3-D Reconstruction of Historical Documents using an X-Ray C-Arm CT System

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***Abstract*—There exist historical documents that can not be inspected without damaging them. We present a non-invasive method for the reconstruction of historical documents which have been written with iron gall ink. Iron gall ink has been used since the 5th century and is still in use as an indelible ink for writings and drawings. The fact, that this kind of ink is based on metallic particles leads to the assumption that modern X-Ray scanners could image the writings such that it can be differentiated from the paper mainly consisting of cellulose. Our work shows a method that is capable of imaging writings written with iron gall ink by using a modern X-Ray imaging system that is commonly used for medical applications. Even though the imaging system is not optimized for the given task, the writing can be identified. Furthermore, we present a method that is able to reconstruct the volume even if the phantom is not centered properly or misaligned. Applying this method makes it possible to image books, writings or drawings based on all metal-containing inks without page-turning or unrolling the paper.**

***Keywords*-X-Ray imaging; Iron gall ink reconstruction; Historical Document Analysis**

Disclaimer: The concepts and information presented in this paper are based on research and are not commercially available.

I. Introduction

The method for digitization of books mainly consists of two steps, which are the page-turning and the photography step. But when inspecting historical documents, using this process is not possible in all cases without damaging them by page-turning or opening them due to the process of aging or an existing damage. The common digitization approach is not applicable for such writings and drawings and also analyzing them just with the human eye is impossible without damaging the paper.

The paper used for books and drawings, which is printed with ink, mainly consists of cellulose. A widely used ink since the third century before Christ is iron gall ink. It has been used to write down the 'Declaration of Independence' by Thomas Jefferson, Goethe used it for writing 'Faust', Mozart used it to record 'The Magic Flute' and Rembrandt's sketches were painted with it [1][2]. There are many historical recipes to produce iron gall ink [3], but all of them are based on the same ingredients – iron salt, tannic acid and gum arabic. The ink is still in use as an indelible ink [4].

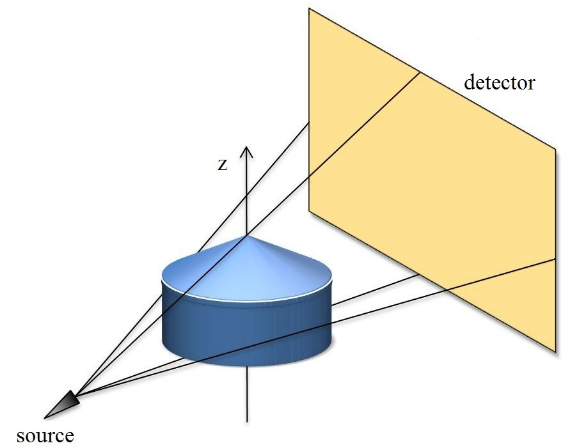


Figure 1. Cone beam geometry

One can remove the ink from the paper with simple methods, but particles that penetrated deeper layers of the paper will still be present. This allows to reconstruct even erased parts of a writing. The fact that the ink has metallic particles leads to the presumption that X-Ray radiation should be able to image those particles such that the ink can be differentiated from the paper through higher absorption of the metal compared to cellulose.

Until now, very few methods exist for imaging and reconstructing such problems. Mocella et al. [5] used X-Ray phase contrast imaging to recover writings on papyri rolls from Herculaneum. Deckers and Glaser [6] used the same technique to reveal even erased or overwritten writings on palimpsests. The downside of the phase contrast method is that it is highly complex, expensive, and not feasible for everyday applications. To the best of our knowledge, we are the first to use state-of-the-art X-Ray systems, such as they are used for medical imaging or material testing, for the reconstruction of document images. The work consists of simulations as well as real data reconstructions with a robotic multi-axis C-arm system [7]. One challenge in imaging several pages is that it is impossible to flatten and align them perfectly. This work will show a method to fix this problem by using a flattening algorithm.

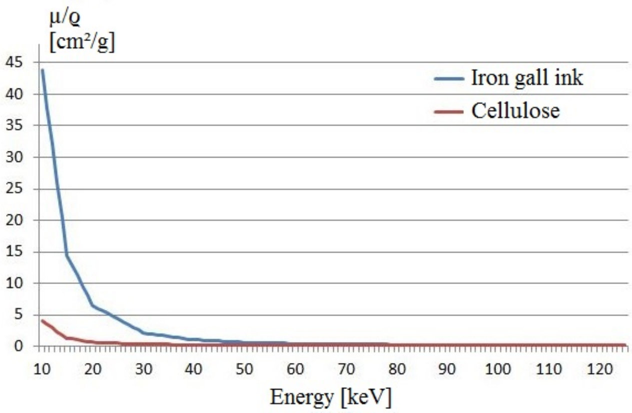


Figure 2. Spectral absorption plot for iron gall ink and cellulose showing the mass absorption coefficient for increasing energy.

II. Materials and Methods

A. Simulations

All shown simulations of this work were made by using the CONRAD framework [8] built for cone beam imaging in radiology [9] which is the commonly used C-arm CT geometry for 3-D imaging named by the cone shaped coverage area around the rotation center as shown in Fig. 1. The clue about the proposed method is that the rotation plane is placed in the plane of the pages such that the axis of rotation is orthogonal to the book's front cover. As medical X-Ray sources have a polychromatic X-Ray spectrum, a polychromatic absorption book model has been built assuming that generated photons from the X-Ray source have multiple photon energies with a defined maximum appearing energy U_a in [keV].

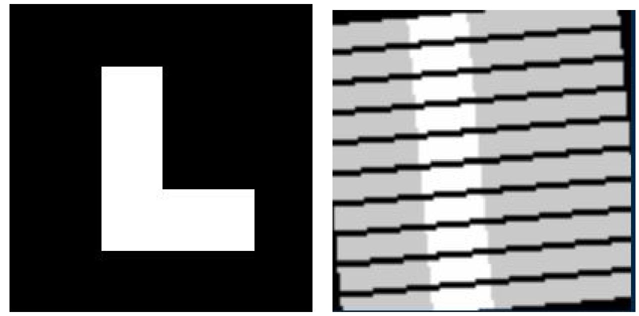
Our simulation model consists of three different materials:

1) Pages were expected to consist of only cellulose with the chemical formula $C_6\,H_{10}\,O_5$ and a specific density ϱ of $1.5\,\mathrm{g}\cdot\mathrm{cm}^{-3}$. This density value is derived by solving Eq. (1) where s is the strength or thickness of the used paper in cm and g denotes the grammage of the paper in $\mathrm{g}\cdot\mathrm{cm}^{-2}$.

$$\varrho = \frac{g}{s} = \frac{0.018}{0.012}\frac{\mathrm{g}}{\mathrm{cm}^3} = 1.5\frac{\mathrm{g}}{\mathrm{cm}^3} \tag{1}$$

2) Iron gall ink is assumed to be iron(II) sulfate heptahydrate ($FE\,SO_4 \cdot 7\,H_2\,O$) with a density ϱ of $1.89\,\mathrm{g}\cdot\mathrm{cm}^{-3}$. The tannic acid and the gum arabic components are not considered in the simulation.
3) Gaps between pages are assumed to be air with a specific density of $0.0012\,\mathrm{g}\cdot\mathrm{cm}^{-3}$.

The spectral absorption plots for iron gall ink and cellulose can be seen in Fig. 2. The mass absorption coefficient on the y-axis is derived by the quotient of the absorption coefficent μ and the density ϱ and describes how easy a material can be penetrated by the X-Ray beam depending on the beams energy in keV. One can see that the mass absorption coefficient for iron gall ink using the mentioned chemical formula is about nine times higher than the paper's mass absorption coefficient for an energy of $10\,\mathrm{keV}$. With increasing energies the ink's mass absorption coefficient approaches the papers'.



(a) Simulation phantom (b) xz-layer of rotated phantom

Figure 3. Central slices of the polychromatic book phantoms used for the simulations

The model for the simulations, which was rendered on the GPU [10], consists of 10 pages with a thickness of $1\,\mathrm{mm}$ and an air gap of $0.3\,\mathrm{mm}$. It is assumed that the paper is fully saturated by ink at the spots where the letters are written at. An "L"-shaped object representing a single letter with the length of $6\,\mathrm{mm}$ and a font thickness of $2\,\mathrm{mm}$ was set. Fig. 3(a) shows the model. As it is hard to perfectly flatten and align the pages in real world applications, an additional model with a slight xz-axis rotation of $5\,^\circ$ was simulated, too, shown in Fig. 3(b).

The simulated system in the framework was configured based on the available X-Ray C-arm CT, a robotic multi-axis C-arm system. The system uses the Short Scan technique [11] to derive the minimal required image set for a reproducible 3-D reconstruction. Within a Short Scan, a $200\,^\circ$ circular trajectory is run and, simultaneously, 496 images are taken (approximately every $0.4\,^\circ$). The source-to-intensifier distance was set to $1200\,\mathrm{mm}$ and the source-to-object distance to $785\,\mathrm{mm}$. The projection size was set to 496 acquired with a polychromatic detector having a pixel size of $150\,\mu\mathrm{m}$. The reconstructions in the simulations were done by using the Feldkamp, David and Kress (FDK) algorithm [12] with a volume spacing of $0.2\,\mathrm{mm}$. The FDK algorithm mainly consists of three major steps where D denotes the focal length of the imaging system, t a detector row, u a detector pixel's coordinate and β the skew angle of the camera system:

1) The first step is to perform a cosine weighting by solving Eq. (2):

$$g_1(t,u,\beta) = g(t,u,\beta)\frac{D}{\sqrt{D^2+t^2+u^2}} \tag{2}$$

2) A ramp filter is applied for each detector row following Eq. (3) with $h(t)$ denoting the ramp function:

$$g_2(t,u,\beta) = g_1(t,u,\beta) * h(t) \tag{3}$$

3) The output is backprojected by solving Eq. (4) with U denoting a distance weighting:

$$f(r,\varphi,z) = \frac{1}{2}\int_0^{2\pi} \frac{1}{U^2} g_2(\hat{t},\hat{u},\beta)\,\mathrm{d}\beta \tag{4}$$

With the Short Scan trajectory having redundant rays in the outer sinogram areas, parker weighting [13] not simply cutting of one redundant ray but weighting them such that their sum equals ‘1’.

B. Real data reconstruction

For the real data reconstructions, letters were written on handmade paper and 10 pages fastened with a wooden holder. Fig. 4 shows the holder while a single page can be seen in Fig. 5. The used iron gall ink is made of oak gall, metallic salts, gum arabic and wood vinegar based on a medieval regulation. The holder was positioned in the X-Ray system’s isocenter while a 3-D Short Scan was performed. The ink was written on the pages two weeks before the scans where performed. For better visualization, a 3-D bilateral filter has been applied to the results [14]. This kind of filtering method is used to smooth noise and simultaneously preserve edges by averaging a preset neighborhood considering their photometric similarity.

C. Flattening algorithm

One major problem lies in flattening the pages such that they are completely smooth. It is also hard to completely center the phantom in the X-Ray systems isocenter. In order to counter this problem, an algorithm was designed capable of setting the right image information to the appropriate slice of the reconstruction volume V_R. Therefore, a manual segmentation in the xz-layer of the reconstructed volume has to be performed. The xz-layer was chosen because one can clearly identify a page and mark the paper (Fig. 6). After segmenting all slices of the reconstructed volume, the segmented volume is stored as segmentation mask V_M with the marked areas set to ‘1’, the unmarked area to ‘0’. The next step is multiplying the original reconstructed volume V_R with the mask volume V_M to extract the voxels of interest and crop the unnecessary ones. Finally, we iterate over the whole volume writing all voxels $v > 0$ into a 2-D image. If pixels at a certain position $(x,y)^T$ are greater than 0 in more than one slice, one can choose either the maximum or minimum value. For the following investigations, the minimum was chosen. The result of the algorithm is the flattened page without any deformation. This algorithm works for arbitrary deformations in every direction.

Figure 4. Wooden holder to flatten the pages

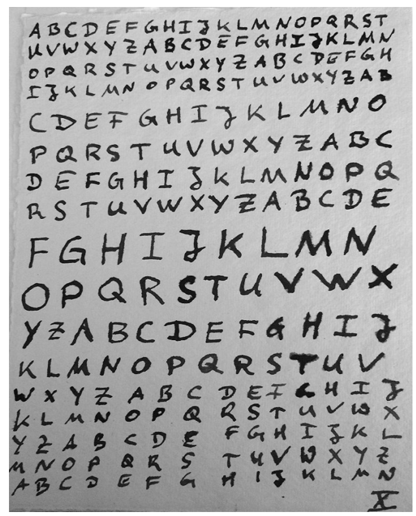


Figure 5. Example of a single page for the real data acquisitions

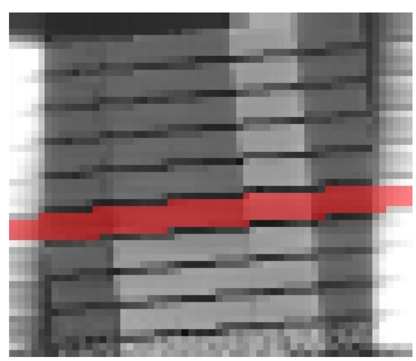


Figure 6. Manually segmented page (red area) of the phantom in the xz-layer

III. Results

A. Simulation results

The simulation results show that the ink can be clearly differentiated from the pages. Fig. 7(a) shows the central slice of the standard phantom without rotation which represents the fifth page. The letter written with the ink can be clearly differentiated from the paper due to the higher absorption of the metallic particles. Unfortunately, the density of the handmade paper is not that consistent.

Next, a small rotation was applied to the phantom to simulate un-smoothed pages. The result for this reconstruction is shown in Fig. 7(b). One can recognize the letter "L" even with some lack of information, but this assumption is only valid in the case for small rotations as the data loss increases with increasing rotation angles. Therefore the reconstruction output has to be fitted with the method from Section II-C.

Applying the algorithm to the fifth page of the reconstructed rotated volume shown in Fig. 7(b) leads to the image shown in Fig. 7(c) where one can clearly see the reconstructed letter "L". The loss of information is fully compensated by the presented algorithm. Although the height of the letter is only $6\,\mathrm{mm}$ with a thickness of $2\,mm$, the ink can be reconstructed well with low artifacts and noise. These results lead to the assumption that the reconstruction of the iron gall ink should work with real data on the given X-Ray C-arm CT.

B. Real data reconstruction results

The result for the real data reconstruction of page 4 is shown in Fig. 8(a)-(c). It can be seen that it is possible to differentiate the ink from the page. When looking at the X-Ray result in Fig. 8(b), the letter "B" can be identified by only using the human eye. While Fig. 8(a) shows the original letter written on the paper, Fig. 8(c) illustrates the overlap of both images. The small deformations of the letter are caused by imprecise positioning of the phantom. The height of the letter is about $15\,\mathrm{mm}$ while the line thickness is about $3\,\mathrm{mm}$. Other filter methods than the bilateral one may be used to improve the image quality further, and may also be used to detect the letter contours.

The result for the real data reconstruction of page three is shown in Fig. 8(d)-(f). The letters "J K L" can be identified by taking a closer look. The letter "L" is clearly while its neighbors "J" and "K" are only slightly visible. An overlap of the page (Fig. 8(e)) with the reconstructed page is shown in Fig. 8(f). The height of one letter is about $12\,\mathrm{mm}$ while the line thickness is about $3\,\mathrm{mm}$.

Comparing both results from Fig. 8 reveals that in the case of the letter "B", the ink has a higher intensity meanwhile for the row "J K L" the ink's intensity is lower than the paper's. When comparing the pages with each other at the significant spots, we notice that in case of the "B" the paper is fully saturated by the ink, while for the letters "J K L" the ink does not completely penetrate the paper.

Afterwards, the flattening algorithm is applied on the real data set's page 6. The page is segmented manually and the calculations are performed resulting in an improved visibility of the letter "M" shown in Fig. 9(a). The resulting 2-D image of the algorithm can be seen in Fig. 9(b) while Fig. 9(c) illustrates the overlap of the two images. The height of the letter is about $22\,\mathrm{mm}$ while the line thickness is about $4\,\mathrm{mm}$.

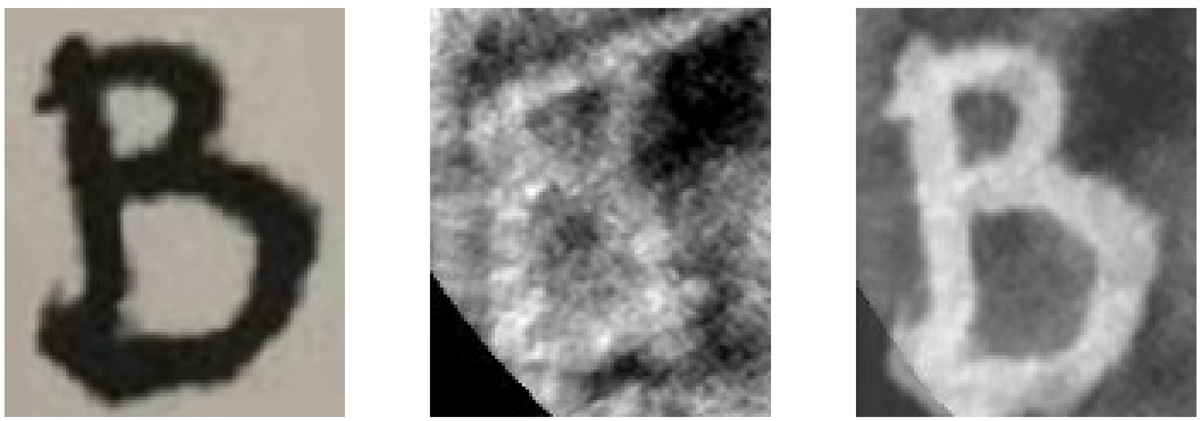
IV. Discussion

The results show that reconstructing iron gall ink is possible with the used X-Ray system, although the system has been developed and adjusted for medical imaging. We are able to reconstruct parts of the writings, however, there are still problems that have to be remedied:

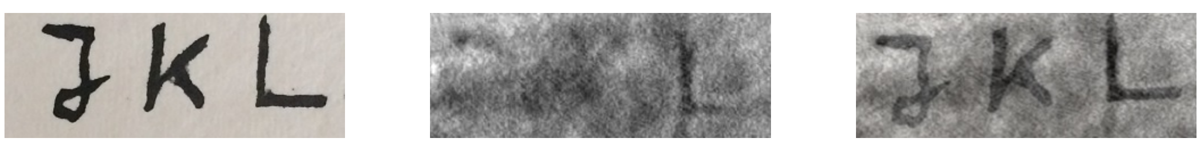
1) The system has to be adapted to the given problem: It was not possible to lower the acceleration voltage U_a such that finer structures could be imaged. For sure, the system specific image preprocessing influences the output result and the given filter methods on the system are limited such that there may be better fitting filters. Applying proper filters in the projection and the image space can help to preserve edges and smooth areas without information. Also iterative reconstruction approaches such as SART [15] or TV-based methods [16] may fit better to the given problem than the FDK reconstruction due to their better noise suppression and faster computation times.
2) A proper collimation could be applied such that only the phantom, the book, a single page or even just a small area of the page is irradiated and reconstructed. This could improve the resolution and computation times by only considering areas with important information.
3) The density of the ink can be lower than the paper's density (Fig. 8(e) and Fig. 9(b)): We assume this happens when the paper was not completely penetrated with ink at the investigated spots. Another reason could be that the iron gall ink was expected to be iron(II) sulfate heptahydrate only. In reality it has more components such as gum arabic or tannic acid. It could also be that the ink has not been completely dried, which also effects the atomic composition of iron gall ink as Viegas revealed in [17].
4) The pages are not flattened enough or misaligned: The presented algorithm gives good results but the segmentation is currently done manually. Further research is necessary to fit the pages such that the reconstruction output gets improved. It is hardly possible to improve the flattening by the wooden holder or its positioning more than presented. To counter this problem the segmentation could be done automatically which will save time and be more accurate.

(a) Standard phantom (b) Rotated phantom (c) Fitted page

Figure 7. Central slices of the simulation results for the 3-D book reconstruction where (a) shows the result for the standard phantom, (b) the rotated phantom and (c) the image of the fitted page smoothed by the flattening algorithm.

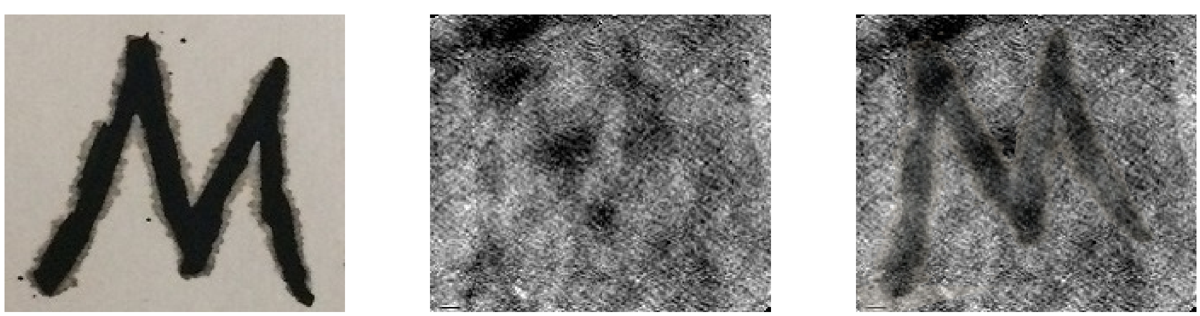


(a) Letter “B” on page 4 (b) X-Ray image of page 4 (c) Overlapping page 4 with X-Ray result



(d) Letters “J K L” on page 3 (e) X-Ray image of page 3 (f) Overlapping page 3 with X-Ray result

Figure 8. Real data reconstruction results by using a C-arm CT 3-D scan. (a)-(c) show the identified letter ’B’ of the fourth page and the overlap of the real and the X-Ray image. (d)-(g) show the identified letters “J K L” of the third page and the overlap of the real and the X-Ray image.



(a) Letter “M” on page 6 (b) X-Ray image of page 6 (c) Overlapping page 6 with X-Ray result

Figure 9. Real data reconstruction results by using a C-arm CT 3-D scan and the flattening algorithm for page 6 showing an “M”.

V. Conclusion and Outlook

The presented method shows that using common modern X-Ray systems, such as the used multi-axis robotic C-arm CT, is capable of reconstructing writings, without opening the book or page-turning but just performing a single common 3-D scan. To ensure good results, the used ink has to consist of metallic particles. Although it was not possible to perfectly flatten the pages by the holder and the adjustment options of the used X-Ray system where limited, we were able to reconstruct and identify parts of the writings. Changing the holder as well as fitting the reconstructed volume could enhance the reconstruction output. However, we showed that even under these circumstances the reconstruction worked for some parts of our real book. Our work is based on iron gall ink writings but we assume that all inks that are based on metallic particles show the same or even better behavior due to other used metals such as iodine, lead or zinc. There also exist many different manufacturing processes for the ink, such that other iron gall inks may absorb the X-Rays better than the used ink. Hence we conclude that using a common C-arm CT X-Ray system can be used to reconstruct writings and drawings written or painted with iron gall ink with much less effort than using X-Ray phase contrast approaches.

In future, we want to apply other filter methods, such as Laplacian or Hessian filters that could help improving edge detection compared to the used bilateral filter. We think this will increase the visibility of ink structures that can not be seen with the naked eye. Also detector pixel measurements should decrease further, such that imaging smaller areas will be improved, too. This would increase the resolution for the image acquisitions such that smaller and thinner letters can be reconstructed properly. Furthermore, we want to concentrate on an automatic segmentation of the pages to get rid of their undulating surface. Another goal lies in testing our methods with more kinds of inks having other ingredients such as iodine or lead and of course, scanning real historic documents. We think that our scanning method is highly promising and interesting for the digitization of historical documents and is a great basis for future research.

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