Reading closed historical manuscripts using dual-source dual-energy X-Ray tomography

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Abstract
In this paper, we employ dual-source dual-energy X-ray micro-tomography (DS/DECT) as a tool for historical handwritten documents reading. The aim to digitize historical documents with progressed degradation faces the question how to read the text and illuminations in manuscripts while preserving them in their original form. Using of standard optical methods may cause irreversible mechanical damage, such as tearing during opening and separation of individual sheets. X-ray computed tomography allows to get page-by-page information non-invasively, as the standard writing and drawing ink used in Europe from about the 5th century to the 19th century usually contained heavy elements (iron) and thus produce sufficient X-ray attenuation contrast. Results of a standard cone beam X-ray tomography are affected by (often very distinctive) structure of used paper. This structure reduces the contrast to such an extent that the places where less amount of the ink (thin lines) or the ink with a lower content of iron was used are masked by the paper structure and might be illegible. These problems can be successfully resolved utilizing the dual-energy computed tomography method typically used for the material decomposition of complex objects. Proposed methodology improves contrast of the written structures and illuminations, while paper structure is significantly suppressed in the images.

Keywords
X-Ray tomography, Dual-source CT, Dual-energy CT, Iron gall ink, Historical manuscript, Paper scroll

1 Introduction
Iron gall ink, also referred to as iron gallotannate ink, is one of the most important inks in the history of western civilization, and was in a widespread use from the middle ages until the 20th century. Unfortunately, iron ions and acids present in these inks induce enhanced degradation of paper, damaging thus severely numerous historical artefacts [1]. Requirements for digitization and deciphering of such documents lead to discovering of new ways of non-invasive imaging. Using X-ray computed tomography (CT) to obtain computer-extracted page-by-page information from sets of projection images could make the virtual reading of manuscripts possible. In most cases, iron in the gall inks produce image absorption contrast suitable for tomography reconstruction, allowing computer extraction of hand-written information [2]. A common problem using standard CT methods in this case is low contrast due to low absorption and distinctive paper structure. However, dual-energy CT (DECT) method, used often for material decomposition, can bear significantly better results. Moreover, employing the dual-source CT (DSCT) system for this task will not extend the time needed for data acquisition. The functionality of the method has been verified using patented modular TORATOM device (Twinned ORthogonal Adjustable TOMograph) in the Centre of Excellence Telč, Czech Republic.

2 Materials and methods

2.1 Specimen
In this paper, we employed dual-source dual-energy X-ray micro-tomography (DS/DECT) as a tool for reading of historical handwritten documents in form of a scroll. To verify the benefits of the DS/DECT measurement for image quality without the risk of damaging of any historical artefact, a specimen was created on purpose as a courtesy of National Archive of the Czech Republic. Three sheets of handmade paper manufactured in Velké Losiny, Czech Republic, were covered with letters using iron gall ink prepared according to [3] as a compound of 3.14 g of Arabic gum, 4.92 g of tannin, 4.20 g of iron sulphate (FeSO₄·7H₂O) and 0.1 l of destilled water. These sheets were enrolled into a scroll (see Figure 1) with 18 layers, the edge length of 210 mm and the diameter of 21 mm and investigated by the DS/DECT.
2.2 Dual energy CT inspection

The DECT method is based on the differences in X-ray attenuation at different photon energies. It is widely used especially in medicine, where the precise methodology for every organ and system is already embedded in commercial medical tomography systems. In other sectors, including the industrial CT, postprocessing techniques are complex, because attenuation differences vary depending on the material being imaged. It should be also mentioned that conventional X-ray tubes provide continuous energy spectra limited by zero from below (or the detection threshold of the detector used) and by the value of the used accelerating voltage from above. In other words, the radiation is not monochromatic. Moreover changes in the attenuation coefficient in the standard energy range provided by conventional X-ray tubes are usually rather small. However, for a sufficient separation of only two components, a relatively large simplification can be achieved.

Since different materials have different X-ray attenuation at different X-ray energies, the effective linear attenuation coefficient in each volume element of a CT image can be expressed as a linear combination of the attenuation coefficients of the basis materials multiplied by their volume fraction [4]:

\[ \mu_{LE} = f_1 \mu_{1LE} + f_2 \mu_{2LE} \]  \hspace{1cm} (1)

\[ \mu_{HE} = f_1 \mu_{1HE} + f_2 \mu_{2HE} \]  \hspace{1cm} (2)

Here \( f_1, f_2 \) are fractions made up by the first and the second material, respectively, \( \mu_{1LE} \) and \( \mu_{2LE} \) are the effective linear attenuation coefficients of the mixture at low and high energies. The linear attenuation coefficients for the two basis materials \( \mu_1 \) and \( \mu_2 \) at low and high energies can be figured out from the CT images containing the respective materials. In practice, CT numbers are often used, being in fact the scaled version of the effective linear attenuation coefficients. The CT numbers in this work (the abbreviation C will be used) represent the attenuation values obtained from tomographic reconstruction [5]:

\[ F_1 = C_{HE} - w_2 C_{LE} \]  \hspace{1cm} (3)

\[ F_2 = C_{LE} - w_1 C_{HE} \]  \hspace{1cm} (4)

Here \( F_1 \) and \( F_2 \) have the meaning of the scaled fraction of constituents 1 and 2, respectively. Weighting factors \( w_1, w_2 \) can be calculated utilizing local CT numbers \( C \), taken from the reconstructed volume in places where only one constituent is presented:

\[ w_1 = \frac{C_{HE}}{C_{LE}} \quad \text{and} \quad w_2 = \frac{C_{LE}}{C_{HE}} \]  \hspace{1cm} (5)

This basic DECT principle is based on the intensity weighting in both reconstructions to obtain equal value in the selected volume. This volume is defined in the region corresponding to the material component which should be suppressed (paper in our case). After weighting it is possible to subtract the datasets one from another according to (3) and (4). Presented results were obtained using dataset where material component to be extracted is more significant as a minuend and dataset where material component to be suppressed is more significant as a subtrahend. To prevent loss of information and significant noise propagation in the result due to rounding of integer values during calculations, we recommend utilization of wide dynamic range of values, e.g. double-precision floating-point number format (float64).

Proposed method is applicable also for 2D data treatment such as for radiograms or CT projections. In this case, preprocessing in the form of dark field/flat field correction is needed. For these purposes custom software for image processing was developed. It is able to work with different image file types enabling among others custom batch calculations with images (e.g. dark field and flat field correction or floating number format conversion and complete DECT calculation of whole datasets in one step). Matter of course is also an embedded image viewer with all visualisation utilities and image information needed.

2.3 Optimization of acquisition energy

The contrast in a radiographic image is influenced by settings of the exposition parameters. Since the attenuation coefficient \( \mu \) is dependent on the beam energy, the contrast in DECT can be influenced by the settings of the accelerating voltage of the X-ray tube. Applying the Lambert-Beer’s law of attenuation, the ratio \( I/I_0 \) between intensity \( I \) obtained behind the object and intensity \( I_0 \) obtained in the open beam (or the normalized intensity \( I_n \) behind an object of the thickness \( d \)) is given as

\[ \frac{I}{I_0} = I_n = e^{-\mu d} \]  \hspace{1cm} (6)

Figure 1: Test scroll of three sheets of handmade paper both side inscribed with letters using iron gall ink.
It has been shown in [6] that the maximum sensitivity of the intensity to a change in thickness in an X-ray image is reached for $\mu = 1/d_0$. Considering (6), it can be seen that the value of $I_n$ in $d_0$ for maximum sensitivity is $I_n = e^{-1} \approx 0.37$, or $I_n$ is at 37% of the intensity for zero thickness $(I_0)$. In practice, when using a standard flat-panel detector, the value $V_{det}$ of the detector pixel as a function of the thickness $d$ of a sample placed in between the X-ray source and the detector is given as

$$V_{det} = (V_0 - V_{DF})e^{-\mu d} + V_{DF}$$  \hspace{1cm} (7)

In (7) $V_0$ is the value detected in the pixel illuminated without the sample presence (open beam image) and $V_{DF}$ is the value detected in the pixel with no illumination applied (dark field image). To set the optimum accelerating voltage for reaching the best possible contrast for small changes in thickness, the optimum pixel values behind the object must be 0.37 of the range, being $V_0 - V_{DF}$. Similarly, the procedure is applicable for determination of the optimum accelerating voltage to get the best possible contrast for material of interest with lower X-ray attenuation (lower DECT energy). Higher DECT accelerating voltage is than optimized to get the best possible contrast for the material with higher X-ray attenuation. However, first the beam is “hardened” using filter placement at the X-ray tube. Filter should be made of a material without any attenuation edges in the used range of energy and in a thickness sufficient to limit (or better completely shield) photons of lower DECT energy. Finally, the current and/or acquisition time is regulated to avoid saturation of the detector and to obtain good statistics in sufficient wide range in the resulting image.

### 2.4 Instrumentation

CT imaging was carried out using advanced TORATOM device [7] patented at European level (EP 14002662.6, 2016) which is a part of the equipment of the Centre of Excellence Telč, Czech republic (see Figure 2). TORATOM consists of a modular assembly of two pairs of X-ray tube – detector in an orthogonal arrangement with an independent geometry setting, shared rotational stage and complex fully motorized 16-axis CNC positioning system that provides unprecedented measurement variability for highly-detailed tomographical measurements. This arrangement provides high modularity suitable for standard tomography, large area 2D scanning as well as simultaneous dual source and/or dual energy tomography and development of new methods of data acquisition. TORATOM is able to operate different types of detectors and its detector holders are designed for fast and easy detector change. It is possible to set the geometric magnification from approximately 1.2 to 100 for both lines (in special cases even more), and consequently, reach the spatial resolution of each voxel from approximately 200 µm under one micron depending on the detector used. Very high stable resolution is also possible thanks to the use of the antivibration table with an active air damping on which the whole assembly is placed and the use of a highly accurate rotational tomographic stage. Motorized rotational filter holders serve for X-ray spectra limitation and data acquisition for image correction (beam hardening effect artifacts elimination).

![Figure 2: TORATOM device (Twinned Orthogonal Adjustable TOMograph) in the Centre of Excellence Telč, Czech Republic.](image-url)

Dataset for low energy CT was obtained with microfocus reflection type X-ray tube (XWT-240-SE, X-Ray WorX, Germany) operating at the microfocus mode with the voltage of 40 kV, the target current of 1500 µA and the power of 60 W. Dataset for high energy CT was obtained with nanofocus transmission type X-ray tube (XWT-160-THCR, X-Ray WorX, Germany) operating at the high power mode with the voltage of 120 kV, the target current of 200 µA and the power of 24 W.
This tube was shielded by 0.6 mm of brass to separate the DECT irradiation spectra by limiting the low-energy photons up to 40 kV (low energy CT). Both datasets of 1200 projections with acquisition time of 1 s and the anglestep of 0.3° were acquired simultaneously. Imaging lines were equipped with GOS Flat panel detectors (XRD-1622-AP-14, Perkin Elmer, USA) with an active area of approximately 41x41 cm, pixel matrix 2048x2048 and a resolution of 200 µm per pixel operating at a capacity of 0.5 pF. The geometrical configuration of both pairs was adjusted to source-object distance of 250 mm and source-detector distance of 1000 mm resulting in projection magnification of 4 and resolution of 50 µm per pixel. Total time of the acquisition in this case was only 45 minutes ensuring a perfect overlap of datasets obtained with two independent orthogonal imaging lines running simultaneously. Reconstructed data were virtually unrolled into the form of the stack of 18 flat sheets and processed using a dual-energy algorithm, explained above. Projections pre-filtering was done using standard “dark field and flat field” correction.

3 Results

Obtained datasets were reconstructed into the 3D virtual models separately. For reconstruction, Filtered back projection (FBP) CT reconstruction module of VG Studio MAX 3.1 (Volume Graphics GmbH, Germany) was used. Custom Script in Matlab (MathWorks, USA) was designed for the purpose of data treatment equipped with functions for virtual scroll unrolling and DECT data fusion. From the presented results in Figure 3 and Figure 4, image quality improvement and enhance in the contrast of individual letters after dual energy processing is obvious. Results obtained at the energy of 40 kV provide sufficient image absorption contrast for letters; however, they are masked by distinctive paper structure and their reading is quite difficult. In the results obtained at the energy of 120 kV, representation of the paper structure overweights and letters are hardly recognized. Using the dual-energy algorithm visible structure of the paper has been filtered out and contrast of the written structures and illuminations was improved making letters clearly visible.

![Figure 3: Visualisation of the resulting 3D volumes (upper) and their lices (lower). At 40kVp letters are visible but there is distinctive paper structure disturbing. At 120 kVp there is low absorption contrast between the paper and the letters. After DECT letters are still clearly visible, but distinctive paper structure was highly suppressed.](image-url)
Figure 4: The photo of the inner specimen part with corresponding part of the tomography slice obtained after specimen unrolling with 40 kV, 120 kV and DECT. Whole words are clearly visible, partially disturbed by the “leaking” letters from the back side of the paper (double sided text).

### 4 Conclusion

It was proven that the proposed method using dual-source dual-energy X-ray micro-tomography is suitable for non-destructive reading of historical handwritten documents in form of the scroll assuming that iron gall ink (or another metal containing ink or pigment) was used. Method can significantly improve the imaging quality of letters written on a paper with distinctive structure, with no increase in time needed for data acquisition compared to a standard cone beam tomography, since the acquisition of datasets for both energies is running simultaneously. The method can be used in further research for virtual reading of the whole ancient books or scrolls while preserving them in their original form.

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### References


