Browsing through sealed historical documents: non-invasive imaging methods for document digitization

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Abstract: *Historical documents are witnesses of history that provide us with valuable information about former times. Many of these relics are too fragile to open them, such that innovative non-invasive imaging techniques can help to reveal hidden contents. In this work, we present our research on Computed Tomography, Phase-contrast and Terahertz imaging. We use image processing methods to visualize the digital data for the naked eye. Our use cases are mainly books, but also Asian bamboo scroll data is shown. As an outlook, our future research will focus on hybrid imaging approaches combined with intelligent image processing. Our research aim is to gain insights, and based on them, provide guidelines for specific documents. Therefore, the space of documents and modalities is presented. We try to utilize advantages and counter disadvantages of certain modalities. Finally, the future of this highly translational research is discussed and possible considerations for potential commercialization are presented.*

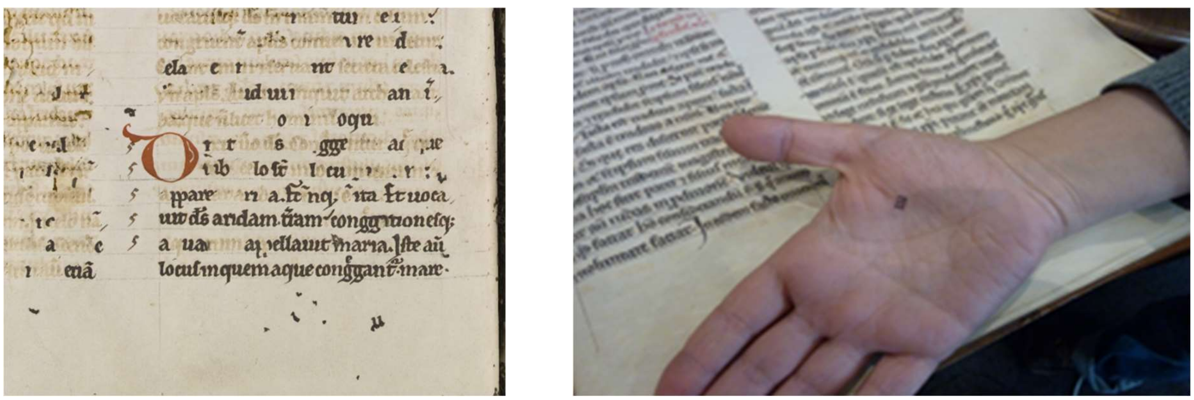
1. Introduction and Motivation

Historical documents are witnesses of history that provide us with valuable information about former times. In Germany alone, there are more than 7,770 libraries (as of 2016) with around 218 million visitors annually providing workplaces for around 200,000 people [1]. As a place of educational and cultural mediation, many of these libraries are currently interested in digitizing their existing collections. Innovative technologies are used to for digitization purposes, such as digitally searching for contents in the database.

Books and manuscripts that are in a good condition are partly digitized automatically by using scanning robots. Subsequently, document processing algorithms like OCR are applied to make information findable, assign drawings, or verify writers of books. External influences such as fires can cause massive damage to well-preserved collections at any time and put the documents in a condition that prohibits any contact. The fire at the

Herzogin Anna Amalia Bibliothek zu Weimar in 2004 serves as an example. The fire and firefighting efforts severely damaged about 62,000 volumes and left them in a very poor condition, and the majority of these documents had not yet been digitized before the accident [2]. Aging processes can also make it impossible to digitize books with scan robots [3]. A common case in libraries is that pages are stuck in the area of the book fold due to aging; instead of placing such a book into a scan robot, all pages would first have to be separated by experts in a time-consuming manual process.

Furthermore, it is possible that the individual written letters may become detached from the book page, as shown in Fig. 1. The manuscript from Saint-Omer (France) is currently at the Institut de Recherche et d'Histoire des Textes in Paris, France. This document was opened, and after it was observed that the letters were peeling off, it was immediately closed and not processed since then.



(a) (b)

Fig. 1: (a) Page of a historical manuscript currently stored in Paris. After opening, letters have peeled off leaving gaps in the text. (b) A peeled off letter "m". (Source: Institut de Recherche et d'Histoire des Textes, Paris, France).

Since such highly fragile documents can only be digitized by the scan robot method at enormous expense, if at all, research has been done in recent years to find a non-invasive, non-destructive document capture method that would result in a digital three-dimensional volume, allowing a view into the document without opening it manually.

Our research focuses on three well-known individual non-invasive imaging techniques for document digitization. Namely, we work on 3D X-ray Computed Tomography (CT), Phase-contrast Imaging, and 3D Terahertz Imaging. Each of these modalities have their advantages and downsides when acquiring digital representations of an object. Our goal is to combine the advantages and counter disadvantages of individual scans by using a hybrid scanning approach. With this, we want to leverage the optimal non-invasive digitization method for a given document, and finally, provide a scanning guideline for future research. The scan itself shall then be smartly combined and image processing algorithms will be used to make the sealed information virtually readable for the naked eye. The unique characteristic of our work is the fact that we are the first collaborative community that researches on a multi-modal approach and comparison for individual documents. Therefore, we also filed a patent [4,5]. Furthermore, we also look into damage that could arise from these techniques, e.g., by applying ionizing radiation. Until now, most work only focuses on a specific imaging technique, where there is no comparison to other approaches and no consideration of harming the documents. We also cover the full pipeline, from starting with detailed material analysis, over scanning to image pre- and post-processing. This article is based on experiments described in detail in further publications. The work on Book-CT has been published in [6]. The work on bamboo scrolls in [7]. Both experiments were extended and are described in [8]. This work gives a short review of these articles and extends them by describing our future vision.

2. Documents

Books

The research our group is conducting is mainly based on books. For our experiments, we use self-made books, as shown exemplary in Fig. 2(a). The pages are of handmade paper (Cellulose) and have a mean thickness of 150 µm. The book cover is made from buffalo leather. For writings, we used the following inks: Iron Gall ink ($FeSO_4$), Malachite ink (Cu), Tyrian Purple ink, Buckthorn ink, Indian ink. In this state of our research, we are working on proof-of-concepts with imaging modalities that are normally used for other purposes, such as material testing or medical imaging. Therefore, we have to vary the dimensions of the books for measuring, as the scanner trajectories can mostly just fit small sizes of samples.

(a) (b)

Fig. 2: (a) Exemplary self-made book consisting of 56 handmade paper pages, writings of different inks and a buffalo leather cover. The dimension of the book is approx. 17 cm × 13 cm × 3 cm (length × width × height). This book was used for the Computed Tomography experiments. (b) Bamboo scroll covered in potting soil. The scroll was completely soiled, rolled up, and put in a plastic bag for measurements with the imaging modality.

Bamboo Scrolls

In addition to books, we also conducted experiments with Asian documents. Bamboo scrolls were widely used before the invention of paper in China during the Han dynasty. In our example, 32 bamboo slips form a complete scroll, where the individual slips are bound together by strings. The slips have a size of 1.2 cm × 15 cm × 0.3 cm (length × width × depth). The wrapped-up scroll has an average diameter of 5.5 cm. Chinese characters and drawings are carved into the surface of the bamboo. The raw bamboo is composed of cellulose, hemicellulose, lignin, ash, and other extractives. Exemplary, we contaminated the scrolls with slightly wet potting soil, as shown in Fig. 2(b). The potting soil is a mix of cellulose and minerals. Here, the minerals have rather high densities where those of cellulose are rather low. To create the worst-case scenario, we pressed the soil onto the recto to fill the air gaps of the carvings. To prevent the scanner from contamination, we put the scrolls into plastic bags that were filled with potting soil and measured the bags with CT.

3. Individual Imaging Techniques and Image Processing

Industrial Computed Tomography

Industrial CT has many applications in the field of non-destructive testing. It is one of the few technologies that allows visualizing the internal and external structures of a component as a holistic measurement. In this imaging technique, X-rays pass through an object from different angles and are attenuated by the object. This attenuation depends, among other factors, on the object density and the transmission length within the object. The X-ray intensity attenuation can then be detected and converted into image data [9].

Since historical documents were often written using metallic inks, which differ in attenuation from paper pages, the written letters can be visualized by scanning a document using a CT system (c.f. Fig. 3**Fehler! Verweisquelle konnte nicht gefunden werden.**). It has already been shown that this technology provides good results for digitalizing ancient books or damaged historical scrolls [10,11]. This is particularly advantageous when historical documents are fragile, and it is no longer possible to open or unroll them without introducing further damage. However, it is not yet possible to simply place any ancient book into the CT system and obtain a digital document of the book content. There are several issues that need to be considered, which is part of our current research.

An important aspect we are investigating is the influence of X-rays on scanned documents. Since CT measurements are based on the effect of ionizing radiation, it must also be considered, whether the X-rays can damage the historical documents during the CT scan. However, this is mainly dependent on the applied radiation energy and this can be reduced by adjusting the measurement settings and applying optimized evaluation algorithms [12].

In addition to scanning books, we also investigated digitization of Asian bamboo scrolls by means of CT. Fig. 4(a) shows the measurement setup, where the soiled scroll was placed on the turntable to acquire the images for the reconstruction. The 3D reconstructed soiled scrolls can be seen in Fig. 4(b), where the writings are visible by the naked eye.

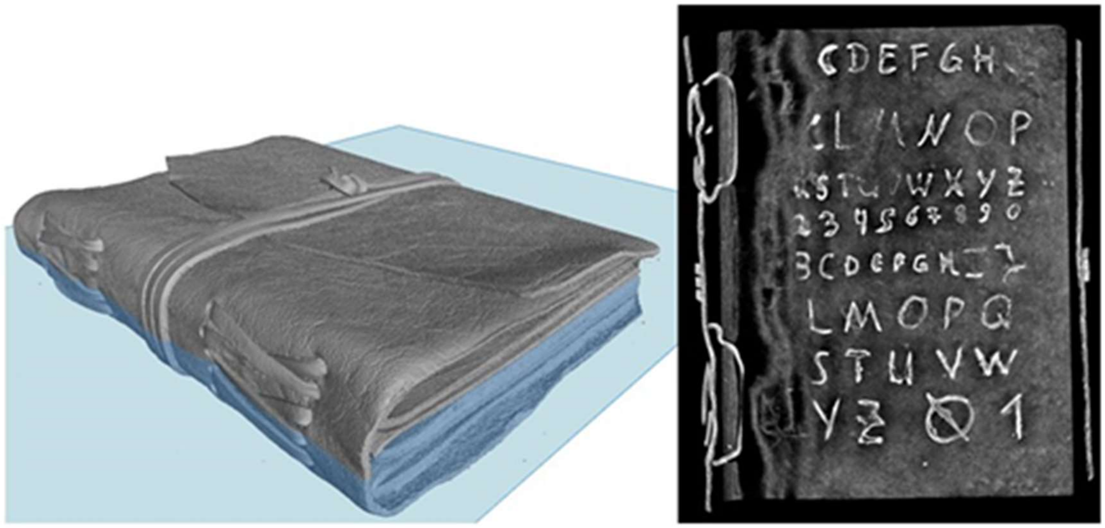
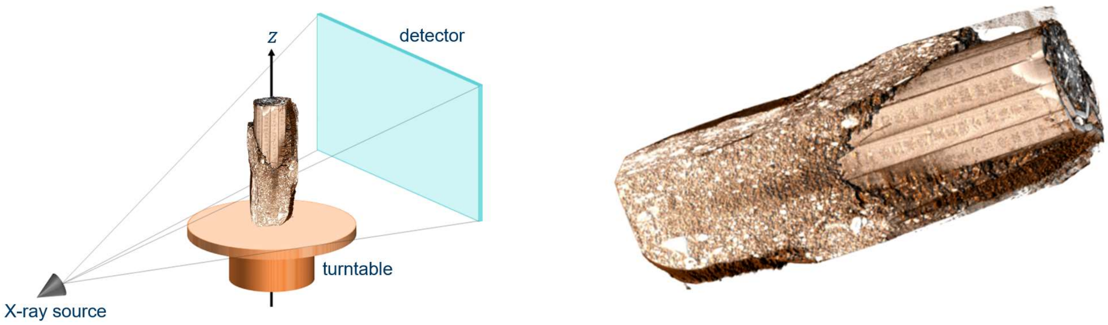


Fig. 3: Visualization of the CT reconstructed volume data of a scanned book, shown in Fig. 2(a). The left image shows the rendered, digital volume. The right image shows a slice through the volume data (blue layer of left image). The letters written with iron gall ink are clearly visible.

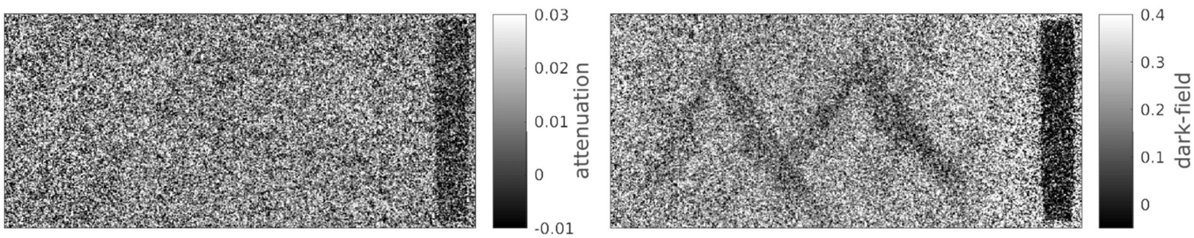


(a) (b)

Fig. 4: (a) The soiled bamboo scroll is positioned on the turntable of the CT scanner for acquiring the images. (b) The reconstructed soiled scroll, rendered for improved visualization. The writings can be seen by the naked eye where the scroll was not covered by soil.

Phase-contrast Imaging

X-ray phase-contrast imaging is an imaging technique which leads to information about both, the object's attenuation and the object's refractive properties [15]. For this purpose, microstructured gratings are placed into the X-ray beam path and build a Talbot-(Lau) interferometer [16,17]. In common X-ray imaging, the attenuation coefficient μ comprises the image information. By X-ray phase-contrast imaging also the phase shift is accessible. X-ray phase-contrast imaging takes advantage of the so-called Talbot effect. The grating behind the object imprints a phase-shift on the incoming X-ray wave. In certain distances behind the grating, self-images of the grating pattern occur. In such a so-called Talbot pattern, local changes in the X-ray wave front caused by the object are encoded. Besides the known attenuation image, additionally the differential phase and the dark-field image are extracted by analyzing the obtained Talbot pattern. The differential phase image is based on the deflection of X-rays passing a sample. For light elements of similar density, the contrast in a differential phase image is enhanced compared to the common attenuation image [16,18]. This could be an advantage for the investigation of certain combinations of ink and paper types. X-ray phase-contrast imaging already showed its potential with impressing results about the digitalization of carbonized Herculaneum papyrus rolls in Mocella *et al*. and Bukreeva *et al.* [19,20]. In both cases, monochromatic radiation from a synchrotron beamline was used. The dark-field image enables a visualization of scattering structures which are smaller than the resolution of the detection system [21]. Because of the fibrous structure of the paper, there are two structural effects caused by writing: The ink soaks into the paper and the texture of the paper changes by the pressure of the writing tool. Hence, also without any ink remains, it is possible to reveal written symbols by the X-ray dark-field image (Fig. 5). Since the attenuation properties are hardly changed, the respective image does not show the letters. Furthermore, the dark-field image should lead to advantages if the ink contains granular particles. The results were obtained with a laboratory X-ray source using a 30 kVp spectrum and a flat-panel detector of pixel pitch 49.5 μm.



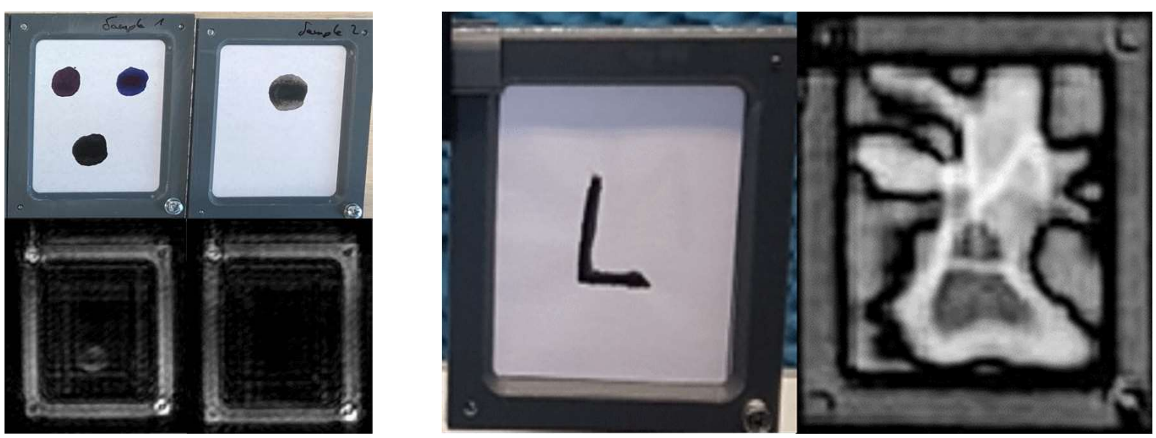
(a) (b)

Fig. 5: Attenuation image (left) and dark-field image (right) of a letter 'M' written without ink. The pressure of the writing tool on the paper leads to a changed texture of the paper which is visible in the dark-field image, but not in the attenuation image

Since X-ray imaging is based on ionizing radiation, which is suspected to cause faster aging of cellulose [22], investigations regarding the applied dose are performed within the project, too. The as-low-as-reasonably-achievable (ALARA) principle is known from the medical field, which aims to obtain all relevant information at the lowest possible dose. To protect the ancient and precious books, an evaluation of the dose is obligatory. Thus, simulation studies are done, where a block of cellulose is placed and irradiated with photons. A deposition spectrum is to be determined within a small volume within the block. In combination with real measurements, the aim is to gain a measure of the deposited dose and its respective damage in paper in dependence of arbitrary settings of the X-ray tube and resulting spectra.

Terahertz Imaging

Radar imaging is a very well-known approach to use electromagnetic (em-) waves for imaging applications. Satellite based or airborne radar have been and are still used for earth observation or environmental investigations due to the very good propagation conditions in various frequency band with the microwave region and the scattering behavior of the earth surface at these frequencies. In contrast to these remote sensing applications, nowadays short range or near field imaging radars in the millimeter wave frequency range (especially around 80 GHz) are used for security scanners and non-destructive testing. The higher frequency allows imaging with resolutions at mm scales and qualifies this technology for finding thread objects at security checks or voids and defects in materials or products. Imaging and artificial reading of historical documents is not feasible, as the imaging quality is not good enough for highly detailed objects like printed or handwritten documents. Increasing the radar frequency to the THz frequency range (~100 GHz – 10 THz) can overcome the resolution problem and remain the positive propagation conditions as electromagnetic waves in this frequency range are still able to penetrate a large variety of non-conductive (i.e., dielectric) materials among them paper and papyrus. The ability to penetrate a stack of papers is one prerequisite to analyze the written content of a documents without the need to unfold it. The second important aspect is that the ink has to deliver a decent imaging contrast compared to the page material weather by high absorption, high reflectivity of em-waves or by a high enough difference of its index of refraction or complex permittivity respectively. The qualification of THz imaging for the analysis of documents and painting has already been proven [23,24], but not for handwritten documents with ink. The current work described here addresses the question on how suitable the THz frequency range is for this task and what imaging approach (transmission, reflection imaging, SAR-based radar tomography) delivers the most information of the document and may be combined with AI character recognition. In a first experiment different water-based iron gall writing inks (Rohrer & Klingner, black ink 40710 & blue 40711), a resin-based drawing ink (Rohrer & Klingner, black ink 29770) and a generic china ink (black) were analyzed with a commercial imaging system (Rohde & Schwarz QAR) at a frequency around 80 GHz in a reflection setup.



(a) (b)

Fig. 6: (a) Photograph of two sample holders (top row) and radar image (bottom row). (b) Photograph of paper with two letters and corresponding radar image.

In Fig. 6(a), photographs of two sample holders (top row) with the following ink samples are shown: left sample with three inks (iron gall black (top left), iron gall blue (top right) and resin-based black ink (bottom)), right sample with a Chinese inkstone circle (diameter of samples approx. 15 mm). In the radar images below, only the resin-based ink shows a contrast. To evaluate improvements in the imaging quality when using higher frequencies, a sample with two handwritten letters (resin-based black ink) on a single page has been measured in a 220 – 325 GHz lab imaging system [25]. Fig. 6(b) shows a photograph of a paper with two handwritten letters (Letter “L” on recto and “N” on verso). In the radar image both letters can be identified but the image also shows artifacts resulting from undulations of the paper. These preliminary results show that THz imaging of documents is potentially able to artificially read ink handwritings without the need to necessarily have physical or visual access to the specimen. The next steps are experiments with a THz TDS system. The bandwidth of such a system is usually in a region in which the range resolution is sufficiently high to separate single pages in the volume of interest. Advanced signal processing approaches like time domain reflectometry and SAR-base image reconstruction will be implemented and figures of merit will be derived to support the creation of a scanning guideline for future research.

Image Processing

In addition to the imaging methods, the digital data provided by the modalities have to be processed adequately. Details on the image processing algorithms can be found in [7]. Fig. 7 (a,c) shows photographs of sample pages from the books with different metallic inks. Fig. 7 (b,d) show the same page, digitized by CT imaging of the closed book after applying the developed image processing prototype. The pages have been virtually flattened such that the writings are made visible without opening the book manually. The metal particles of the ink generate a contrast that makes it possible to distinguish ink from the cellulose-based pages.

(a) (b) (c) (d)

Fig. 7: (a) Original page of a sample book with writings of Malachite ink. (b) 3D CT reconstructed and image processed page. (c) Original page of a sample book with writings of Iron Gall ink. (d) 3D CT reconstructed and image processed page. The images have been extracted by an algorithm and the writings are clearly visible and readable.

For the bamboo scrolls, we developed a different processing pipeline. First, the scanned scroll is getting virtually cleaned from the soil and then unwrapped by a second algorithm. Finally, the unwrapped bamboo elements get sampled at the dense surface such that the carvings are made readable. The results are shown in Fig. 8, where the carvings are made digitally visible for the naked eye.

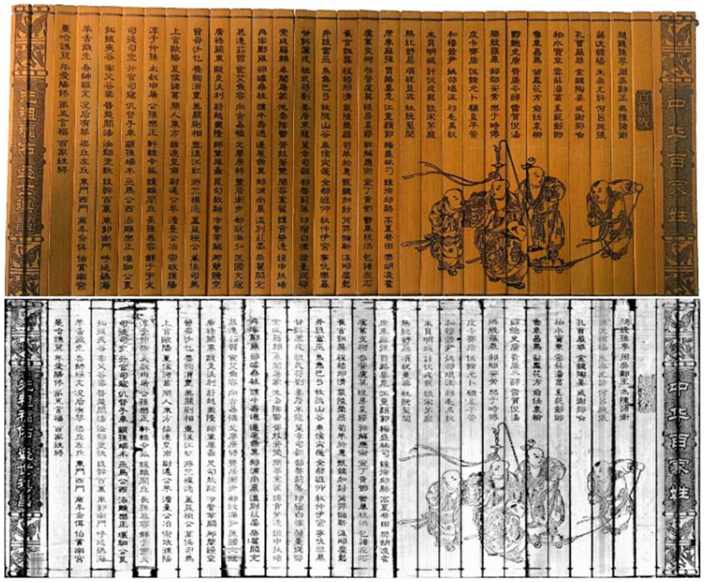


Fig. 8: (Top) Photograph of unwrapped scroll. (Bottom) Virtually cleaned and unwrapped scroll. The carvings are made readable by erasing the soil from the volume and unwrapping the bamboo elements.

4. Hybrid Imaging

Until now, most investigations are performed by using a single modality for a certain document. To the best of our knowledge, there are no publications on hybrid/multi-modality non-invasive imaging experiments performed on the same document so far. Our research focuses on combining the advantages of the presented imaging techniques to counter their disadvantages, and ultimately, use image processing methods such as registration or segmentation to provide a visual output of the digitally acquired data.

Therefore, we developed a sketch, shown in Fig. 9, demonstrating the space of document digitization and the attributes that play important roles for the success of the methods.

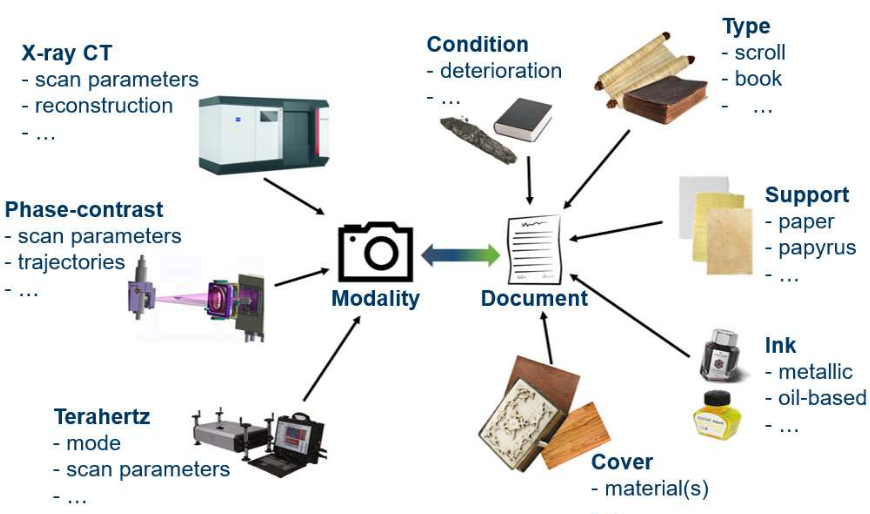


Fig. 9: The space of digitizing documents can be divided into two main fields. The document itself has different types of attributes such as condition, type, cover, ink, etc. On the other hand, different modalities exist such as CT, Terahertz or Phase-contrast.

In our project, we are working on guidelines that provide information on measurement techniques with certain documents. The (open source) document database shall grow by time, as well as the modality and measurement parameter information. The outcome of our research will be a standard operating procedure (SOP) cookbook for a given document, delivering automatically measurement parameters and other considerations that have to be taken into account.

5. Discussion and Outlook

For the research we conduct, the problem space is manifold. The project is highly translational as there is a need for lots of expertise of very different fields such as humanities, electrical engineering, material science, physics, chemistry or computer science. Only with collaboration between these fields, valid outcomes will be generated.

Next, most documents that are hardly digitizable are unique and have very specific conditions. Creating scalable solutions for digitization ending up in concrete business models is a very challenging task, as also the scanners are normally made for imaging at certain labs in closed environments. In contrast, carrying the fragile documents to measurement center is sometimes not feasible as insurance and transportation costs will be very high. Therefore, when thinking of commercializing the techniques we present, one would have to identify valid use cases that justify sustainable business in terms of monetization. Also, interdisciplinary research and development will be key.

If in the future, more and more research in this relatively new field would be conducted and methods evolve, there will be seen parallels to the medical field when it comes to leveraging AI methods for gaining insights into the digital data. Learning from that field when it comes to data privacy regulations or ethics can be leveraged and extended to this use case for future products and business models. When it comes to artificial intelligence, federated learning would be a great principle to gain deeper insights into the data to build connections and train machine learning algorithms.

6. Conclusion

In this article, we present our current research on using different non-invasive imaging modalities such as CT, Phase-contrast and 3D Terahertz for gaining visible insights into closed documents. To reveal the hidden content, we use image processing algorithms subsequently to the image acquisition. In future, we aim to combine these methods to utilize the advantages of the different techniques and provide guidelines for digitization.

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