

3-D Reconstruction of Iron Gall Ink Writings

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Abstract

Some historical writings cannot be investigated anymore without causing damage by touching or browsing them. Our work shows a non-invasive method for the 3-D reconstruction of historical writings and drawings written with an historical ink consisting of metallic particles. Since the 5th century Iron Gall Ink is in use as an indelible ink and is still in use. Modern, adaptable X-ray scanners used for material testing are able to image this ink such that it can be differentiated from the cellulose-based paper. The first part of our works proofs this assumption by taking single shot X-ray acquisitions. The second part focuses on a novel method that is able to image all pages of a book by a single circular X-ray CT scan followed by a 3-D reconstruction. Applying this method makes it possible to image complete books, writings or drawings without the need of page-turning or touching them anymore.

Keywords: 3-D reconstruction, X-ray imaging, Iron Gall Ink, Historical Document Analysis.

1 Introduction

The process of aging or an already existing damage prevents the investigation of many historical writings. Commonly, the digitization process is performed by document scanning systems that photograph each page and browse through the entire book allowing to digitize up to 2500 pages per hour. This technique has the drawback that the documents that should be digitized have to be touched or each page has to be turned separately, which is not applicable for documents that cannot be touched, opened or unrolled anymore due to their age or pre-damages such as burns.

For this work, we assumed that paper is made of cellulose and the writings are made with Iron Gall Ink, an ink that has been widely used since the 5th century. Not only Mozart wrote ‘The Magic Flute’ with it but also Thomas Jefferson wrote the ‘Declaration of Independence’ with that kind of ink [1,2]. The ink consists of metallic ingredients allowing X-ray scanners to image its leftovers in the paper. The ink can be removed from the paper, but, however, particles are still present in deeper layers which enables the reconstruction of even erased or overwritten parts of the original writings.

Several preliminary works exist, for example Mocella et al. [3] recovered papyri rolls from Herculaneum by using X-ray phase contrast imaging (Synchrotron) while Deckers and Glaser [4] were able to reveal erased or overwritten writings on palimpsests. The drawback of the phase contrast method is that it is highly complex, expensive, and not feasible for everyday applications due to the immobility of the scanning system.

To the best of our knowledge, we are the first to use state-of-the-art X-ray systems for the reconstruction of document images. Simulations revealed that differentiation of the ink from the paper is basically possible [5]. Our first experiments, tested on a medical X-ray C-Arm CT robotic system, showed that the 3-D reconstruction of the ink was possible, but the imaging system was too inaccurate, such that we were only able to image a very small area of the ink. As it was not possible to set parameters to the range that we needed, we choose an X-ray system that is built for material testing. Figure 1 shows the used system with the X-ray source in the front and the flat panel detector in the back.

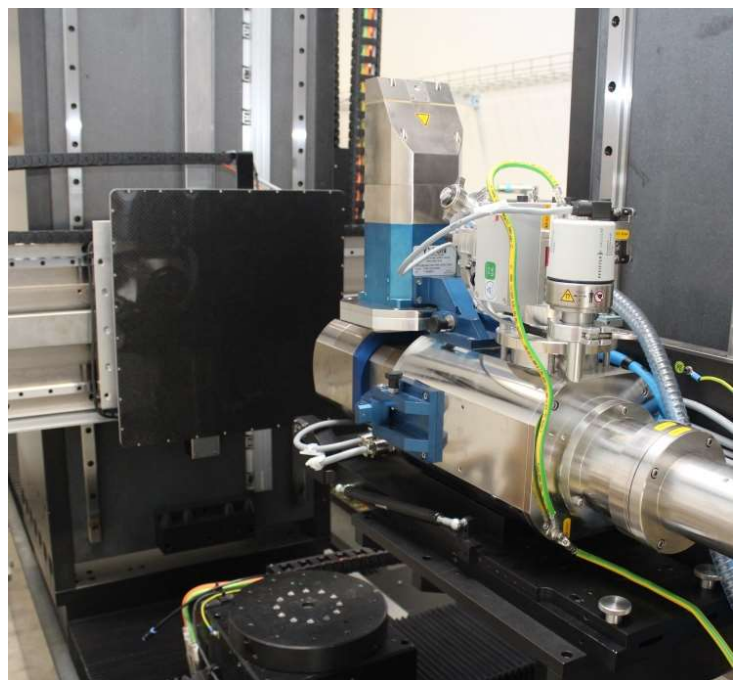


Figure 1: X-ray Cone Beam CT system used for material testing.

One challenge that showed up in the first experiment was that when imaging several pages at once, the pages have to be flattened and aligned very precisely. As mentioned before, we want to avoid touching the pages, such that we also want to present an algorithm to automatically extract and flatten the pages.

2 Materials and Methods

2.1 Material absorption

For our work, we consider the paper to be made of cellulose ($C_6H_{10}O_5$) with a specific density of $1.5 \text{ g} \cdot \text{cm}^{-3}$ and Iron Gall Ink to be modeled as $FeSO_4 \cdot 7H_2O$ with the specific density of $1.89 \text{ g} \cdot \text{cm}^{-3}$. At first, simulations were performed by using the CONRAD framework for cone beam reconstructions [6].

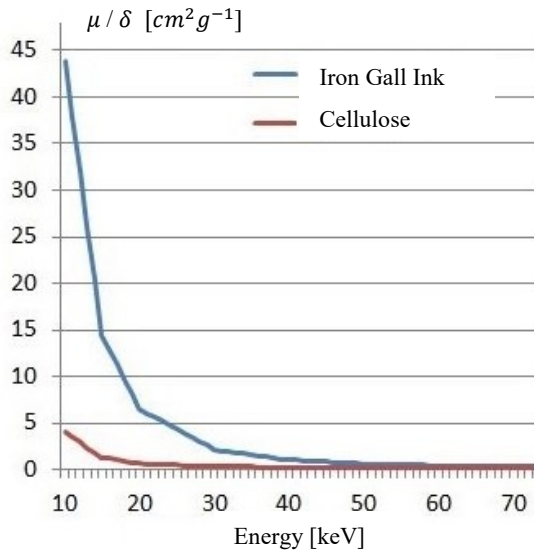


Figure 2: Spectral absorption plot for Iron Gall Ink and cellulose showing the mass absorption coefficient for increasing energy.

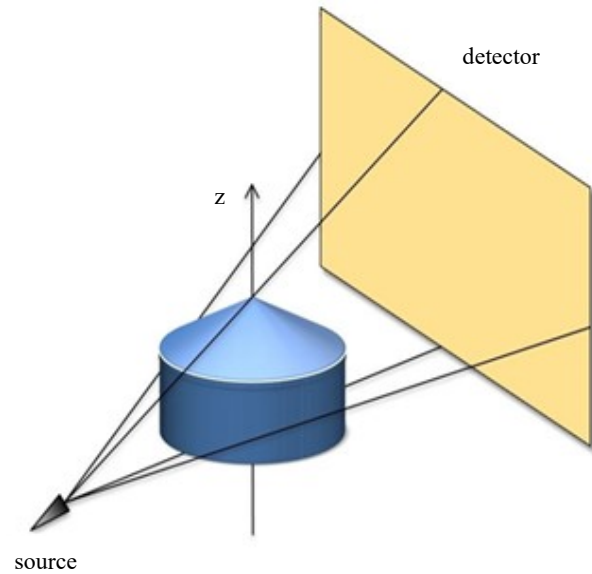


Figure 3: Cone beam geometry of an X-ray CT scanner.

Figure 2 shows the spectral absorption plot for the two main components, ink and paper, showing that the lower the energy gets, the more the mass absorption coefficient can be differentiated. At first, we perform two single shot acquisitions orthogonal to the page with 50 keV and 30 keV of the page shown that is shown in Figure 4, which has been handwritten on handmade paper 6 months before the acquisitions were made ensuring that the ink has dried enough.

Our currently used X-ray CT scanner is able to operate reliably with down to 30 keV, which should be enough to image the ink. Further decreasing of the energy would yield to higher noise and acquisition times and could be considered for ongoing research if the results are not accurate enough. For this work, we decided to start at 70 keV and decrease the energy stepwise to analyze differences.

2.1 X-ray CT Scan

Figure 3 shows the general arrangement of the used system consisting of an X-ray source emitting radiation and a detector positioned to the opposite of the source measuring the attenuation of the material in the region-of-interest. The object is placed centered on a rotary plate. A small angular increment is driven and at every angular step a 2-D projection image is acquired. The geometry is called cone beam geometry due to the resulting shape of the field-of-view. Cone beam imaging is the commonly used imaging technique for 3-D X-ray imaging [7]. The detector is quadratic and has 2864×2864 pixels with a pixel shift of $74 \mu\text{m}$. We configured 459 projections for a 70 keV scan and 818 projections for a 50 keV scan while driving a 360° full circle trajectory. Due to high acquisition times we did not have time to further decrease the energy. Now, the novelty of our method is that the rotation plane for the CT scan is placed in the plane of the pages such that the axis of rotation is orthogonal to the book's front cover and we scan around the air gap of a wooden holder (Figure 5) which is used to pre-flatten the pages.

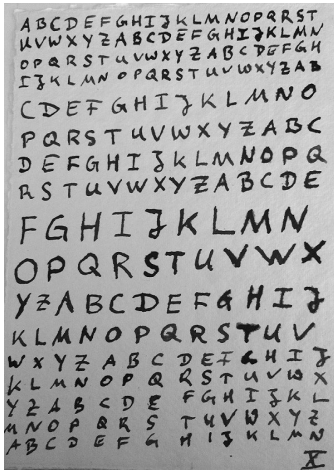


Figure 4: Iron Gall Ink writings on handmade paper



Figure 5: Wooden holder to flatten the pages

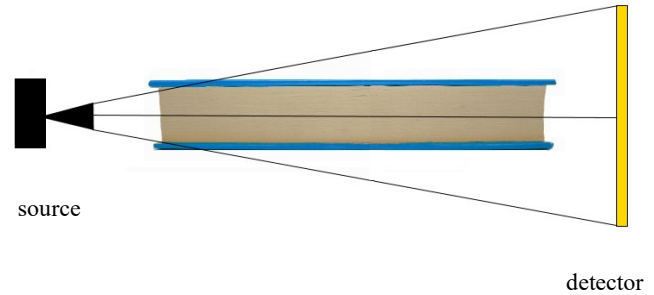


Figure 6: The X-ray beam path leads through the books pages such that the axis of rotation is orthogonal to the front cover.

2.2 3-D Reconstruction algorithm

For the reconstruction, the FDK algorithm is used, consisting of a cosine weighting, ramp filtering and back projection step [8]. The FDK algorithm should be accurate enough because we have a large number of projection images. The voxel size for the reconstruction is $68.14 \mu\text{m} \times 68.14 \mu\text{m} \times 68.14 \mu\text{m}$. For the CT scans, ten of the handmade and handwritten pages were put into the wooden holder and scanned with the described method.

2.3 Volume Post-Processing Pipeline

2.3.1 Image Denoising and Thresholding

The acquired X-ray volume has to be adapted by applying post-processing steps. At first, a 3-D bilateral filter is applied on the volume [9] because the images are noisy due to the low energy of the X-ray source. Standard filtering methods like mean or median filtering cannot be applied because they would smooth the fine structures too heavily. Bilateral filtering has the advantage that the images are smoothed while preserving edges. It combines photometric similarity and a geometric neighborhood. We set a kernel width of 8 px , $\sigma_d = 100$ and $\sigma_g = 20$ (16-Bit Unsigned Integer images). At last, the air gaps were set to zero by applying global thresholding (setting values below a certain gray value to zero).

2.3.1 Page Extraction and Flattening

A major problem when investigating the pages is that they are not flat and the book or object might be misaligned such that the pages are distributed over several slices of the volume making it difficult for the human eye to inspect the writings as shown in Figure 7. Therefore, an algorithm for a page extraction and flattening was developed. Figure 8 shows a block diagram of how the algorithm is working. At first, an empty mask volume M is defined and the user has to select a voxel $v_i = (x_i, y_i, z_i)$ in the original volume on the specific page that should be investigated. For this, the volume is rotated around the z -axis to make it easier for the user to pick a point. Starting from there, the algorithm first walks up and down the y -axis comparing the gray value of v_i with its two direct x -axis neighbors

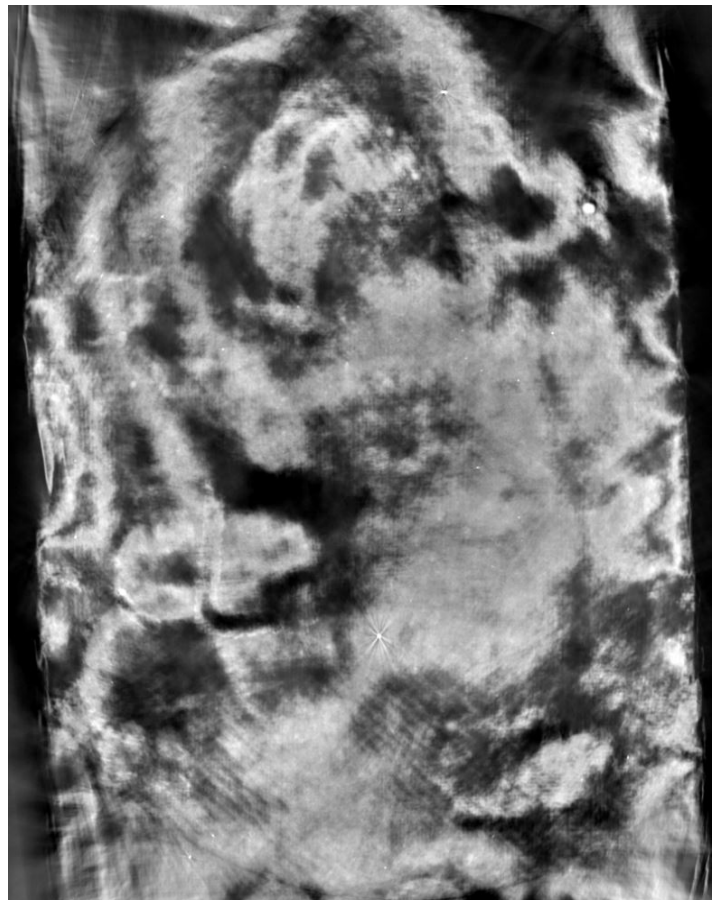


Figure 7 Original X-ray volume image of a slice in the center

$v_{n1} = (x_{i-1}, y_i, z_i)$ and $v_{n2} = (x_{i+1}, y_i, z_i)$ setting a '1' at the position in M . Then, v_i 's neighbors $v_{i,n1}$ and $v_{i,n2}$ are calculated for $z + 1$ and $z - 1$ and the walking process is repeated. This steps are repeated for all slices z . The complete mask is 3-D median filtered [10] with a kernel of $11\text{ px} \times 11\text{ px} \times 11\text{ px}$ for smoothing the output and outlier suppression [11]. The mask is multiplied with the original volume, the maximal value of a slice is being searched by iterating over the volume and this value is saved in the final 2-D output image.

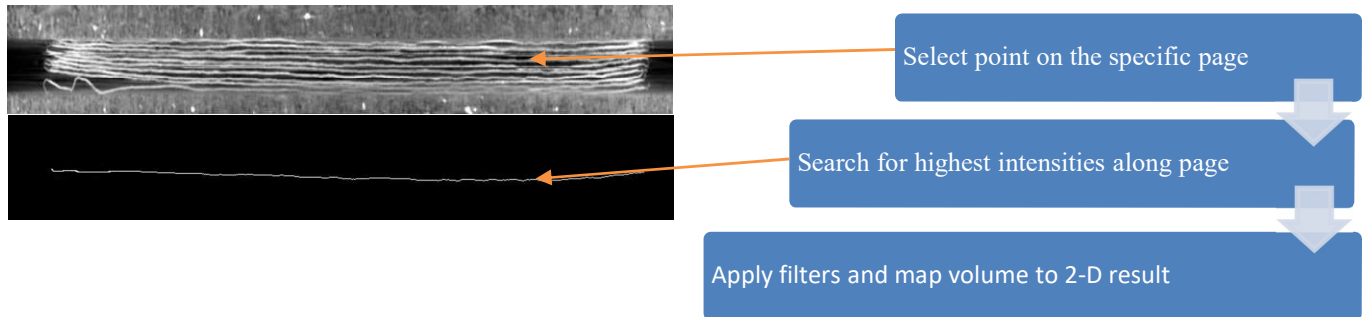


Figure 8 Page extraction and flattening algorithm

3 Results

Figure 9 shows the 30 keV single shot acquisition, where the page has been fixed with adhesive strips to the detector and the Source-to-Intensifier Distance was set to 500 mm. The electron current was 1000 μA , the exposure time 3 s and we averaged over 256 images. It shows that even some small letters on the top and the bottom can be imaged and the different paper saturations of the ink are also clearly visible. With only using the human eye, 180 out of 223 letters can be recognized, which is about 80.7 percent, with decreasing recognizability to the top and end of the page where the letters get smaller. Figure 10 shows a Canny-Edge filtered image [12] which highlights the best readable letters where the ink fully saturated the paper.

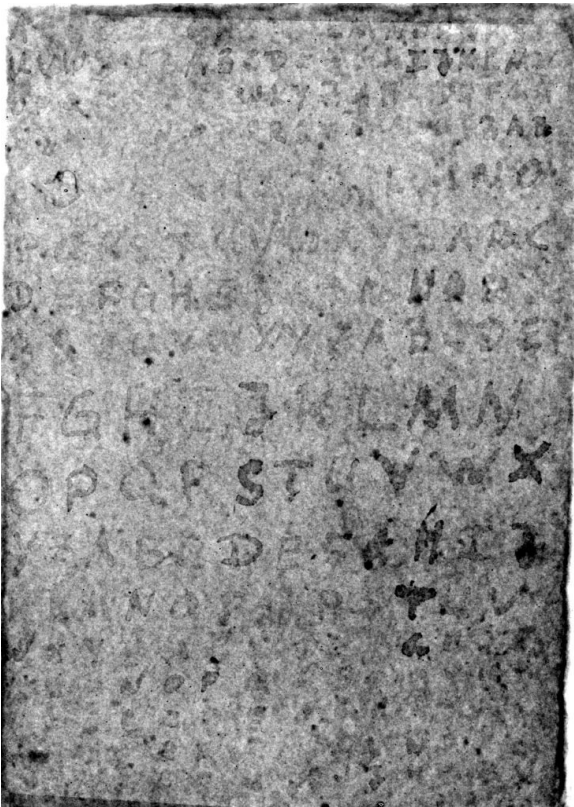


Figure 9 Single shot acquisition X-ray image of the ink written on the paper

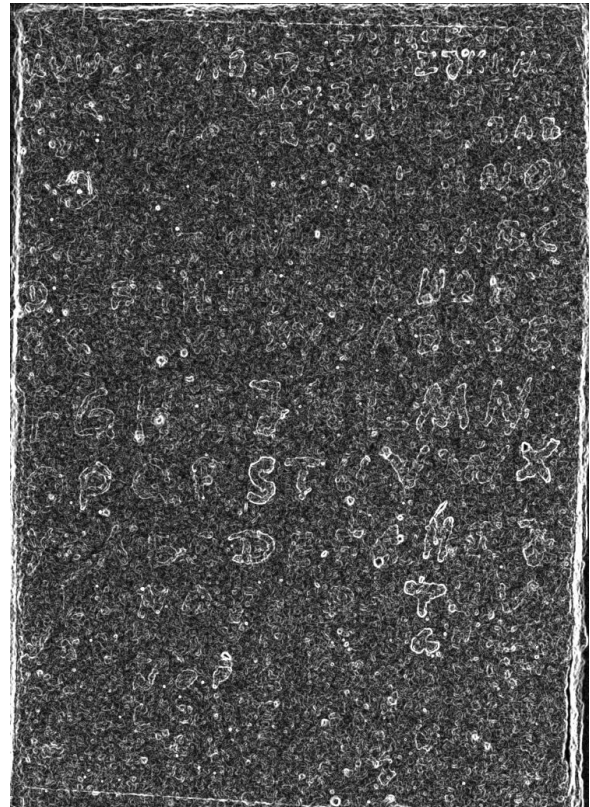


Figure 10 Canny-Edge filtered single shot acquisition X-ray image of the ink written on the paper

Figure 11 shows page 5 which should be reconstructed by performing the X-ray CT. The letters are thick and the ink fully penetrates the paper. One letter is about 2.5 cm tall and the lines about 0.3 cm thick.

Figure 12 shows the reconstruction of page 5 after performing the CT scan with 70 keV. The first three middle row letters are visible while the rest of the writings are only slightly observable with the human eye.

Figure 13 shows the reconstruction of page 5 after performing the CT scan with 50 keV. The writings in the middle and top row are much better observable with the lower energy when taking a closer look at the orange boxes. The bottom row letters visibility also improved, however, they are not visible as clearly as the other rows which is due to the distance to the central beam. The letters 'L' and 'M' which are in the center of the trajectory are fully visible.

Taking a closer look at the letter 'L' in the center row reveals that the intensity of the ink is higher at the border of the writing which could be due to an increased deposition of metallic particles in that area. There are also still some streaks at the borders of the image which should be caused by inaccuracies in the reconstruction.



Figure 11: Page number 5 of the book phantom

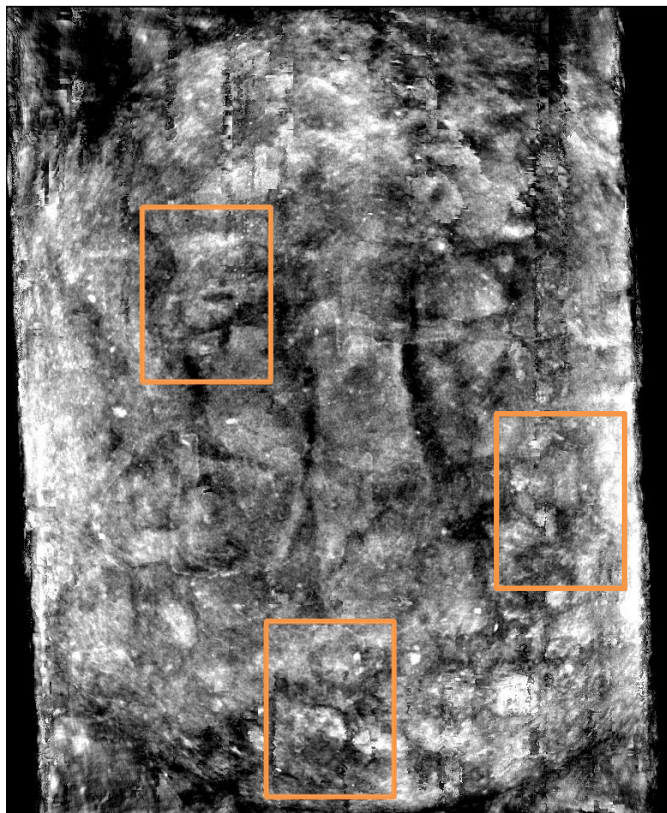


Figure 12 X-ray CT reconstruction result of page 5 with 70 keV

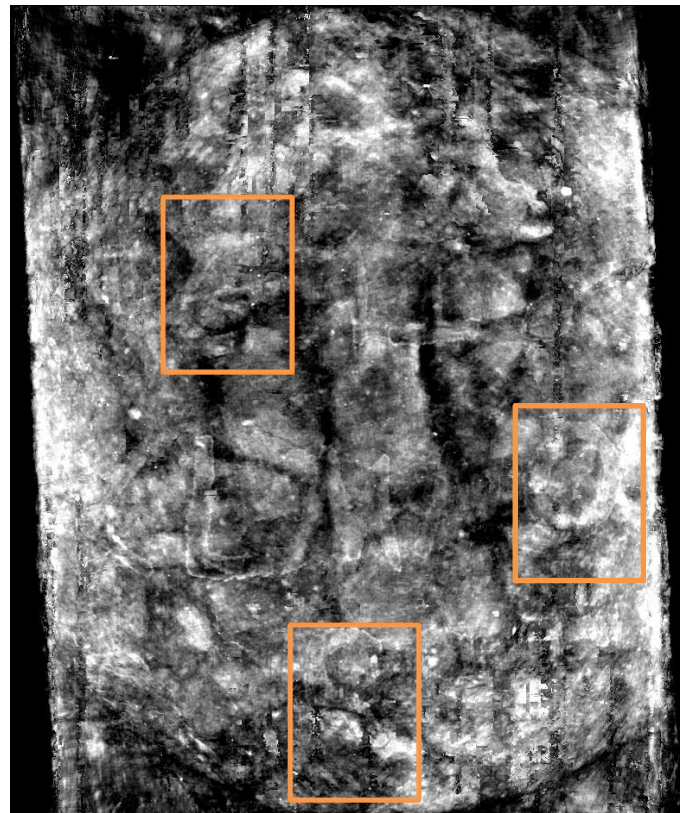


Figure 13 X-ray CT reconstruction result of page 5 with 50 keV

Figure 14 shows writing snippets of two different pages (page 1: top line / page 2: center line) with letter heights of approximately 1.5 cm while Figure 15 shows their reconstructed and post-processed X-ray CT image with 70 keV and Figure 16 the 50 keV version. One can obtain the same results with the lower energy than on the center page. The lower the energy the better the ink can be differentiated, even at the border of the imaging region (bottom row).

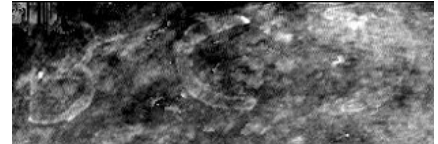
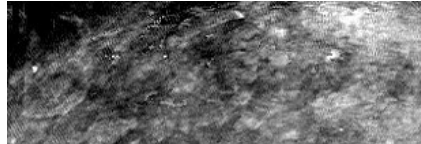
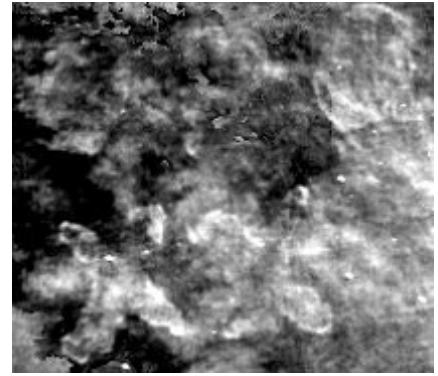
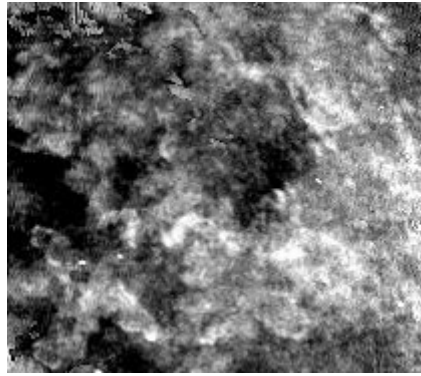
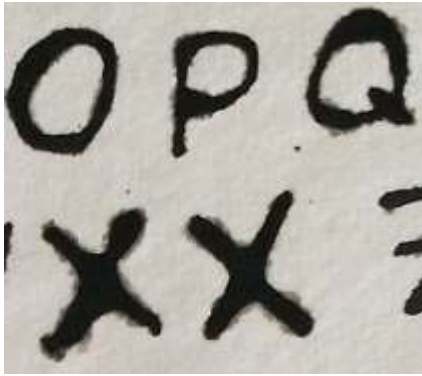


Figure 14 X-ray CT of page 5 with 70 keV

Figure 15 X-ray CT of page 5 with 70 keV

Figure 16 X-ray CT of page 5 with 50 keV

4 Discussion and Outlook

Our work shows that using modern X-ray CT scanners, such as they are used for material testing, can be deployed for 3-D imaging of historical ink writings on handmade paper. An initial experiment showed that we are capable of reconstructing writings of a single page by a single shot acquisitions with a relative low energy of 30 keV. We showed that within the X-ray CT scans, the ink can be differentiated from the paper when applying the presented trajectory. Tests with several settings revealed that lower energies lead to a better visibility of the ink. However, within the given time period we were not able to perform scans with even lower energies.

A quantitative evaluation of the X-ray CT volume has not been created yet, because firstly, the X-ray parameters have to be optimized such as finding the best radiation energy. Also the applied dose and runtimes were not investigated in our work due to that we wanted to proof our basic concept. We will focus on those parameters in our future research.

To obtain improved results, a proper collimation which will also reduce acquisition and reconstruction time can be applied. Also smaller pixel shifts than the used 74 μm 's are possible with the provided X-ray scanner, but for the first step we wanted to proof the concept itself and keep the computation times at an acceptable level. The wooden holder to pre-flatten the pages could also be removed to reduce scattering and other artifacts.

Another possibility to improve the resulting output could be to apply different reconstruction algorithms such as SART or TV-based iterative methods [13,14]. Within these algorithms the huge projection size could be reduced to lower the acquisition times. Also more work on the filtering of the results has to be done to improve the visibility, suppress the noise and outliers and enhance the contrast.

The page-extraction algorithm could be improved by adapting the extraction algorithm. An interesting approach was recently published from Seales et al. in [15], which could be adapted to our given problem.

One could also think about hybrid or multimodality approaches. Another trajectory could be driven, even with other imaging systems than an X-ray CT, and the outputs could be registered with certain algorithms.

This approach can be also applied to other inks with other ingredients. There are many different recipes for this kind of ink and we are not sure how close the ink is to a real historical ink. We think that future research should be done with real historical documents.

We believe that our method will allow the digitization of unreadable, damaged historical documents written with various inks, but further research is necessary to get improved results.

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