primitives are always limited. Taking Fig. 2(b) as an example, architectural parts can be fitted accurately by a hybrid approach, but the free-form silhouette of the Kuan-yin statue is nearly impossible to fit well.

To support free-form curves, tracing-based methods were proposed. Instead of producing low-degree geometric primitives, tracing-based methods produce point sequences that can discretely present any curves. However, a new issue arises, that is topology preserving. The simplification has to preserve the major drawing structures while removing redundant structures that are created by drawing roughness. As shown in Ref. [3], topology-preserving is not trivial, even for clean line drawings. To overcome this issue, Noris et al. [3] first extracted the topology by computing a minimum spanning tree and then simplified it by leaf pruning. Based on this simplified topology, centerlines are further extracted and different types of junctions are recovered by a reverse drawing process.

For rough line drawing, it is more challenging to extract its topology. Based on the over-segmentation produced using the trapped-ball algorithm, Chen et al. proposed an iterative region removal approach and an open curve removal approach to clean up the topology [4]. However, segmentation usually consumes much computation and time, thus this method is relatively slow. For this sake, inertia is introduced in the line tracing, where junctions are better mapped within only a pass [5]. This inertia-based method speeds up the performance to less than 0.1 on average, which is much faster than the most existing simplification methods.

2.3 Field-based method

Topology-driven methods made big progress on simplifying rough line drawings, but they are far from perfect. The topology extracted in the region that contains multiple lines is barely correct. To solve this issue better, direction fields are employed to drive the tracing instead of the lines themselves earned more attention. The direction field is a two-dimensional (2D) field, where a 2D direction vector is defined at each point. There are many direction field estimation methods for images in the literature, including gradient fields estimated by Gabor filter or weight least square [10], and tensor fields [8]. Guided by the direction field, the tracing is then implemented by a line integral convolution process. To reduce the accumulating errors during the convolution, special correction mechanisms are also integrated [8].

Junctions are key points in the topology, and different types of junctions reveal the continuity property of the topology. Taking junctions with three branches as examples, there are T-type, Y-type, and γ-type junctions, as shown in Fig. 3. Strictly speaking, there are only two branches in Y-type and γ-type junctions, as at least two branches can be regarded as one due to their continuities. Junctions with four branches have much more types, which are summarized in Ref. [6], as shown in Fig. 4. More junction types, including L-type, T-type, Y-type, E-type, X-type, are identified in the sketching reality system for architectural designs [11].

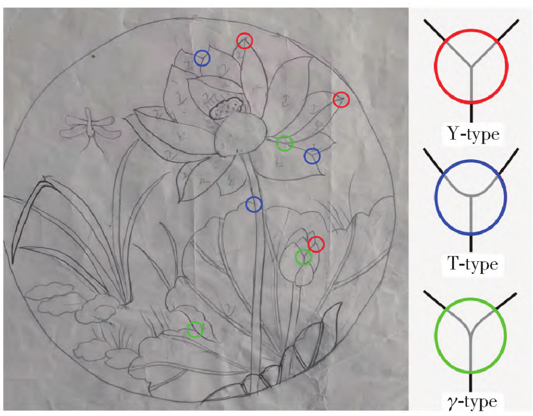


Fig. 3 Illustration of three types of junctions

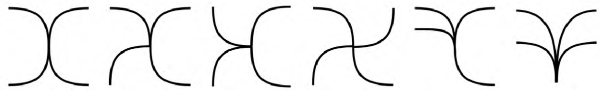


Fig. 4 Illustration of different types of junctions with four branches

Though these junction types are not frequently observed in the line drawings, they are also critical for the topology extraction and topology-driven simplification methods.

Ideal line drawing simplification methods should preserve continuities at junctions, but aforementioned simplification methods were not aware of this requirement. Direction fields at junctions are difficult to estimate, as more than one prominent direction exists at junctions. To solve this issue, Bessmeltsev et al. upgraded the direction field to a frame field, called PolyVector field [7]. It reliably and efficiently disambiguates Y- and T-junctions, while staying true to curve shapes and connectivity. This method is very powerful for the vectorization of line drawings, but not capable to simplify very rough line drawings. For this sake, integer grids that are aligned with line drawings are employed to locally parameterize strokes [8]. Neighboring parallel strokes are automatically snapped to the same isoline, while junctions are snapped to grid nodes. Thus, it succeeded on both clean and over-sketched line drawings. Recently, a novel geometric flow, called PolyVector flow, was proposed [9]. It aligns a given curve to the frame field capturing drawing directions, thus can robustly disambiguate directions around Y-, X- and T-junctions.

2.4 Learning-based method

Besides the roughness, line drawings from Chinese traditional artworks may also have other challenges for simplification, as most of them are preserved in easily-damaged environments for a long time.

With the rapid development of deep learning techniques, learning-based stroke simplification was paid more and more attention. By training a neural network, they can automatically convert an image with rough line drawings into an image with clean ones that represent the same content. Thus, they are particularly useful to solve the broken issue of line drawings.

Table 2 shows the statistics of learning-based simplification methods for raster line drawings. In Table 2, datasets employed or created by these methods are also summarized. The last one from Ref. [2] is not simplification method, but is the first benchmark to evaluate and focus sketch cleanup research.

Table 2 Statistics of learning-based simplification methods for raster line drawings

Method	Neural model	Roughness	Input	Output	Code	Dataset
Method in Ref. [13]	CNN	High	Raster	Raster	√	68 pairs constructed inversely
Method in Ref. [14]	CNN	Middle	Raster	Raster	√	71 pairs from Leonardo da Vinci dataset + synthetic dataset
Method in Ref. [15]	Discriminator	High	Raster	Raster	√	68 pairs for supervised + 194 individuals for unsupervised
Method in Ref. [16]	Multi-layer discriminator	High	Raster	Raster	√	140 pairs drawn bidirectionally
Method in Ref. [17]	Multi-task CNN	Middle	Raster	Vector	×	8 000 pairs synthesized program-matically
Method in Ref. [9]	Pyramid network	Middle	Raster	Vector	×	About 9 300 vector doodles rasterized with 10 different artistic brushes
Method in Ref. [18]	RNN	High	Raster	Vector	√	QuickDraw
Method in Ref. [19]	Transformer-based	Middle	Raster	Vector	√	About 10 000 vector architectural or mechanical CAD drawings
Method in Ref. [2]	–	Codes for automatical evaluation			√	281 pairs in the wild and a curated subset of 101 pairs

In the learning-based direction, a fully convolutional neural network (CNN) architecture that can simplify sketches directly from images of any resolution is proposed, which is very efficient and does not require any user intervention [13]. Images are first segmented into patches, and a rough sketch dataset was collected by inverse construction to train a supervised CNN model, which was employed to detect and complete gaps in line drawings as well [14]. And a new end-to-end neural network that consists of two sub-networks (one for line extraction, the other for image restoration) was designed to restore deteriorated line drawings [20]. Though only a small dataset was used, these methods can automatically remove the paper texture background.

Though data augmentation is employed, the simplification results have a strong dependency on the quality and quantity of the training data. To release the limitation of lack of high-quality training samples, Simo-Serra et al. improved the neural architecture by integrating a discriminator network [15]. The discriminator network not only encourages the output sketches of the simplification network to be more similar in appearance to the training sketches but also makes use of additional unsupervised data that are rough sketches and line drawings that are not corresponding to each other. To simplify very sketchy and complicated drawings, Xu et al. designed a multi-layer discriminator by fusing all visual geometry group (VGG) feature layers to differentiate sketches and clean lines [16]. The loss function used in the network is upgraded to perceptual loss, which can obtain aesthetic and neat simplification results preserving both global structures and fine details without blurriness [18].

The end-to-end line drawing simplification methods produce images with clean lines as output. It requires further vectorization if vector graphics are expected. Though clean line drawing images are much easier to vectorize than rough ones, it is still challenging, as mentioned in Sect. 2.1. Instead of assembling patch prediction back to an output image, Egiazarian et al. proposed a transformer-based network to predict vector primitives in each patch, and merged them by a straightforward heuristic algorithm after a refinement [19]. This adaption makes it work well for technical drawings. To deal with more general artistic line drawings, Mo et al. employed a recurrent neural network instead that generates the corresponding vector line drawings directly [18]. A virtual pen surrounded by a dynamic window is designed to move along with the stroke drawing, and a stroke regularization loss is developed to enlarge the window and draw long strokes for simplicity.

Since junctions are the most challenging part of line simplification, learning to identify junctions (i. e. key points) instead of all primitives seems more reasonable and efficient. For instance, Guo et al. designed a line subdivision neural network to separate the centerline image and the junction image, and then designed a topology construction neural network to predict the line connectivity at junctions [17]. Puhachov et al. designed and trained a deep pyramid network to predict locations and types of all key points in line drawing images, then found a set of paths between these key points guided by the frame field and the key point types, and finally proposed a novel PolyVector flow to create the vectorization results [8].

2.5 Datasets

Most of the aforementioned learning-based simplification methods collected a dataset for training and test purposes. The OpenSketch dataset contains more than 400 sketches representing 12 man-made objects drawn by 7 to 15 product designers with varying expertise [21]. But they are all rough, do not have corresponding clean ones, which are not suitable for most supervised learning methods.

The QuickDraw dataset is a collection of 50 million drawings across 345 categories, contributed by players of an online game [22]. Since most of these doodles are drawn by novices all over the world, the quality is not satisfied to directly meet the sketch simplification purpose yet, neither as the doodle dataset [23]. To make use of them, Puhachov et al. rasterized them using 10 different artistic brushes of different width, randomly assigned on a per-stroke basis, and added 250 manually-labeled pencil line drawings to solve the generalization issue [8]. Besides QuickDraw, Mo et al. utilized the pencil art generation and rough augmentation techniques from Ref. [15] to synthesize the corresponding rough sketches from clean ones for the evaluation of rough sketch simplification [18].

Guo et al. observed that it required patch datasets for keypoint-driven neural networks, rather than whole image datasets [17]. Based on this observation, they synthesized a patch dataset by programmatically generating vector drawings and rasterizing them in different rendering configurations. But it only supports simple line drawings, whose roughness and complexity are very limited. Simo-Serra et al. collected the first dataset that contains rough sketches and corresponding clean lines for sketch simplification purpose [13,15]. Artists are asked to over-draw rough sketches on top of clean line drawings. Such an inverse dataset construction can guarantee the alignment between rough and clean line drawings, but the artists have little deviation when the positions of initial lines are given. To solve this issue, Xu et al. bidirectionally constructed their rough sketch dataset, in which both direction construction and inverse construction were applied to prepare a paired dataset [16]. In total, 140 sketches were drawn.

Recently, Yan et al. presented the first benchmark to evaluate and focus sketch cleanup research [12]. Their dataset consists of 281 sketches obtained in the wild and a curated subset of 101 sketches. All sketches are created by a variety of artists with different styles and includ both artistic and technical categories. Most sketches in this dataset have creative commons licenses allowing derivative works and commercial uses, and the rest permit academic use. Computational metrics for evaluating sketch simplification algorithms are proposed and are used to evaluate seven recent algorithms and two pipelines.

Until now, there is not a simplification dataset dedicated to Chinese traditional art. First of all, there is not a sufficient quantity of ancient artworks to train a neural network model. Secondly, line drawings for different art forms have distinct style differences, which should be well separated in the dataset, which significantly increases the difficulty of dataset preparation. Finally, ancient line drawings are very different from modern ones, thus existing neural networks trained can be hardly re-used for the analysis of ancient line drawings.

3 Simplification of vector line drawings

Though ancient line drawings are all in raster form, many modern artists prefer to use digital pens as they can freely undo any stroke at any time, such as Apple Pencils and Wacom Stylus. These digital pens can record the trajectories of the pen movement at a very high frequency, thus can generate vector graphics that are storage-friendly and editing-friendly. Rendered with artistic brushes, these vector graphics can be further converted into Chinese artworks, such as Chinese ink painting. Fig. 5 (a) shows a Chinese ink painting drawn using a Wacom Stylus with artistic brushes from Adobe Photoshop, and Fig. 5 (b) shows a Chinese painting simulation generated by a digital CPaint system [24].

(a) Ink painting creation with digital pens (b) Ink painting simulation using CPaint

Fig. 5 Two examples of digital Chinese ink painting

Chinese ink painting emphasizes picture simplicity, its drawing trajectories are usually very smooth and simplified. From this viewpoint, it is more challenging than the western oil painting, which can be partially re-drawn many times by pigment overlay. The simplification of drawing trajectories can automatically convert free-hand line drawings into smooth and simple curves, thus can facilitate the digital creation of Chinese ink painting. For this reason, it is necessary to review existing simplification methods for vector line drawings as well.

A line in vector form can be described as a strokes that consists of points $\{p^m\}, m = 1, 2, \ldots, M$, and then a line drawing in vector form is a set of strokes $\{s_n\}, n = 1, 2, \ldots, N$, where M and N are the total numbers of points in the stroke s_n and the total number of strokes respectively. As artists quickly draw a sketch, it is usually over-drawn. Thus, the simplification task is to find another set of strokes $\{s'_{n'}\}$, $n' = 1, 2, \ldots, N'$ to replace the original strokes, where N' is the number of simplified strokes. Note that $\{s'_{n'}\}$ can be not only completely re-generated but also selected from $\{s_n\}$ partially. Overall, N' should be much less than N to meet the simplification requirement.

To preserve the original visual content, it is also important to guarantee $\{s'_{n'}\}$ is loyal to $\{s_n\}$. This loyalty is usually evaluated in the image space in most existing line drawing simplification methods, for instance, the overall distance between $\{s'_{n'}\}$ and $\{s_n\}$.

Considering the number of requirements and the loyalty of simplified strokes, the line drawing simplification can be regarded as a balance problem. In most cases, $\{s'_{n'}\}$ is more likely loyal to $\{s_n\}$ if more strokes are used, but is less simplified on the other hand. Therefore, both the stroke number and the loyalty degree have to be constrained to achieve an acceptable balance. But, it is very challenging to specify these constraints, including predicting the number of strokes and computing the overall loyalty without all simplified strokes.

One possible way to solve this balance problem is to decouple these two constraints. For instance, Barla et al. [25] solved it by two steps, they first grouped input strokes and then merged each group into only one stroke to replace them.

Table 3 shows the statistics of simplification methods for vector line drawings. From Table 3, it can be found that the most methods follow the idea of decoupling the balance problem into two processes, grouping and merging.

Table 3 Statistics of simplification methods for vector line drawings

Method	Metric	Roughness	Input	Output	Code	Grouping	Merging
Method in Ref. [25]	Proximity	Middle	Vector	Vector	×	√	√
Method in Ref. [26]	Proximity + hierarchy	Middle	Vector	Vector	×	√	√
Method in Ref. [27]	Closure-aware proximity + continuity + parallelism	High	Vector	Vector	×	√	√
Method in Ref. [28]	Aggregate curves	High	Vector	Vector	Binary	√	√
Method in Ref. [29]	Base complex	Middle	Vector	Vector	×	√	√
Method in Ref. [30]	Stroke stripe	High	Vector	Vector	√	√	√

3.1 Stroke grouping

Generally, strokes sharing similar properties should be put in one group, and ones with very different properties should be divided into different groups. One intuitive property that existing methods considered most is the spatial position on the drawing canvas. For instance, Barla et al.[25] defined ε-line that does not fold itself at the scale ε, and then defined ε-group that is a group of lines where an ε-line can be found to cover all lines in this group. Following these definitions, lines are first clustered into ε-groups using a greedy algorithm, and then a single line is created for each ε-group. A point-based pair ability value for any pair of strokes was estimated, which measures how near, locally parallel, and similar in color they are[26]. By using a $(1+\varepsilon)$-spanner to determine stroke proximity, their method dynamically builds and maintains a stroke hierarchy based on the high-level principles of proximity and continuity.

Based on the gestalt laws, Liu et al. pointed out that the law of closure was missed in many existing work, though the law of proximity and the law of continuity had been already employed in existing work[27]. Based on this key observation, a novel approach to simplifying sketch drawings was proposed, in which semantic contents of the input line drawings were considered in the stroke grouping due to the employment of the law of closure. By leveraging principles derived from human perception and observation of artistic practices, Liu et al. proposed a coarse-to-fine stroke clustering that was refined by analyzing interactions both within and in-between clusters of strokes[28].

3.2 Stroke merging

The most intuitive way to merge strokes for each group is to select a representative one from this group. However, there is not always such a stroke that can represent the whole group. For instance, if many short strokes are sketched to represent a single long curve, none of these short strokes is qualified to replace the long curve. And if strokes are added to adjust the gestures of existing strokes, any of them should not be considered the ultimate gesture that the artist expected. Therefore, generating a new curve for each group makes more sense. For instance, given two strokes in an ε-group, a new line is created to lie in the middle of these two strokes. In the mixed region, the path is interpolated from one extremity to the other. Such a construction ensures that this created line is ε-line since the given two strokes are ε-lines[25].

Most of the grouping-and-merging simplification methods require tuning many parameters, thus Liu et al. adapted the iterative decimation algorithm of three-dimensional (3D) mesh simplification to 2D sketch simplification[29]. A geometric structure called base complex is created to inherit the crucial geometric information of the input vector graph, which can be easily controlled using a single parameter. This method is efficient and can achieve a tradeoff between efficiency and geometric fidelity. Rough line drawings always have a large variation on line thickness, existing fitting algorithms often fail when stroke groups have non-trivial geometry or topology. It was pointed out that stroke groups are usually regarded as continuous, varying-width strips whose paths are described by the intended curves[30]. Therefore, a joint one-dimensional parameterization was applied to re-cast the curve-fitting problem, which is the restriction of the arc length parameterization of this strip to the strokes in each group.

4 Discussion, challenge and future direction

In this paper, we have summarized existing simplification methods for artistic line drawings. Simplification methods for raster line drawings were reviewed, where lines are hardly separated. These methods can be divided into four categories according to their main ideas: fitting-based, tracing-based, field-based, and learning-based. Deep learning technique showed its power in both identifying junctions and repairing discontinuities. Simplification of raster line drawings sometimes achieves line drawing vectorization as a side-product. In contrast, simplification of vector line drawings has a clearer goal, most of which have two major steps, strokes are first clustered into groups that share similarities in proximity, continuity, parallelism, etc. Then a representative stroke is re-created or selected for each group.

4.1 Challenge

Though a big progress was made for the simplification task of line drawings, there are still many unsolved problems, especially for Chinese traditional art.

1) Roughness. Very rough line drawings are still difficult to simplify. As shown in Tables 1 – 3, the roughness of input line drawings is always an important criteria to evaluate simplification methods. Though learning-based methods can simplify line drawings with high roughness, it is still far away from perfect. Sometimes, the roughness scale may be larger than the scale of structural features that should be preserved. In such a case, global methods are more suitable than local ones. And it will be even difficult if one line drawing has different roughness in different regions. A better self-adaption mechanism may relieve the roughness issue.

2) Styles. Artists prefer various styles of line drawings, including straight lines, smooth curves, zigzags, dash lines, curly lines, ink brushes in Chinese ink painting, etc. To the best of our knowledge, none of the existing simplification methods is capable to simplify all of them, and none of the datasets has collected line drawings with various styles. And there are large variations before different Chinese traditional artworks.

3) Auxiliary lines. Lines are not always used to depict shapes. There are lines for many other purposes in Chinese traditional art. For instance, annotation lines shown in Fig. 2(b) should be separated from architectural lines. It is very challenging to deal with these auxiliary lines properly, as they are mixed with common lines together in bitmaps. Few work can solve this problem until now.

4.2 Future direction

According to many interviews with Chinese traditional craftsmen and amateurs, we would like to summarize future direction that they are concern about most, which should be paid more attention by the research community.

1) Effectiveness. The effectiveness of line simplification methods on Chinese traditional art has not been systematically evaluated until now. Many factors impact the effectiveness, such as noises, color fading, paper-broken, neither of which is easy to solve by existing simplification methods. Ideally, deep learning techniques can deal with them properly if sufficient samples are provided. However, there are only a few samples of ancient line drawings, and they are hard to re-produce or synthesize. Besides, the effectiveness may be subjective for different art forms, thus user studies can help to evaluate these methods if quantitative evaluation is impossible. Therefore, effectiveness investigation is one of the most important research directions in the future.

2) Cultural expression. Lines do not only describe shapes but also express cultural meanings. In many Chinese traditional art, particular meanings are expressed only if multiple lines are shown together. Taking the papercut as an example, a copper pattern always contains a circle outside and a rectangle or a rhombus inside that consists of four curves. And there are many different manners to express lines in the

artwork. Meanings should be considered in the process of simplification. For raster line drawings, neither fitting nor tracing can infer meanings, and deep learning techniques are employed only for junction identification at present, but for semantic understanding yet. Therefore, more investigation on cultural expression will be needed in the future.

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