GEOMETRIC CORRECTION OF MEASURED HISTORICAL MAPS WITH A PIXEL-ORIENTED AND GEOBROWSER-FRIENDLY FRAMEWORK

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ABSTRACT:

This paper discusses the geometric correction of measured historical maps and the evaluation of accuracy with case studies on Silk Road maps, “Innermost Asia” and “Serindia,” made by Aurel Stein about 100 years ago, and Beijing maps, “Complete map of Peking, Qianlong period,” made about 250 years ago. The former case study deals with maps that cover thousand kilometers, and we delivered the error table for each major oasis in Tarim Basin so that historical maps can be interpreted under information on errors. The latter case study deals with maps of a city, and we proposed a new geometric correction method “line-preserving distance weighting method” that focuses on the problem of linear features which are relevant in the map of cities. Based on these experiences, we summarize this paper with a few points of discussion about how to deal with historical maps, and show the potential of historical maps from the viewpoint of spatial visual sources and linkage across multiple databases.

1. INTRODUCTION

This paper discusses the geometric correction of historical maps which are measured to some extent, but do not have as high accuracy as today’s standard. We specifically deal with two maps - (1) the map of Silk Road made by Sir Aurel Stein in the beginning of the 20th century (about 100 years ago), and (2) the map of Beijing made under the order of Emperor Qianlong in the mid of 18th century (about 250 years ago). Those maps are not pictorial maps in the sense that the spatial structure of those maps is relatively accurate. Hence it is clear that those maps have some errors, mainly due to technological limitation of the time. Those errors, however, have been unknown and the usage of those maps has been focused on visual interpretation and usage. Making georeferenced maps will open up new vistas for the usage of those maps.

Therefore, the purpose of this paper is to show the geometric correction methods for those two types of maps, and characterizes the accuracy of those maps. The paper is divided into two main parts – the geometric correction of Stein maps, and that of Beijing maps, because those two types of maps have different characteristics and hence requires different approaches. Those two maps are also discussed from the viewpoint of applications and academic infrastructure. Finally we compare two approaches and discuss the general issues of historical maps. The detail of the Section 2 and Section 3 is described in (Nishimura, 2007) and (Nishimura, 2008).

2. SILKROAD MAPS BY AUREL STEIN

2.1 Description of the maps

Aurel Stein is one of the representative figures in the history of expeditions in Silk Road in the beginning of the 20th century. His first expedition was done in 1900, and he explored the central Asia four times in his life. The report of the first expedition (1900-1901) was published as “Ancient Khotan” (two volumes), the second expedition (1906-1908) as “Serindia” (five volumes), and the third expedition (1913-1916) as “Innermost Asia” (four volumes). In particular, in his second and third expeditions, Stein surveyed all over Tarim Basin (now Xinjiang Uyghur Autonomous Region of China), which is the central part of Silk Road, and he created detailed maps of the area with longitude and latitude in his reports, Serindia and Innermost Asia. Those maps are still considered as the most reliable and informative maps of the area, and as the basic academic references in the study of Silk Road.

The accuracy of maps, however, has not been evaluated for entire maps, because of the large number of sheets, namely 94 sheets for Serindia and 47 sheets for Innermost Asia. The large number of sheets makes it difficult to evaluate the accuracy of the map across sheets and to understand the entire nature of the map. For the evaluation and usage of the map divided into many sheets, we need to connect many sheets into one large map through the georeferencing of sheets and seamless connection of them.

2.2 Simple Geometric Correction

Because Stein maps have latitude and longitude on the maps, we can simply use that information for georeferencing. Namely, using latitude and longitude grid drawn on the maps, we focus on the intersection of the lines as control points. Because each sheet has 3 or 4 longitude and latitude lines, we can pick up about 30 control points for each sheet. Then we focus on a quadrilateral from four neighboring control points, and within a quadrilateral, bilinear interpolation is applied for each pixel. The interpolation is done from the image coordinate to the world coordinate and each sheet is georeferenced so that we have one large georeferenced map connected seamlessly.

During this step, there is a problem of map projection and datum, because the map projection and datum is unknown (not clearly written) in the Stein’s report. From the inspection of maps, we assumed that map projection is a simple geographical linear projection, so a simple bilinear interpolation works.

About the datum, it is also unknown, but due to the error of several kilometers on the map, which will be described later, the choice of a datum does not give a significant impact on the evaluation of the map. So we assume that the datum is the same as that of the current map or satellite images.

After georeferencing, an important next step is to publish the map on the Web so that we can share the maps with many other people. We used the KML standard for publishing the data on the Web by creating a series of images with different resolutions, and by organizing them using a so-called "Super-Overlay" method specified in the KML format. Using this method, one can reduce the amount of data because images of appropriate resolutions are retrieved and rendered. The product is now accessible on the Web (http://dsr.nii.ac.jp/geography/).

Figure 1. (left) Grid of the original map, (right) Map of Innermost Asia on Google Earth.

2.3 Control Points for Evaluation

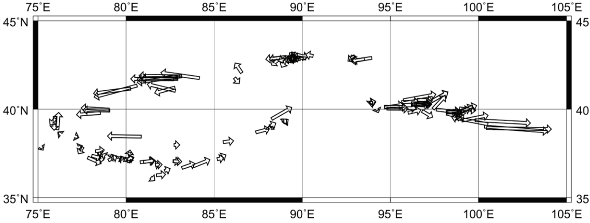
In the previous section, we used the intersection of latitude and longitude grid as control points for geometric correction. However, comparison between the corrected map and recent satellite images on Google Earth shows that their matching is not accurate. For example, we can focus on a famous ruin which has not been moved for these 100 years since the Stein's expedition. The ruin on the historical maps and on the high resolution satellite image is not mapped onto the same location, or the same latitude and longitude. Obviously the location of the high resolution satellite image shows the correct location, so the ruin on the historical maps is located on a wrong place. Hence we can evaluate the error of the map at control points selected for evaluation.

Those control points include ruins which can be identified on Google Earth, and drawn on at least one of Stein maps. Based on the past survey of the site, and the past experience and measurement of one of the authors, we could finally identify 70 control points. It should be remembered, however, that the identification of ruins on Google Earth is a difficult task without any experiences of surveys at the site. Hence the identification of control points is mainly limited to the area where the author has some knowledge about the site. With the help of other experts, however, the number of control points may be increased in other areas of Silk Road.

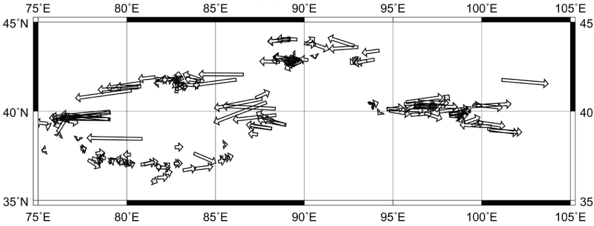
Another source of control points is oases. Stein collected many place names in alphabet, obtained from listening to the pronunciation of local people who speak Uyghur, so this information can be used to identify oases by comparing with the current map of China. Then we identified about 130 control points from oases. The following caveats should be studied when using oases as control points.

1. An oasis might move to a different place due to the movement of a nearby river, and so on.
2. An oasis might be extended to suburbs or a new center might be developed recently, so the representative point of the oasis can be chosen arbitrary.

We selected control points for oases that can be assumed not to make any movement for these 100 years, and the representative point of an oasis as the center of the current town.



(a) Serindia



(b) Innermost Asia

Figure 2. Distribution of errors on Stein maps using control points from ruins and oases.

2.4 Distribution of Errors

The accuracy of Stein maps is evaluated for about 200 control points selected as described in the previous section. Figure 2 shows the result. Arrows in the figure starts from the current location of control points to the location of control points on each historical map, but the length of arrows is 10 times longer than the real length for easier interpretation. The result shows that the overall distribution of errors shows the same tendency. An error, which is defined as distance between the current location and the location on a historical map, is roughly measured to be the order of several kilometers, ranging from 250 meters to 32 kilometers. Observations from the map can be summarized as follows.

1. Two maps show similar tendencies, indicating that maps of Serindia and Innermost Asia are related.
2. Errors are larger in longitude than in latitude.
3. Direction and size of errors is related to the route of Stein's expedition.
4. Aksu, which is located in the west of Tarim basin, shows a large error to the west.
5. Ganzhou, which is a city in Hexi corridor, shows a large error to the east.
6. Errors in the local neighborhood are relatively uniform, so errors can be evaluated by major oases in Silk Road.

2.5 Interpretation of Errors

Most of the observations above can be explained from the survey method employed by Aurel Stein. He published at least two references on his maps, of which (Stein, 1923) has a detailed description on the survey. For the most part, they used plane-table surveys, and more accurate trigonometrical surveys were used for only a limited part. They also used cyclometers where plane-table surveys cannot be used. Because the survey was not the main goal of the expedition, they could not spend enough time for accurate surveys, so it is natural that the result of survey has errors for quick processes.

Other fundamental problem is the lack of measurement methods for longitude. At that time, latitude can be measured accurately using astronomical survey, but longitude was difficult to measure in spite of many researches for accurate measurement.

Wireless communication technology had just begun to be introduced in that area, so it did not give a significant improvement on the accuracy of maps. This is the reason that errors in longitude are much larger than that in latitude.
Cyclometers are also the reason of large errors, because the error tends to accumulate as the length of an expedition route increase without any good points for resetting the error. This may be the reason of large errors in some parts of maps.

2.6 Error Table for Major Oases

We assume that error distribution is relatively uniform in the vicinity of a major oasis, but shows different patterns across major oases. To check the validity, Figure 3 shows an example of local error distribution around Turfan oasis. The representative point of this oasis is shown as a star. At this point, it is measured that the error is about 4.9 kilometers toward south-west (SW) in Serindia, while the error is about 8.2 kilometers toward west-south-west (WSW) in Innermost Asia. Other control points have different errors but error distribution is relatively uniform within this area.
Then we create an error table showing the azimuth and length of error for each major oasis. This table can be used as a rough estimate of error for each major oasis. The more detailed distribution of errors can be obtained using not only control points but also features on the terrain such as mountain peaks and valleys that does not change significantly in 100 years. It is important to use other sources of information such as terrain to improve the identification of actual positions.

Table 1. Error table for major oases.

Oasis Name	Serindia		Innermost Asia	
	Azimuth	Distance(km)	Azimuth	Distance(km)
Kāshgar	SW	4.5	NW	1.2
Aksu	W	17.0	W	26.7
Kuchā	W	19.0	W	3.2
Korla	SE	4.3	SW	20.3
Bugur	W	17.9	W	6.5
Khōtan	NE	5.1	N	1.2
Niya	E	2.6	E	3.1
Charklik	ENE	4.4	WNW	10.0
Turfān	SW	4.9	WSW	8.2
Hāmi	SW	6.2	SW	6.2
Mīrān	NE	2.7	NW	12.3
An'xi	E	13.3	E	15.2
Suzhou	E	4.7	E	3.5
Ganzhou	E	32.0	E	15.6

2.7 Gazetteer

Stein also published the list of place names in Innermost Asia, so this can be used as a gazetteer of Silk Road. Each place has its name, the sheet number, and the classification of the place. To use this gazetteer, we digitized this list first, and corrected several errors, and organize the classification system by merging similar classes. As a result, we have 5490 place names into 6 classes (101 detailed classes). This gazetteer is not yet complete, but is partially accessible from maps so that users can search a map sheet from a place name.

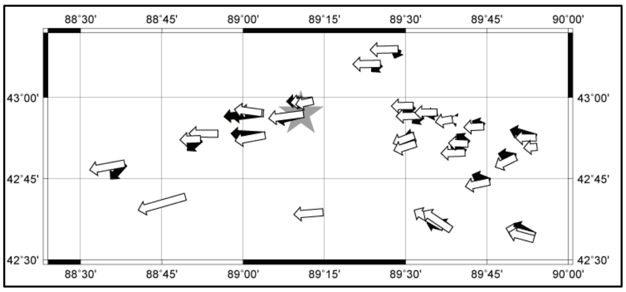


Figure 3. Error distribution around Turfan oasis. The star shows the representative point of the oasis. Black arrows: Serindia; White arrows: Innermost Asia.

3. BEIJING MAP IN QIANLONG PERIOD

3.1 Description of the map

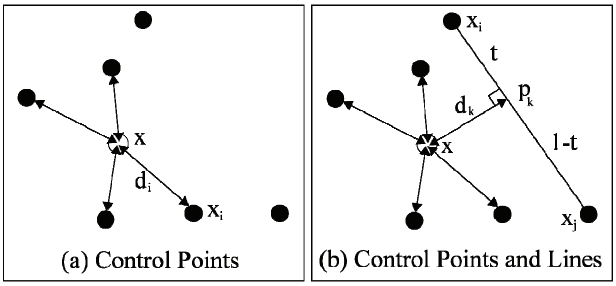
“The complete map of Peking, Qianlong Period” was created around 1750 under the order of Qianlong Emperor (Reign 1735-1795) of Qing Dynasty. This is known to be the oldest measured map of Beijing with the scale of 1/650. This map was first stored in Forbidden City, discovered in 1935 at National Palace Museum, and has been stored there since then. The original map is very large, with the height of 14 meters and the width of 13 meters, so the original map is not appropriate for browsing and is not accessible to the general public. Available is the copy of the map, and we use a copy published in 1940 by Koa’in, and now archived at the Toyo Bunko, the Oriental Library. This copy is known to be the best copy among others for the high resolution beautiful printing. Another advantage of this copy is the appendix of place names created by the person who discovered the map later.
The problem of this map is also the large number of sheets. The map is divided into 17 lines from north to south, and 11-13 pages from east to west, and the total number of sheets amounts to 203. With this number of sheets, it is difficult to study the connectivity of neighboring sheets, and the characterization of the entire map has not been feasible. For the evaluation and usage of the map divided into many sheets, we need to connect many sheets into one large map through the georeferencing of sheets and seamless connection of them.

3.2 Geometric Correction for Beijing Map

A large difference between this map and Stein maps addressed in the previous section lies in the presence of latitude and longitude on the map. Stein maps had latitude and longitude, even if they are not correct. For the Beijing map, however, it does not have that information, so control points should be selected from the historical map and the current satellite image for geometric correction.
A typical method of geometric correction using control points is based on Delaunay Triangulation (Triangular Irregular Network). This method organizes control points into a network of triangles, and estimates local geometric correction parameters for each triangle. This method is established and has been applied to many maps, but this method has an important problem in our case. The first problem is a minor problem; if the distribution of control points is skewed, the Delaunay Triangulation produces skewed triangles, which lead to a deteriorated result for those triangles. The second problem, which is a more fundamental problem, is about the preservation of linear features in a city, such as streets and surrounding walls. Geometric correction by Delaunay triangulation transforms a straight line to a poly-line, which may look like a zig-zag line.

In Beijing, straight lines are symbolic features of the city, so the preservation of linear features is an especially important requirement in the geometric correction. Hence a traditional method cannot be used for this task.

To solve this problem, we propose a new geometric correction method, namely "line-preserving distance weighting method." This method is an extension to a traditional distance weighting method so that it can preserve linear features, such as streets and walls. In the following, we will introduce the basic idea of our method in addition to traditional methods.



(a) Control Points (b) Control Points and Lines

Figure 4. Concept of distance weighting methods

3.3 Line-Preserving Distance Weighting Method

3.3.1 Distance weighting method for control points

The basic idea of distance weighting methods is that the effect of control points is modelled as the function of distance between a control point and the point to interpolate. As in Figure 4 (a), suppose that we interpolate point x using N control points in the neighborhood, namely x_i $(i = 1, \ldots N)$, where the point x_i takes value z_i. In this paper, z_i represents a vector of displacement from the historical map to the current map. Then the value $z_p(x)$ at point x is computed as the weighted sum.

$$z_p(x) = \sum_i w_i z_i / \sum_i w_i$$

The weights w_i are the function of distance d_i between the point x and a control point x_i. We use a function $w_i = (1 - d_i^2 / d_{\max}^2)$ where $d_{\max}$ is distance to the Nth nearest control points. We set $N = 5$.

3.3.2 Distance weighting method for control lines

We extend this method naturally to control lines for preserving linear features relevant in the map of cities. Mathematically speaking, a line is a set of points. Hence we can regard a control line as a set of points whose values change continuously from one endpoint to another. Then we can define a virtual control point on a control line whose distance can be measured on the perpendicular line to the control line. Namely, distance d_k between point x and control line l_k is defined as length of the perpendicular line to p_k, which is the virtual control point on the control line. Assuming the endpoints of control line l_k are x_i and x_j, and define a parameter t on the line as $t = | p_k - x_i | / | x_j - x_i |$. Then value $z_l(x)$ at point x is the linear combination of M lines l_k $(k = 1, \ldots M)$,

$$z_l(x) = \sum_k w_k [(1-t) z_i + t z_j] / \sum_k w_k$$

We use the same function for w_k. Finally we obtain the value $z(x)$ at point x as the linear combination of values from control points and control lines.

$$z(x) = w_p z_p(x) + (1 - w_p) z_l(x)$$

Here the parameter $0 < w_p < 1$ represents the relative importance of control points, and we set $w_p = 0.25$.

3.3.3 Query on Control Points and Control Lines

The disadvantage of our method is the computation cost. Our method is pixel-oriented in the sense that geometric correction parameters should be estimated for each pixel. This is in contrast to Delaunay triangulation-based methods where parameters need to be estimated for the unit of a triangle. Estimating parameters for each pixel requires much higher computation cost, but leads to smooth interpolation results. To reduce the computation cost of this method, we need a spatial access method to speed-up searching nearest control points and lines from the database. The most basic method is linear scan of points and lines, but the indexing of control points and lines should be considered. We currently use kd-tree for control points, and for control lines, we sample a line by a set of points and index those points in a kd-tree as special points of the line. However, we need to evaluate other indexing methods, such as quadtree to find out the best indexing method for this problem.

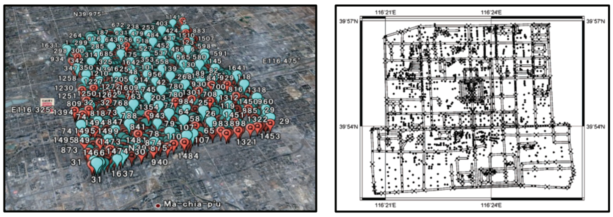


Figure 5. (left) Control points selected on Google Earth. Cyan and red represents the current and the old location, respectively. (right) Distribution of control points and control lines.

3.4 Control Points and Lines

We selected about 1800 control points from palace, large houses, intersections of streets and hutongs. These are regarded as features that have not been moved for these 250 years. In addition, we selected about 500 control lines from streets and surrounding walls of the inner and outer castle. Those points and lines are identified on the current satellite image of Google Earth, and later used for geometric correction. We created software for geometric correction, and applied it to the problem of 29 billion pixels on 203 sheets. For this large scale problem, we used Linux clusters to speed up the process. The final product is available at "Digital Maps of Old Beijing" (http://dsr.nii.ac.jp/beijing-maps/).

3.5 Discovery of Mis-arrangement

Control points and lines are used in our proposed geometric correction method, and we obtained seamlessly connected map that can be viewed on Geobrowsers. However, the study of the result revealed that some parts of the map seem to be inaccurate, so we studied the reason of this problem.

The problem was found in the west of the outer castle, and we observed the following problems.

1. Some parts are too different from the current map.
2. Some regional features (such as temples) are not connected across neighboring sheets.
3. Some features that should be located at the current place are found in wrong places.

These problems cannot be explained simply by the inaccuracy of the map. Hence we hypothesized that map sheets are arranged in a wrong manner. Then we discovered that the horizontal exchange of sheets between neighboring sheets and exchange of half-sheets within a sheet can solve all inconsistencies present on the map. Mis-arrangement occurred on 5 sheets as Figure 6 shows.

3.6 Interpretation of Errors

It has been known that the map has some errors. (Hou, 1988) reported that some parts of the Qianlong map have errors in direction and scale. (Ihara, 1997) also reported that the historical map cannot be matched with the neighborhood of Fayuan si, and research should be based on not only this map but also on other maps currently available. Finally (Li, 2004) reported that he has found the mis-arrangement (exchange of sheets for the horizontal direction) at 9, 10, and 11 pages of Line 14. Those results, however, just pointed out some errors they found, but the study of the entire map has not been done due to the large number of sheets. Hence the accuracy of the map has been unknown, but our analysis on georeferenced map revealed that the map is relatively accurate.

1. Mis-arrangement can be found not only on Line 14, but also on Line 15 and Line 16. The number of pages involved in mis-arrangement is five. However, there is no problem in Page 9 of Line 14 as Li pointed out.
2. The problem around Fayuan si is due to the mis-arrangement in that part, and not due to the inaccuracy of the map. After rearrangement, the historical map can be compared with the current map.

Finally, we found two clues on the cause of mis-arrangement. Firstly, the mis-arrangement is found on fragmented parts which were later restored (there is no record on this restoration, however). Secondly, the mis-arrangement within a sheet never occurs during the editing process of the copy, where only intra-page mis-arrangement could occur. These observations suggest that the mis-arrangement of the historical map was caused by the restoration after the map was found later.

3.7 Gazetteer

As addressed before, the copy of the map has the list of place names, and it is known to be the most reliable index available because it is made soon after the discovery of the map. So we digitize this list, and checked the correctness of place names by comparing each place name with the map. As a result, we found out that of around 3600 place names, about 800 place names contain errors. We also found out that about 400 place names are missing from the index. We corrected those errors and now the gazetteer has about 4000 place names. To allow multilingual access, we added Japanese, simplified Chinese, and Pinyin in addition to traditional Chinese, which is the original language of the index. Furthermore, some place names are georeferenced so that access to place names from Google Earth is possible. As a result, we created a gazetteer of Beijing which is more comprehensive and reliable than the original.

4. DISCUSSION

4.1 Advantages of Geobrowsers for Historical Maps

Geobrowsers such as Google Earth was used for the important steps of this research, namely the selection and management of control points (and lines), and the publication of maps on the Internet. Another important part, namely geometric correction, was done by software made by ourselves. We suggest that traditional GIS software, which has been used by many researchers for historical maps, has several limitations in comparison to Geobrowsers. Firstly, it does not have high resolution satellite images as default base maps for free. They can be purchased for the city level, but it is not feasible over the entire Tarim Basin (in addition, high resolution maps of Tarim Basin are not available due to military reasons of Chinese government). This suggests that the geometric correction of Stein maps, in particular, was not realistic before the introduction of Geobrowsers. Secondly, Geobrowsers are designed for the Internet environment, so the publication of data in a Geobrowser-friendly format such as KML is not difficult. Even an extremely large map can be published on the Internet so that people can see any part of the map using zooming-in and zooming-out functions. On the contrary, the publication of data using traditional GIS is not easy, and usually involves the development of a dedicated system. Thirdly, Geobrowsers are

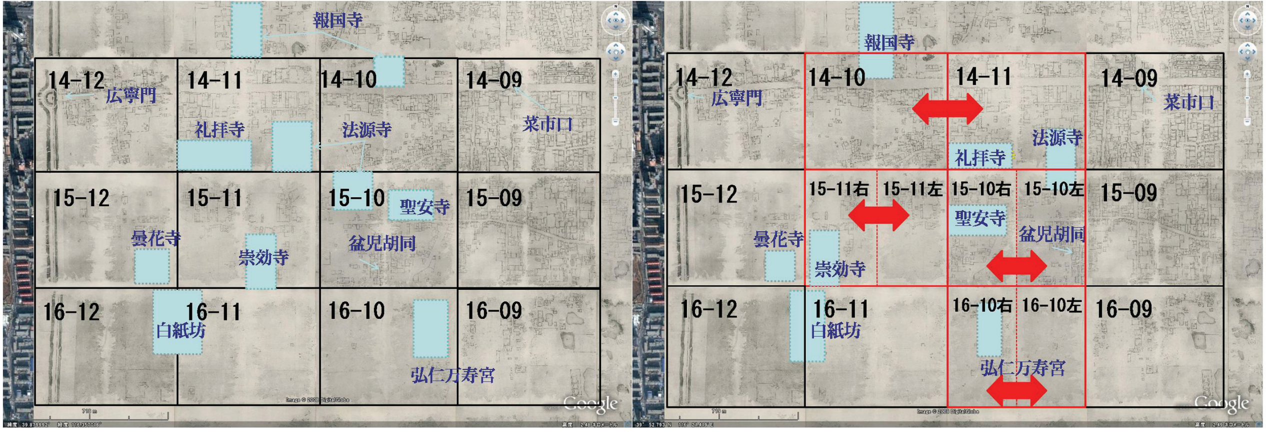


Figure 6. Mis-arrangement in the west of the outer castle. (left) before correction; (right) after correction.

designed for novice users and the functionality is limited, so learning cost for novice users is lower as a result. Annotation and management of control points and lines is also straightforward and does not require the training of software. Those advantages are the reasons that we used Geobrowsers as a main platform for historical maps.

The current disadvantage of this framework, however, is that there is no integrated platform for this workflow. Import and export of data requires the handling of data on the role of administrators. To solve this problem, we need integrated software for this workflow so that even novice users can manage the workflow by themselves.

4.2 Complexity of Geometric Correction

Geometric correction of historical maps is an indispensable step for providing digital maps in a usable manner, and we showed two approaches in this paper. The first approach is to apply a simple geometric correction method, and show an error table at control points. The second approach is to apply a complex geometric correction method so that the historical map can be directly compared with the current map. Note that the first approach can be considered as producing an intermediate product before the second approach, because control points for evaluation can be used for geometric correction in a later stage. However, the second approach is not always the best solution. When we do not have enough control points, even if geometric correction is accurate at control points, the map may be deformed so significantly that its appearance is too much distorted. Some users may not accept this result.

In a wider context, this problem may be considered as a problem of overfitting, which refers to a good balance between the goodness-of- fit and the number of parameters. If we increase the number of parameters, we can improve the goodness-of-fit, but the usage of too many parameters results in complex interpolation, and fitting becomes worse at points which are not evaluated. Hence a good balance between fitness and parameters needs to be found for interpolation problems. We have not considered this problem in this context, but we feel that the goodness-of-fit is not the only factor to evaluate the usability of the historical map.

4.3 Spatial Visual Resources

In addition to historical maps, we also have other resources with spatial coordinates such as historical photographs. To deal with these resources, we propose a concept of “spatial visual resources,” which is the union of spatial resources and visual resources. Here spatial resources have spatial coordinates which can be georeferenced, and visual resources have visual information which can be interpreted. The union of those two resources allow us to better understand the real scene.

For example, we identified one ruin from Stein maps where the present location has been unknown. We combined the historical map and several historical photographs, and identified the present location through the visual comparison of historical photographs with the real landscape. Another interesting result from Beijing map is about the real scene of streets. A wide street on the map is actually a narrow street on the photographs because houses and shops invaded into the street. This fact has been described in text, namely books and records, but the real scene can be understood only from spatial visual resources.

4.4 Linkage across Multiple Databases

Because of the limitation of the space, we did not deal with the application of the maps. However, from the analysis of Stein maps, an interesting application is emerging, namely what we call “digital excavation.” This concept refers to our method of digging the “cyberspace” to find out important clues for ruins. In that context, we are interested in making links between multiple databases, especially the reports made by European expeditions in the early 20th century and the databases made by local cultural heritage offices in China. To make links across many records in the database, the key technology is name identification and place identification.

The identity of names is the easiest case to make a link, but usually the same ruin is registered in different names with variation, so we need to make rules to match between differently represented names. Another interesting clue is place identification, where the similarity of spatial coordinates is used for making links between database records. For this identification to work, we need to apply geometric correction to historical maps, and georeference the feature to the correct location. Using this approach, we have already identified a few ruins which were recorded by European expeditions but later rediscovered as new ruins by Chinese cultural heritage offices. Making links between European expedition records and local surveys is a promising direction for digital excavation.

5. CONCLUSION

We discussed the geometric correction of historical maps with two case studies. Both historical maps have not been evaluated due to the large number of sheets, but we applied our geometric correction method to provide them as seamless maps accessible on the Internet. They also have potential in new research areas such as digital excavation. Future work includes making a geobrowser-friendly framework so that people can easily use the workflow described in this paper.

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