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Accuracy testing of cartometric scanners for old maps digitizing

Keywords: maps digitizing, large format scanner, accuracy testing

Summary: The article is focused on old maps digitizing, especially on accuracy testing of equipment for digitizing. Mentioned are reasons why old maps should not be digitized as documents or books are and why it is important to choose different approach. Factors that have impact on a quality and the accuracy of digitized map are also listed.
Major part of the article is given to methods for accuracy testing of scanners. Test sheets for doing tests are also presented. Results from long-term monitoring are also presented. These results describe behavior of scanners and show how a distortion of digital images (maps) is changing in a time.

1. Introduction

Old maps, plans, atlases and globes are an important part of our cultural heritage. They form a piece of our history illustrating period situation and supplementing other historical sources. They are also a testament to the skill, knowledge and artistry of our ancestors.
Compared to other historical documents maps are unique by virtue of their creation. The oldest maps are more sketches and works of art than maps as we understand them today. But at the beginning of 18th century advances in both theory and practice led to new maps based on geodetic surveys and mathematically defined cartographic projections. These new maps allowed accurate (for their time) measurements of distances, angles and areas. In this context it is important to realize every map has its own accuracy characteristics defined by its origins - instruments and methods used for surveying, cartographic projection, scale of the drawing. Only by knowing and respecting these specific attributes can maps be used to full extent.
The need for digitization and popularization of archive materials is obvious. Researchers appreciate comfortable and fast access to information. To provide them with old maps in the best possible quality and with all the information of the original maps it's necessary to carry out the digitization as accurately as possible. Let us leave alone the question of colour capture fidelity and focus on geometric distortions caused by the process of scanning.

2. Map digitization

Digital copy of and old map can be published on internet as an image, for example in Zoomify format or it can be georeferenced and provided as Web Map Service (WMS). To ensure as accurate georeference as possible the shrinkage of paper must be eliminated, and cartographic projection and potential transformation in the projection plane must be taken into account. The accuracy is affected by the number and position of control points, and their image coordinates' acquisition precision. In the case of old maps created on geodetic surveys and utilizing cartographic projections the achievable accuracy is in the order of several tenths of millimetre in the map's scale. For example the maps of 3rd Military Survey of Austria-Hungary covering the Czech Republic were georeferenced with standard error of position of 9.1m, which is 0.36mm in map's scale 1 : 25 000 (Talich et al. 2013). This example demonstrates how the use of proper transformations allows to achieve high precision of goereference.

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At the very beginning of the georeferencing process is digitization - conversion of analogue maps into digital form. If we strive to achieve as good georeference as possible then it's important to know the accuracy of this process. The scanning precision should be around 0.1mm as to not affect adversely the georeferencing.
Digital cameras are not suitable for map digitization, because they can't provide stable conditions for minimizing geometric image errors (camera axis perpendicular to original, straightened original, low radial distortion of the optical system, exact DPI). Whenever precise localization is required the maps have to be scanned on precise cartometric scanners.

3. Large format cartometric scanner

Old maps are often quite large. Part by part digitization on small table scanners is difficult and the results are not very good in terms of quality. Therefore large-format scanners are the instrument of choice for digitization of large maps. These scanners come in two varieties: sheet-fed scanners and flatbed scanners. In the former the original moves through the scanners, in the latter the imaging cameras move over stationary original. The flatbed scanners are more friendly to the originals.

Figure 1: Large format flatbed scanner ScannTech 800i.

The scanners' cameras image the original sequentially from a short distance away (up to 20cm). This minimizes the optical errors of the imaging system. Large-format scanners are equipped with several cameras next to each other to cover the whole bed width with their slightly overlapping view angles. The scanners' software combines images from the individual cameras into a single image. During this process various geometric distortions can arise.
If the original is completely flat and the cameras view angles' connections are properly set there are usually no errors. Unfortunately these conditions cannot be always met. Old maps are often damaged, folded or too stiff to be properly flattened. Another problem is bend spines of atlases (or books in general). The magnitude error caused by these influences depends on distance from the scanning glass. The distortions caused by these errors are eliminated in software by local defor-

mations. For his to work properly the cameras view angles connections have to be set up properly and regularly checked.

The continuity of drawing can be tested by scanning a simple template consisting of several test lines. The test lines are 0.1mm thick, they are distinguished by colours and cover the whole scanning area. A scan of this template then immediately shows problematic places - where the lines are in any way interrupted or bent.

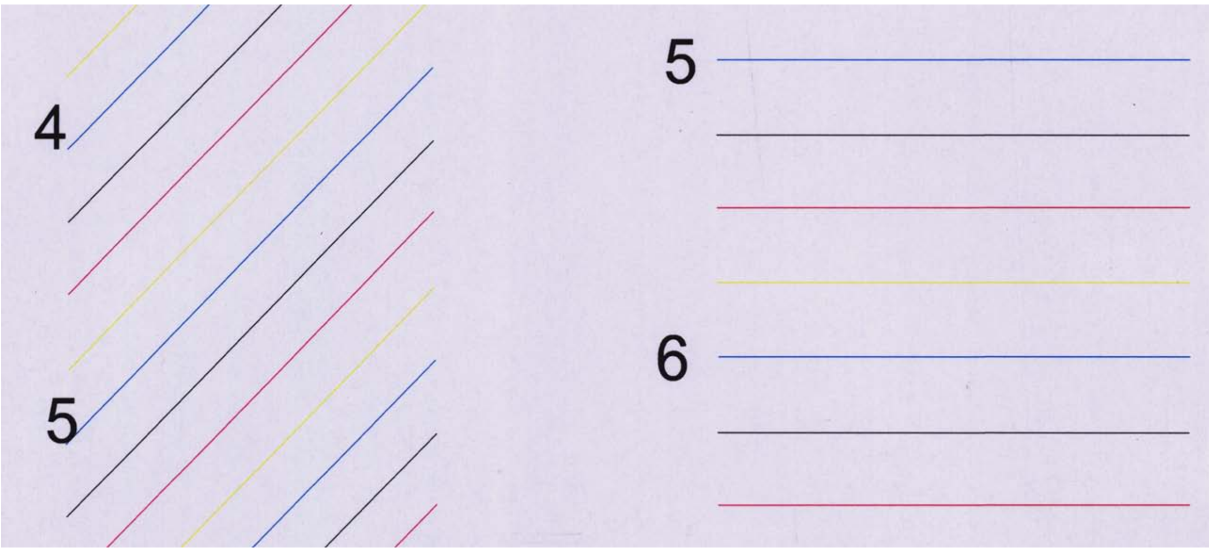

Figure 2: Section of a template for testing the camera view angles connections in horizontal direction (left side) and vertical direction (right side).

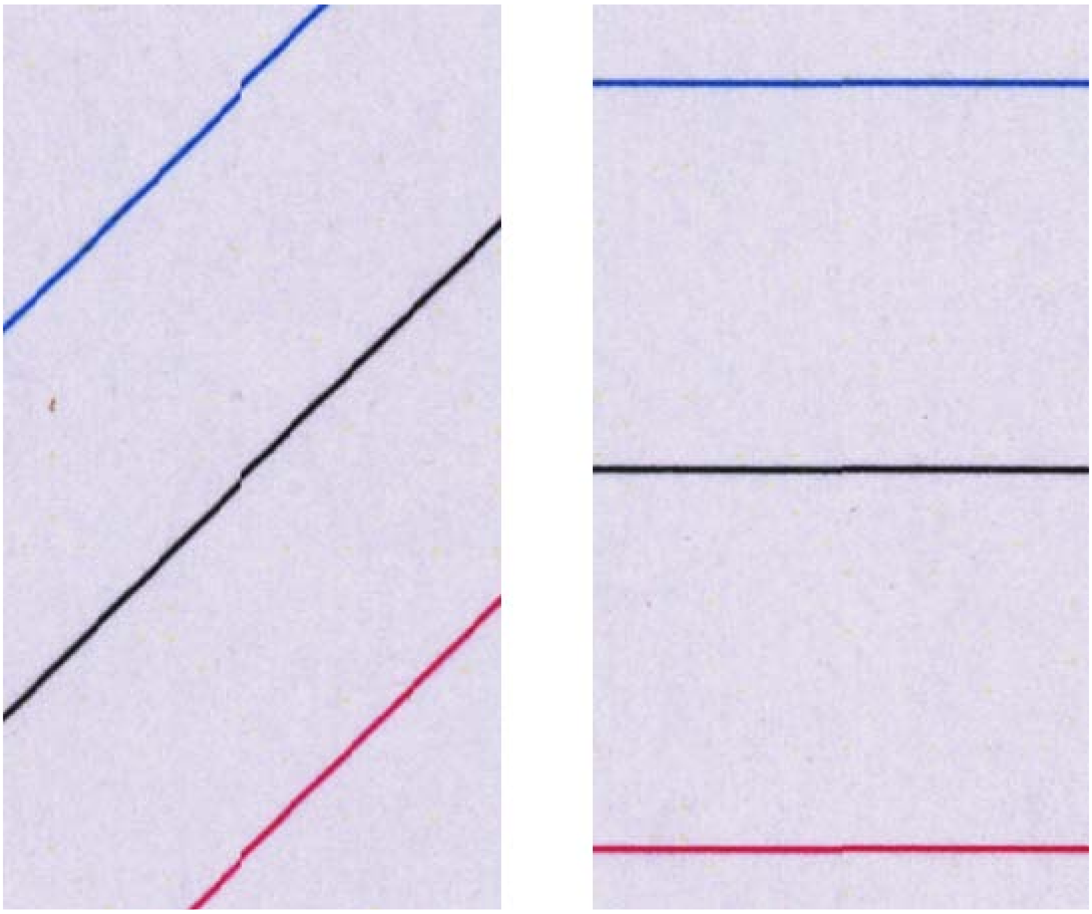

Figure 3: Detail of drawing discontinuity on the connection between two adjacent cameras.

4. Testing scanner accuracy

Scanner accuracy can be evaluated in two ways. First we can test how well the scanner captures the original, i.e. how much are distances and angles deformed in the process of scanning. Second point of view is stability of the accuracy over prolonged periods of time. That means discerning any potential time correlated changes to the fidelity of scanner's reproduction.

4.1. Testing the absolute accuracy

The absolute accuracy of a scanner is measured with the help of a special template with regular grid of crosses. The more dense the grid the better description of local deformations caused by scanning it can provide. The lines forming the crosses shouldn't be over 0.1mm wide, because that line width means 3 pixel width at 600 DPI resolution. The position of crosses in original has to be determined with order of magnitude better precision than what the line width of the crosses is, ie. with the precision in order of hundredth of millimetre (in case of 0.1 line width). A suitable instrument to determine the crosses' position is a laser interferometer. It's important the template is made from material with low thermal expansivity and that it is flexible so it can be put into a sheet-fed scanner and pressed well to the glass of flatbed scanner.
The image coordinates of crosses, determined in the scan of the template, are compared to reference (real) coordinations obtained from direct measurement of the template. The resulting shift vectors can be depicted in the scan.
In the Czech Republic this test is a basis for a certification granted by Czech Office for Surveying, Mapping and Cadastre according to Instruction n. 32 for Scanning of Cadastral Maps. The maximum permitted deviation in position for scanner for digitization of cadastral maps is 0.3mm.

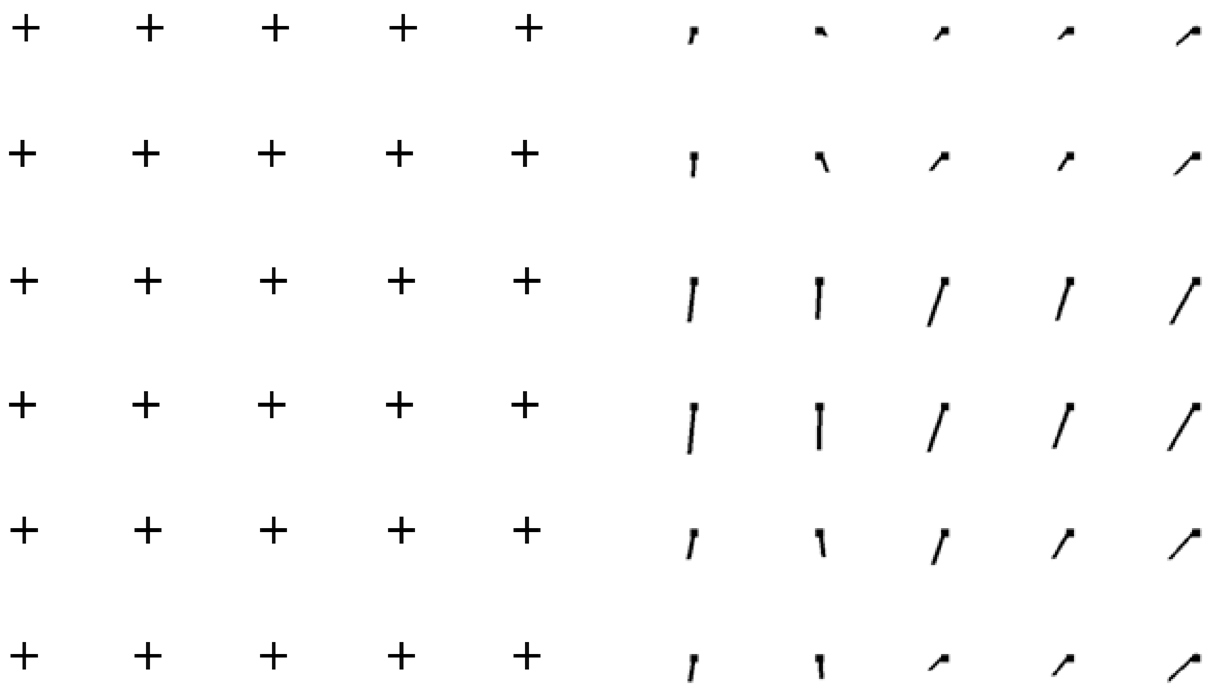

Figure 4: Section of a template with a grid of crosses (left side) and evaluation of geometric distortion by means of shift vectors. The section shows roughly central part of the template, shift are magnified 20x.

4.2. Testing the relative accuracy

The relative accuracy can be also tested with the use of regular grid of crosses template. In this case we don't have to know the real position of all the crosses, because we need to measure only their shifts between multiple acquisitions. In theory any template could be used for this test, but a grid of crosses has the advantage of covering regularly the whole area. Furthermore the crosses can be relatively easily automatically detected and the whole process can be automatized to a large extent.
When we want to test the change of coordinates we need to solve the problem of template placement for each subsequent scanning. It's practically impossible to place the template in the exact same position every time. At the same time the placement has direct effect on image coordinates of the crosses. Because of that it's necessary to choose a suitable common coordinate system, transform every cross coordinates into this system and only then compare their coordinates.
Let us assume we have several scans of given template (regular grid) acquired at different times. The procedure for relative accuracy evaluation is as follows:

1. detect the crosses
2. transform crosses into common coordinate system
3. calculate the shifts
4. visualize and evaluate the results

4.2.1. Crosses' detection

The scanned image is first converted to a binary format, i.e. an image containing only the values of 1 (white) or 0 (black) by thresholding. In this image the crosses' positions are detected by template matching (Goshtasby 2005). A representative cross from one of the scans can serve as the template.
First edges are detected in the binary image. This is done by convolution with kernel:

$$\begin{bmatrix} -1 & -1 & -1 \\ -1 & 8 & -1 \\ -1 & -1 & -1 \end{bmatrix}$$

This results in a list of points comprising edges in the image. These poins are potential approximate crosses' positions. The number of these candidates is much greater than the actual number of crosses so they are filtered out by their relative distance - from every set of points whose relative distance is less than chosen limit distance D_0 only one point is kept and the rest are discarded. The resulting list of points is a list of approximate crosses' positions.
In next step the precise crosses' positions are found using correlation. For each approximate position a suitable neighbourhood is taken and for every pixel from this neighbourhood is calculated correlation coefficient C_i with cross template. The correlation coefficient in this case can be calculated as sum of absolute difference between pixels in image and template.
The final cross position is then a pixel that meets these conditions:

1. its correlation coefficient C_i is greater than limit value C_0
2. its correlation coefficient is the maximum coefficient in the neighbourhood under consideration.

The choice of D_0 and the neighbourhood size for correlation is dependent on the cross size and their distance from each other. D_0 should be greater than the cross size, the correlation neighbourhood should at least be a little larger than D_0 but at most half the distance between crosses. The choice of minimum correlation coefficient C_0 is less clear. If the original grid is not very good the crosses can be relatively varied and lower C_0 value can improve the detection quality (more crosses detected). At the same time it can lead to false positives (detection of crosses where there are none) or wrong cross detection (it's hard to determine exact position of badly depicted cross).

4.2.2. Coordinates transformation

The common coordinate system is defined as follow:

- the origin lies in upper left cross of the grid
- the positive Y axis points from upper left cross to lower left cross
- positive X axis is perpendicular to Y axis and points to the right image edge

The relation between this coordinate system and image coordinate system x, y is congruent transformation:

$$\boldsymbol{X} = \boldsymbol{T} + \boldsymbol{R}\boldsymbol{x},$$

where **X** is vector of target coordinates
x is vector of image coordinates
T is translation vector
R is rotation matrix by angle $\boldsymbol{\varphi}$

Translation is determined by image coordinates of upper left cross. Rotation angle $\boldsymbol{\varphi}$can be calculated from the coordinates of upper left and lower left crosses. Provided:

x_1, y_1 are image coordinates of upper left cross and
x_2, y_2 are image coordinates of lower left cross
then:

$$\mathbf{T} = [-x_1, -y_1],$$

$$\boldsymbol{\varphi} = \boldsymbol{arctg}\frac{\boldsymbol{x_2} - \boldsymbol{x_1}}{\boldsymbol{y_2} - \boldsymbol{y_1}}$$

4.2.3. Shift calculation

After transforming all crosses to common coordinate system we have a time sequence of coordinates for each cross. The shifts are simply distances between these coordinate points.

4.2.4. Visualization and result evaluation

The previous steps results in a chronological order of shifts for all (or at least for all detected) crosses. We can examine every cross individually, plot its shifts over time in a figure or write it into table and compare the values to expected or limit values to decide if these shifts are significant in relation to required scanning accuracy.
Another option is to use statistical methods and calculate the mean shifts and other moments characterizing the set of shifts. Based on that we can potentially look for outliers - points or set of points with shifts significantly different from the rest of the set.
A good illustrative way to visualize the shifts is plotting the shifts (in suitable scale) in the first scan. Fig. 5 shows an example of this visualization. Each acquisition is plotted with different colour.

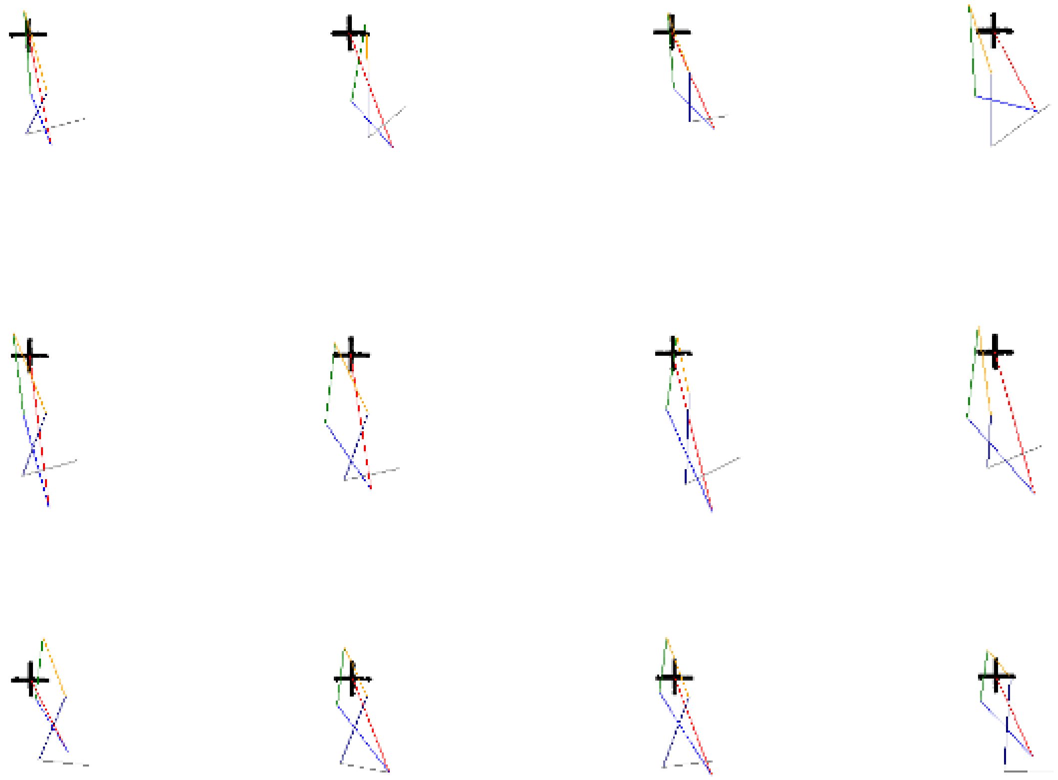

Figure 5: Section of a relative accuracy evaluation with grid template (900x950mm, 1886 crosses) with shift visualization. The number of template scans is 7, shifts are magnified 20x. Section shows roughly central part of the template.

5. Results

All mentioned methods of scanner accuracy testing were tried on a flatbed scanner ScannTech 800i by manufacturer Proserv. This scanner is used in the Research Institute for Geodesy, Topography and Cartography, v.v.i. for old map digitization in project "Cartographic Sources as Cultural Heritage". As part of this project around 10 000 maps are scanned every year including maps from stable cadastre, military surveys etc. The scanner's absolute accuracy is tested regularly every year and in between the relative accuracy is tracked via regular monthly scans of the grid template.
The scanner's maximum error of position is under 0.2mm. The evaluation of temporal changes shows shifts of random directions and magnitudes. These shifts are caused primarily by uneven movement of scanner during the template digitizing. This was verified by a test when the template was digitized ten times in row and still in the same position. The evaluation in this test shows the standard error of position of 0,03mm. If the temporal shifts showed a common trend we could assume a systematic error of the scanner (bad camera view angle connection, some mechanical problem etc.).

6. Conclusions

Knowing the geometric accuracy of scanner used for map digitization allows to realistically evaluate attainable accuracy for georeferencing and decide for how precise analysis these maps can be used. Accuracy testing with the use of test templates is relatively simple and fast. At the same time it provides realistic view of geometric deformations of scanned images caused by the scanner and their changes over time. The required scanner accuracy should be derived from accuracy of scanned maps and the demands on their georeferencing accuracy. For accurate maps the scanner accuracy should be around 0.2mm.

This contribution was supported by the European Regional Development Fund (ERDF), project "NTIS - New Technologies for Information Society", European Centre of Excellence, CZ.1.05/1.1.00/02.0090.

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