Ground truth model, tool, and dataset for layout analysis of historical documents

Article *in* Proceedings of SPIE - The International Society for Optical Engineering · February 2015

DOI: 10.1117/12.2075858

6 authors, including:

Kai Chen
Université de Fribourg

Mathias Seuret
Université de Fribourg

Hao Wei

Marcus Liwicki
Université de Fribourg

Ground Truth Model, Tool, and Dataset for Layout Analysis of Historical Documents

Kai Chen[a], Mathias Seuret[a], Hao Wei[a], Marcus Liwicki[a], Jean Hennebert[ab], and Rolf Ingold[a]

[a]Department of Informatics, University of Fribourg, Bd. de Pérolles 90, Switzerland;
[b]University of Applied Sciences, HES-SO//FR, Bd. de Pérolles 80, 1705 Fribourg, Switzerland

ABSTRACT

In this paper, we propose a new dataset and a ground-truthing methodology for layout analysis of historical documents with complex layouts. The dataset is based on a generic model for ground-truth presentation of the complex layout structure of historical documents. For the purpose of extracting uniformly the document contents, our model defines five types of regions of interest: *page*, *text block*, *text line*, *decoration*, and *comment*. Unconstrained polygons are used to outline the regions. A performance metric is proposed in order to evaluate various page segmentation methods based on this model. We have analysed four state-of-the-art ground-truthing tools: TRUVIZ, GEDI, WebGT, and Aletheia. From this analysis, we conceptualized and developed DIVADIA, a new tool that overcomes some of the drawbacks of these tools, targeting the simplicity and the efficiency of the layout ground truthing process on historical document images. With DIVADIA, we have created a new public dataset. This dataset contains 120 pages from three historical document image collections of different styles and is made freely available to the scientific community for historical document layout analysis research.

Keywords: ground-truth model, layout analysis, ground truthing, dataset, historical document

1. INTRODUCTION

Layout analysis is a prerequisite step in the pipeline of document image analysis and understanding. It aims at splitting a page image into regions of interest and distinguishing text blocks from other regions. Due to the complex layout, degradation of the page, and different writing styles, layout analysis on historical documents is a challenging task. In order to develop machine learning based approaches and compare the performance of different page segmentation methods, ground truth is needed. Therefore, ground truthing is considered as a crucial part for the whole layout analysis process.

Some layout analysis methods of historical documents were published in the document image analysis community. However, each of these methods was evaluated on a specific dataset. The ground truth is rarely publicly available. Some datasets do not have ground-truth information. Panichkriangkrai et al.[1] proposed a text line segmentation and character extraction system of Japanese historical woodblock printed books. The ground truth of that dataset is not mentioned in that paper. Cohen et al.[2] presented a method which segmented historical document images into text and non-text elements, then the non-text elements were segmented into drawings, background, and noise. This method was evaluated on the manuscripts from the Islamic Heritage Project[*]. The ground truth was generated by using PixLabeler[3] and is available upon request from the corresponding authors. Their pixel level ground truth do not provide detailed layout information, e.g., the ground truth should indicate not only which parts on the documents are text but also which foreground pixels belong to the same text line. Mehri et al.[4] reported historical document image segmentation with different texture features. The evaluation is made on 25 simplified historical document images. The ground truth is not presented in that paper. Bulacu et al.[5] proposed a line separation method of handwritten historical documents from the archive of the cabinet of the Dutch Queen - Kabinet der Koningin (KdK)[†]. Because they did not have ground-truth information, their method was evaluated by manually checking the results and counting the errors.

Further author information: (Send correspondence to Kai Chen)
Kai Chen: E-mail: kai.chen@unifr.ch, Telephone: 0041 26 300 84 73

[*]http://ocp.hul.harvard.edu/ihp/

[†]NL-HaNA, 2.02.14, Archief van het Kabinet der Koningin, Den Haag(Netherlands), year 1902

There exist several datasets for historical document image analysis. GERMANA[‡] consists of the Spanish manuscripts written in 1891 by one author. The text lines were manually marked and transcribed by palaeography experts. The manuscript includes many notes and appended documents that were written in languages different from Spanish, namely Catalan, French and Latin. The dataset is available for handwriting recognition research. As announced by the authors, the original manuscript was well-preserved and most pages only contain nearly calligraphed text written on ruled sheets of well-separated lines, therefore text line extraction is not very difficult. RODRIGO[§] is a handwritten text dataset which consists of the manuscripts from 1545 from the Spanish Ministerio de Cultura. The manuscript is much older than that of GERMANA. Similar to those of GERMANA, most pages in RODRIGO only contain a single text block of calligraphed handwriting on well-separated lines. Therefore, text block and text line extraction is not a particularly difficult task. A contemporary dataset was presented in the Historical Document Layout Analysis competition of ICDAR 2011.[6] The dataset consists of gray scale image of machine-printed documents from books, newspapers, journals, and legal documents. To the best of our knowledge, there is no ground truth for historical document images with complex layouts which is publicly available for layout analysis research. Consequently, there is a significant need for ground truthing of historical document images for layout analysis. Our main goal is to provide not only a realistic ground truth dataset but also a flexible ground-truthing methodology for historical document layout analysis.

1.1 Model

A model is considered as a key prerequisite for ground truthing. It is used to store the ground-truth information. Baechler et al.[7] proposed a model to represent the layout ground truth for medieval manuscripts. Based on this work, we propose a new layout model for historical document images. We use unconstrained polygons to draw regions[¶]. Region types are extended in order to represent more detailed layout information. Due to the restriction of using isothetic polygons, a specific XML format was defined by Baechler et al.[7] However, this XML format is not easy to understand. Moreover, the source code for reading and writing ground truth to that XML format file is not publicly available. It is not easy to implement these functions due to the complexity of that XML format. Therefore, we decide to use the PAGE format[8] which is a comprehensive XML representation for document layout structure and has been widely used in the document image analysis community. The source code for reading and writing our model to the PAGE format file is available at `https://diuf.unifr.ch/main/hisdoc/divadia`.

1.2 Tool

Several ground-truthing tools for document images have been proposed in the literature: TRUEVIZ,[9] GEDI,[10] WebGT,[11] and Aletheia.[12] These tools have been developed according to some labeling tasks, eventually targeting the genericity. However, these tools present some drawbacks for layout ground truthing of historical documents. From the analysis of these tools, we developed DIVADIA, the DIVA (Document, Image, and Voice Analysis) research group[‖] ground-truthing tool for historical Document Image Analysis. This tool overcomes some of the drawbacks of the state of the art. It aims at providing a simple and efficient user interface for the ground truthing of layout analysis of historical documents. The effectiveness and flexibility of this tool have been proven by performing a layout ground-truthing task. The task included an annotation of 120 pages from three different historical manuscript image datasets by three users.

1.3 Dataset

In contrast to existing datasets, our dataset provides comprehensive and accurate ground truth representation of the layout structure for historical documents with complex layouts. The dataset currently consists of 120 images from three historical manuscript collections of diverse nature. Notably, 61, 39, and 20 manuscripts were

---

[‡]`https://www.prhlt.upv.es/page/projects/multimodal/idoc/germana`

[§]`https://www.prhlt.upv.es/page/projects/multimodal/idoc/rodrigo`

[¶]In the previous work, regarding the simplicity of comparison of the ground truth with the segmentation results, isothetic polygons (i.e., an isothetic polygon is composed by vertical and horizontal segments.) were used to represent regions. However, it is inefficient to use isothetic polygons to draw text regions on handwritten documents, where text regions are often not axis aligned and each word does not have a neat shape. Therefore, in this work, unconstrained polygons are used.

[‖]`http://diuf.unifr.ch/main/diva/`

calligraphed in the $9th$, $13th$, and $18th$ century respectively; the typically difficult characteristics of historical documents are evident. Some of the documents are richly decorated with drop capitals and illustrations. The textual contents were written in three different languages with different styles. Some parts of the documents are degraded. Their layouts vary from standard multi columns to more complex structures. By using DIVADIA, the layout ground truth is generated based on our generic model. The dataset is available for scientific research at `https://diuf.unifr.ch/main/hisdoc/divadia`.

In summary, the main contributions of this work consist of: (1) conceptualization of historical document image layout model, (2) a graphical user interface tool for the layout ground truthing, (3) production of ground truth dataset. This paper is organized as follows. Section 2 presents the proposed model for the layout ground truthing and describes a performance metric for page segmentation methods based on this model. Section 3 describes our ground-truthing tool and compares it with the state of the art. Section 4 presents our dataset. Section 5 concludes this paper.

2. MODEL FOR LAYOUT GROUND TRUTH

Ground truth is not only used for the performance evaluation of different methods but also needed for the training phase for any supervised machine learning approaches. Our goal is to meet the requirements for meta-data storage as well as assessment of historical manuscripts layout analysis on page level. The proposed model is based on the previous work.[7] Polygons are used to draw different regions on the documents[**]. Compared with the previous work, the features of our new layout model are described below.

Instead of using isothetic polygons, we use unconstrained polygons to outline the regions, i.e., we remove the restriction that only vertical and horizontal lines could be used to outline the regions. Using isothetic polygons is a suitable solution for printed or non cursive handwritten documents. In those types of documents, the text blocks and the text lines are axis aligned and well-separated. Therefore, using isothetic polygons to outline the regions will not lose any information of the textual content. However, it is not well-suited for drawing text regions on handwritten documents, where text regions are often not axis aligned and each word does not have a neat shape. Therefore, users should be very careful to draw regions by using isothetic polygons in order not to lose any parts of the textual content. However, using unconstrained polygons can outline accurately regions of interest on handwritten documents and is more efficient than using iosthetic polygons. Figure 1 compares the previous ground truth with our new ground truth. The pages are chosen from the *George Washington*[††], *Saint Gall*[‡‡], and *Parzival*[13] datasets. It can be seen that using isothetic polygons is ineffective and imprecise to outline text lines, especially for the cursive handwritten documents, e.g., the *George Washington* dataset. Contrarily, using unconstrained polygons is easier and more efficient for drawing the regions. Furthermore, we observe that there are some errors in the previous ground truth, e.g., some parts of the text lines are not outlined by using isotethic polygons. Some examples of these errors are illustrated in Figure 1(a), 1(c), and 1(e).

In the previous work,[7] regions on the documents are composed by vertical and horizontal straight segments. The segments are stored according to a predefined XML format. One drawback of this approach is that the XML structure is complex and difficult to understand. Furthermore, there is no publicly available tool which could be used to manipulate the ground truth. Due to the complexity of that XML format, it is not trivial to write a program to read or write the ground truth based on that XML format file. In this work, we use the PAGE[8] format XML file to store the ground truth. PAGE is a widely-used document image representation framework. It has been used to represent ground truth of the datasets in the ICDAR Page Segmentation competition series and ICFHR 2014 Handwritten Text Recognition on the tranScriptorium Dataset competition[‡‡]. In the ground truth, each region on the document is represented by a polygon. For each document image, we store the coordinates

[**]In this work, we do not use the pixel labeling method for layout ground truthing. The pixel level ground truth can be used to separate different regions, e.g., the PixLabeler.[3] However, it is inefficient to present detailed layout ground truth. Because in order to store the layout information, for each pixel, we need several bits, e.g., the ground truth should not only indicate which pixels belong to the textual content, but also which pixels belong to the same text line. Furthermore, in historical documents, for each decoration, we need to know which text line it belongs to.

[††]`http://memory.loc.gov/ammem/gwhtml/gwseries2.html`

[‡‡]`http://www.e-codices.unifr.ch`

[‡‡]`http://www.transcriptorium.eu/~htrcontest/`

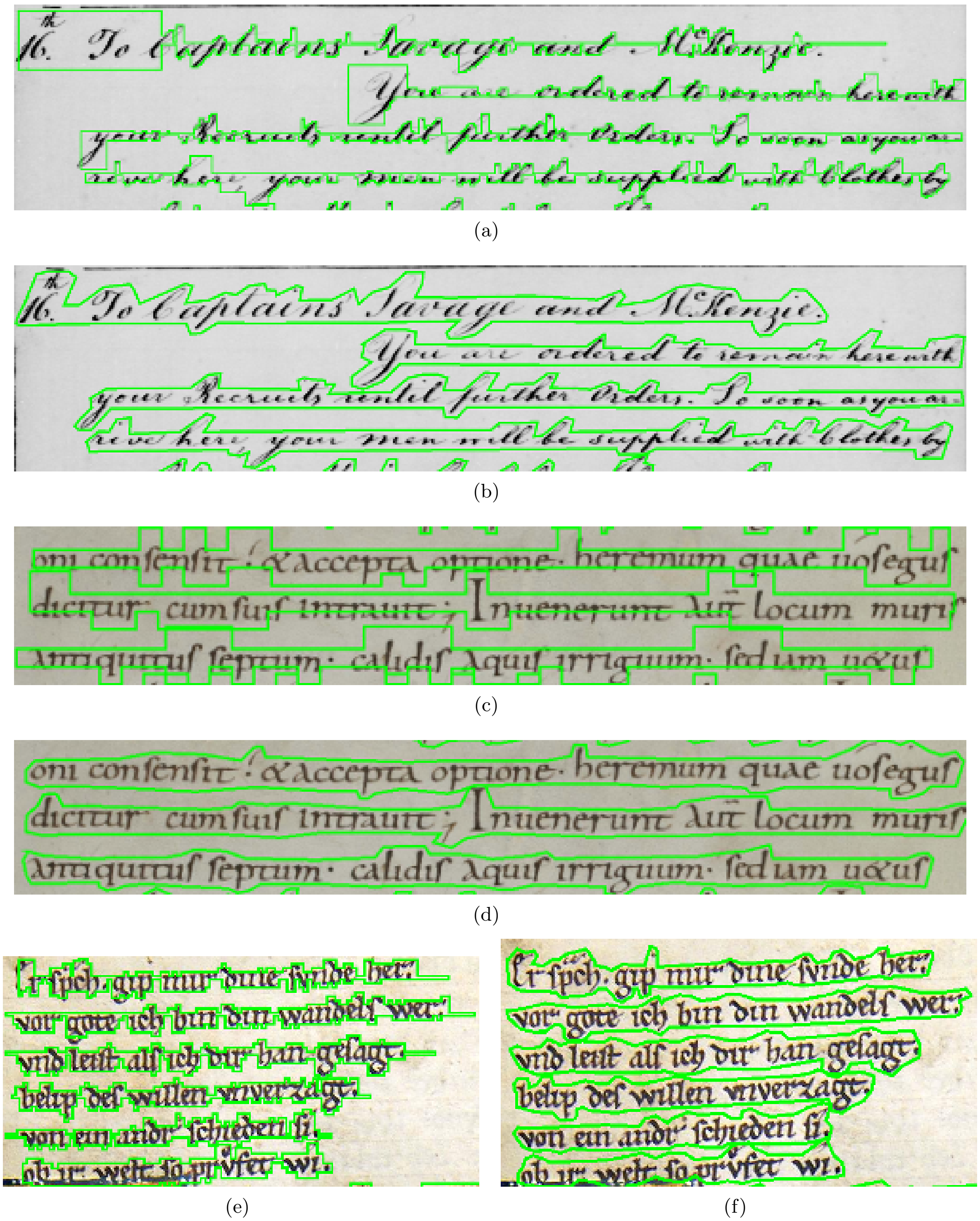


Figure 1. Text line ground truth examples. Text lines are outlined with polygons in green. The previous ground truth 1(a), 1(c), and 1(e) from the *George Washington*, *Saint Gall*, and *Parzival* datasets respectively are generated with isothetic polygons. The new ground truth 1(b), 1(d), and 1(f) are generated with unconstrained polygons by using our ground-truthing tool DIVADIA.

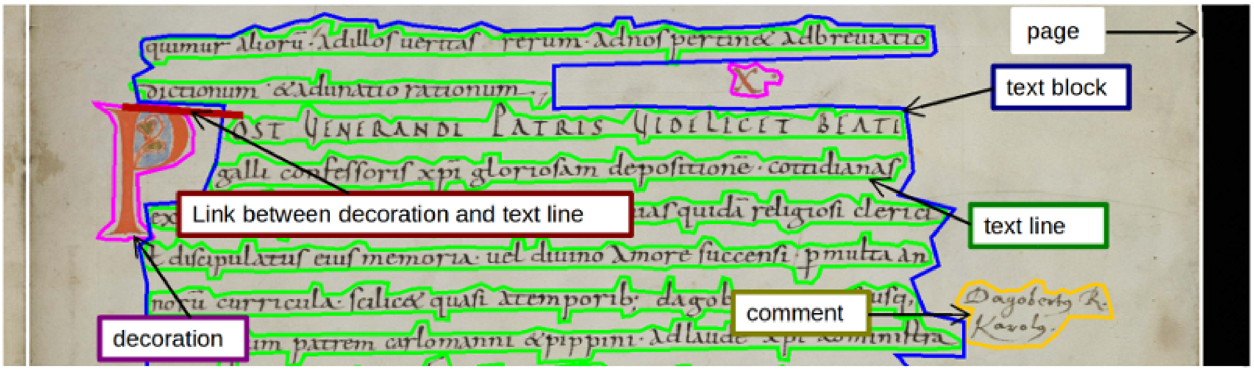


Figure 2. Layout ground truth example from the *Parzival* dataset.

of the points of all its polygons into a PAGE format file. In this file we also store the polygons' region type and their *id*[*]. Each polygon has one of the five following lables:

- The *page* represents a whole page of the manuscript. It separates a page from the periphery.
- The *text block* represents the main text flow of the manuscript. It consists of text regions.
- The *text line* represents a line fragment composed of a set of written text.
- The *decoration* represents the decorative elements such as drop capital, decorative initial, and ornament.
- The *comment* represents the annotation and inserted text between text lines or in the margins.

Figure 2 illustrates the five elements. In order to create a link between decorations with text lines[†], for each *decoration*, it is able to store the *id* of its *text line* in the PAGE format file. The Java source code of reading/writing polygons from/to the PAGE file is available at `https://diuf.unifr.ch/main/hisdoc/divadia`.

Although in[7] a layout model is proposed, there is no publicly available tool which can be used to create and modify the ground truth. For this reason, we propose a ground-truthing tool DIVADIA in order to efficiently create and modify the ground truth. We present this tool in Section 3.

Performance metric for layout analysis

In order to evaluate the performance of different page segmentation methods for layout analysis based on this model, we propose a performance metric. We consider the performance evaluation of a page segmentation method as a comparison of the similarity between two sets of polygons, i.e., the ground-truth polygon set and the segmentation results polygon set. For this purpose, we propose to use two well known criteria: the precision and the recall of the foreground pixels contained in the polygons.

The result polygons may not be sorted in the same sequence as in the ground truth so a matching maximization has to be done. If P is a polygon in a document image then let F_P be the number of foreground pixels belonging to this polygon. These pixels can be obtained by a binarization method. If extracting the foreground pixels is not possible, then we can assume that F_P is the area of the P. Let G and S be the set of polygons of the ground truth and a segmentation result. The recall of matching candidates i and j is $R(S_i, G_j) = \frac{F_{(S_i \cap G_j)}}{F_{G_j}}$. In order to find the matching maximizing the overall recall, the Hungarian algorithm[14] which has been applied successfully for assignment problems, is applied on a matrix M such that the value of the cell (i, j) is $M_{i,j} = R(S_i, G_j)$. The matrix can be made square by adding lines or rows of zeros. We fill the matrix with the recall instead of the

[*]The *id* is a unique integer.

[†]Often a decoration belongs to a text line, i.e., it is a lettrine. A *link* is used to represent the relation between a decoration and a text line.

precision to maximize the matched surface. Resultant polygons which have not been matched are assumed to have a precision and a recall of zero.

Once the polygons have been matched, it is possible to compute the result precision for each of them. The recall has already been computed in the previous step. Evaluation of page segmentation methods should indicate the mean precision and mean recall for the polygons of each class.

3. GROUND-TRUTHING TOOL

To facilitate and accelerate the ground truthing for historical document layout analysis, we developed a java based tool DIVADIA[†]. DIVADIA provides two shapes (i.e., unconstrained polygon and rectangle) for drawing regions of interest. Users can easily manipulate any shape by adding, moving, and deleting points. An undo function helps users to recover the previous changes. The zooming function allows users to work with high precision. Various viewing and setting options can be used to offer better visual perception. Figure 3(a) shows the workspace of DIVADIA. A open source OCR library *java OCR*[‡] is integrated in order to extract text lines and automatically draw the polygons, then users can manually modify these polygons. Figure 3(b) shows an example of text line extraction in DIVADIA.

3.1 Comparison with the state of the art

In this section, we compare DIVADIA with four state-of-the-art tools.

TRUEVIZ[9] is an early tool for visualizing and editing ground truth for document image analysis. Different regions (i.e., zones, lines, words, and character) are represented by rectangle or polygon. Users can also edit the textual context of the region. However, it supports only TIFF image files. Furthermore, it is not possible to edit the rectangles or the polygons by changing the position of their vertices.

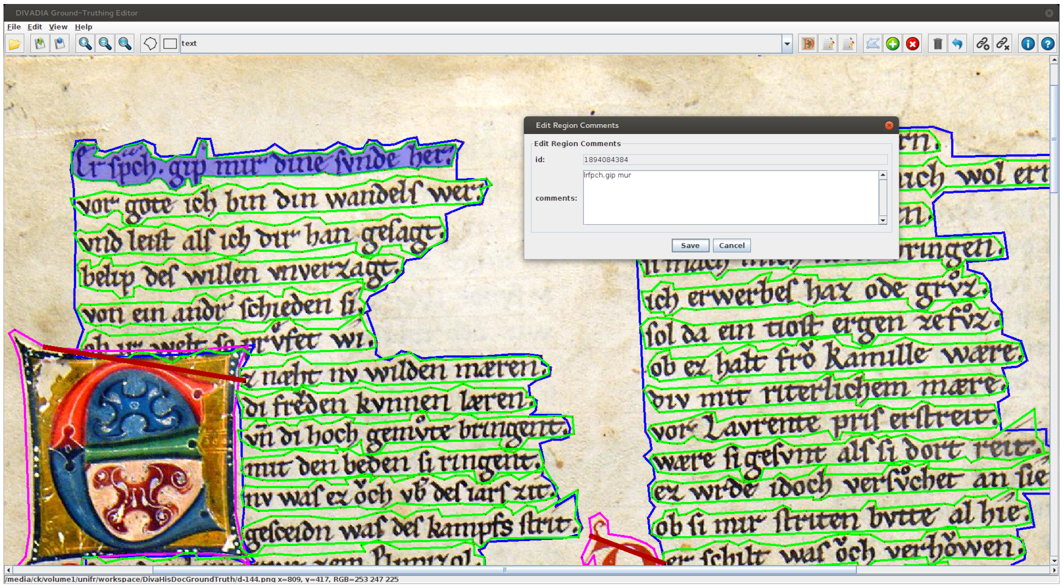
GEDI[10] is another well-known tool for editing ground truth for document image analysis. For each image, the meta-data is an XML based representation storing information at document, page and zone levels. One drawback is that when users annotate high quality image (e.g., >3 mega pixels), the system becomes very slow, e.g., drawing a text line in an image (2200×3400 pixels) from the *George Washington* dataset with GEDI takes about 2 minutes. By using DIVADIA, it takes approximately 40 seconds. Furthermore, when the image is zoomed in, it becomes even slower to draw a region by using GEDI.

WebGT[11] is a web-based ground-truthing system for historical document images. Users are able to upload their document collections to the server and assign annotation tasks to other users. However, they can only draw rectangles, therefore it is inefficient for layout ground truthing on document images with complex layout. Furthermore, the authors claim that WebGT provides an automatic character selection function, i.e., by clicking any pixel of a character using the mouse, the connect component corresponding to the pixel and its bounding box is captured. But this function often failed to capture correctly bounding box of the character on degraded document images.

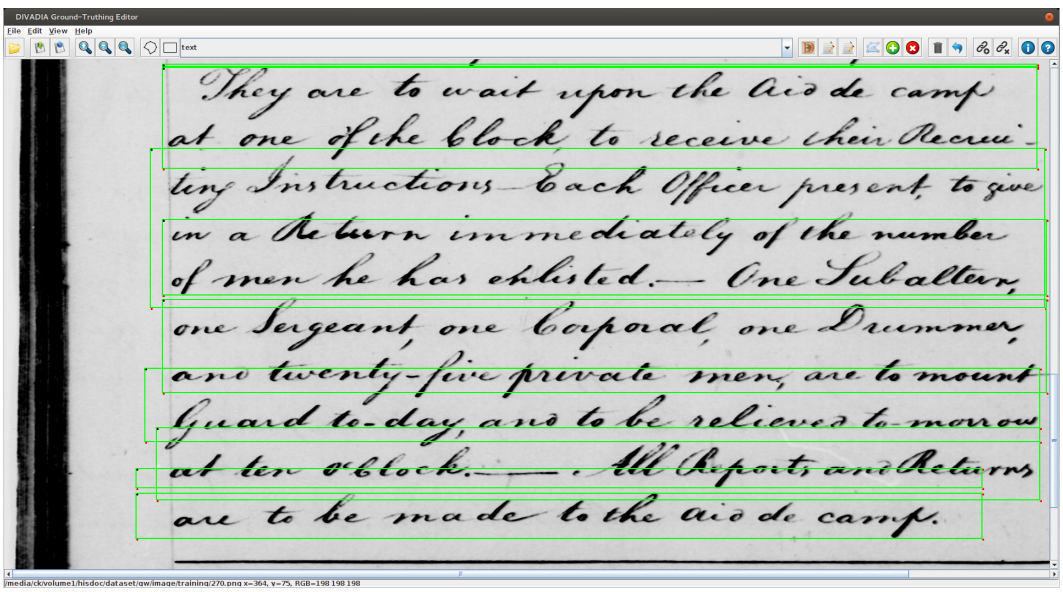
Aletheia[12] is a flexible and richly functional ground-truthing system developed for printed historical documents. It provides top-down ground truthing with splitting and shrinking functions as well as bottom-up aggregation of lower-level elements to complex structures. However, these functions are not simple to use and only parts of the functionality are well documented. Another drawback of Aletheia is that it works only in Windows. But DIVADIA is system independent because of the java implementation. By our experience, we note that while, Aletheia is a complete system and some functions are useful for grount truthing, reducing the number of functions could improve the simplicity of the system.

[†] `https://diuf.unifr.ch/main/hisdoc/divadia`

[‡] `http://roncemer.com/software-development/java-ocr/`



(a) Workspace of DIVADIA.



(b) Text lines extraction by using *java OCR*.

Figure 3. DIVADIA layout ground-truthing tool.

3.2 Evaluation

In order to test our tool and compare the usability with the state of the art, we have asked different users to do the same task, i.e., ground truthing one page from any of the three datasets which are described in Section 4 by drawing regions of interest with TRUEVIZ, GEDI, WebGT, Aletheia, and DIVADIA. Seven users from the University of Fribourg participated in this evaluation. One is from the Medieval German Literature department and the others are from the computer science department. We asked them which tools they prefer for this ground-truthing task¶. Table 1 shows that Aletheia was selected 4 times and DIVADIA was selected 6 times.

The System Usability Scale (SUS)[15] was used to evaluate DIVADIA. The average score is 85 which is above

¶Users were allowed to select more than one tools.

Table 1. User preferences

	TRUEVIZ	GEDI	WebGT	Aletheia	DIVADIA
#selection	0	0	0	4	6

the average of 68. While the usability test were limited, we noticed that DIVADIA is useful for layout ground truthing on historical document images.

According to the participants' feedback, we conclude that for ground truthing the layout on historical document images, DIVADIA contains the most important functions. It is easy to use and also has a good performance for ground truth correction. It compares favourably in terms of intuitiveness and efficiency with other available tools for layout ground truthing on historical document images.

4. DATASET

Three high quality historical manuscript image datasets are chosen from different sources so as to represent various layouts and styles. The document images are chosen from the IAM Historical Document Database‖. These images have already been used for the research of handwriting recognition[16] and word spotting.[13] However, there is currently no ground truth publicly available for the layout analysis.

The three image datasets are:

- The *George Washington* dataset was created from the George Washington Papers at the Library of Congress. The manuscripts were written by George Washington and his associates in English in the 18^{th} century and contain cursive handwritten text. The image size is 2200×3400 pixels.
- The *Saint Gall* dataset consists of medieval manuscripts written in Latin by a single writer from the 9^{th} century. The text flow is richly decorated with drop capitals and illustrations. Some pages contain annotations (e.g., page number) and comments were added to the margins. The image size is 1664×2496 pixels.
- The *Parzival* dataset consists of medieval German manuscripts from the 13^{th} century. The manuscripts contain the epic poem Parzival by Wolfram von Eschenbach and were written by three writers. The text flow was split into two columns. Similar to those of the *Saint Gall* dataset, the manuscripts were richly decorated. However, the pages contain more degradation and comments. The image size is 2000×3008 pixels.

The three image datasets are of different nature. The George Washington dataset consists of images of manuscripts written with ink on paper and the images are in gray levels. The other two datasets consist of images of manuscripts written with ink on parchment and the images are in color, while the former suffers from many degradations. The manuscripts have typically difficult characteristics of historical documents. Our dataset consists of 20, 61 and 39 images chosen from the *George Washington*, *Saint Gall*, and *Parzival* collections respectively. These images are carefully annotated by using DIVADIA based on the proposed model as described in Section 2. The dataset is available for scientific research at `https://diuf.unifr.ch/main/hisdoc/divadia`. Figure 4 gives some examples showing the original pages with their layout ground truth.

5. CONCLUSION

With the aim of layout analysis on historical documents, we propose a new public dataset constructed from degraded historical manuscripts with various layouts. Currently the dataset contains 120 high quality images which are taken from three historical handwritten document image datasets with different layouts and styles. The new model used for layout ground truthing is based on the previous work[7] and overcomes some of its drawbacks. We use unconstrained polygons to outline regions of interest. Five types, i.e., *page*, *text block*, *text line*, *decoration*, and *comment*, are used to present different elements on the document images. The gound-truth

‖`http://www.iam.unibe.ch/fki/databases/iam-historical-document-database`

Figure 4. Example pages 4(a), 4(b), and 4(c) with their ground truth 4(d), 4(e), and 4(f) respectively. The example pages are taken from the *George Washington* (letterbook 1, page 278), *Saint Gall* (Cod. Sang, 562, page 5), and *Parzival* (Cod. 857, page 144) datasets respectively.

information is stored in the PAGE format file. Source code for reading and writing ground truth from the PAGE format file is publicly available. Based on this model, a performance metric is proposed which could be used to evaluate various page segmentation methods for layout analysis. The layout ground truth is made by a new tool DIVADIA. The evaluation shows that DIVADIA compares favourably in terms of intuitiveness and efficiency with the state of the art for the layout ground truthing on historical document images. Our future work includes using DIVADIA to enlarge the present dataset and accelerating the ground truthing by integrating more robust and flexible page segmentation methods into DIVADIA.

ACKNOWLEDGMENTS

We would like to thank Michael Stolz for providing us with the Parzival data set. The project is part of HisDoc and HisDoc 2.0 funded by the SNF via the grant numbers CRSI22 125220 and 205120 150173.

REFERENCES

[1] Panichkriangkrai, C., Li, L., and Hachimura, K., "Character segmentation and retrieval for learning support system of japanese historical books," in [*Proceedings of the 2Nd International Workshop on Historical Document Imaging and Processing*], *HIP '13*, 118–122, ACM (2013).

[2] Cohen, R., Asi, A., Kedem, K., El-Sana, J., and Dinstein, I., "Robust text and drawing segmentation algorithm for historical documents," in [*Proceedings of the 2Nd International Workshop on Historical Document Imaging and Processing*], *HIP '13*, 110–117, ACM (2013).

[3] Saund, E., Lin, J., and Sarkar, P., "PixLabeler: User interface for pixel-level labeling of elements in document images.," in [*ICDAR*], 646–650, IEEE Computer Society (2009).

[4] Mehri, M., Gomez-Krämer, P., Héroux, P., Boucher, A., and Mullot, R., "Texture feature evaluation for segmentation of historical document images," in [*Proceedings of the 2Nd International Workshop on Historical Document Imaging and Processing*], *HIP '13*, 102–109, ACM (2013).

[5] Bulacu, M., van Koert, R., Schomaker, L., and van der Zant, T., "Layout analysis of handwritten historical documents for searching the archive of the cabinet of the dutch queen," in [*Proceedings of the Ninth International Conference on Document Analysis and Recognition - Volume 01*], *ICDAR '07*, 357–361, IEEE Computer Society (2007).

[6] Antonacopoulos, A., Clausner, C., Papadopoulos, C., and Pletschacher, S., "Historical document layout analysis competition.," in [*ICDAR*], 1516–1520, IEEE (2011).

[7] Baechler, M. and Ingold, R., "Medieval manuscript layout model.," in [*ACM Symposium on Document Engineering*], 275–278, ACM (2010).

[8] Pletschacher, S. and Antonacopoulos, A., "The PAGE (page analysis and ground-truth elements) format framework.," in [*ICPR*], 257–260, IEEE (2010).

[9] Lee, C. H. and Kanungo, T., "The architecture of TrueViz: a groundtruth/metadata editing and visualizing toolkit.," *Pattern Recognition* **36**, 811–825 (2003).

[10] Doermann, D., Zotkina, E., and Li, H., "GEDI - A Groundtruthing Environment for Document Images," in [*Ninth IAPR International Workshop on Document Analysis Systems (DAS 2010)*], (2010).

[11] Biller, O., Asi, A., Kedem, K., and Dinstein, I., "WebGT: An interactive web-based system for historical document ground truth generation.," in [*ICDAR*], 305–308, IEEE (2013).

[12] Clausner, C., Pletschacher, S., and Antonacopoulos, A., "Aletheia - An advanced document layout and text ground-truthing system for production environments.," in [*ICDAR*], 48–52, IEEE (2011).

[13] Fischer, A., Keller, A., Frinken, V., and Bunke, H., "Lexicon-free handwritten word spotting using character hmms.," *Pattern Recognition Letters* **33**, 934–942 (2012).

[14] Kuhn, H. W., "The Hungarian Method for the Assignment Problem," *Naval Research Logistics Quarterly* **2**, 83–97 (1955).

[15] Brooke, J., "SUS: A quick and dirty usability scale," in [*Usability evaluation in industry*], Jordan, P. W., Weerdmeester, B., Thomas, A., and Mclelland, I. L., eds., Taylor and Francis (1996).

[16] Fischer, A., Indermühle, E., Bunke, H., Viehhauser, G., and Stolz, M., "Ground truth creation for handwriting recognition in historical documents," in [*Proceedings of the 9th IAPR International Workshop on Document Analysis Systems*], *DAS '10*, 3–10, ACM (2010).