EUROGRAPHICS Workshop on Graphics and Cultural Heritage (2014)
R. Klein and P. Santos (Editors)

Extending Philological Research with Methods of 3D Computer Graphics Applied to Analysis of Cultural Heritage

D. Fisseler[1] and F. Weichert[1] and G.G.W. Müller[2] and M. Cammarosano[2]

[1]Department of Computer Science VII, TU Dortmund, Germany
[2]Department of Ancient Cultures, Ancient Near Eastern Studies, University of Würzburg, Germany

Abstract

Philological research on ancient cuneiform texts with the goal of analyzing and reconstructing manuscripts from a large quantity of available unsorted tablet fragments is a time consuming task. As the number of tablet fragments and the number of signs on the fragments both exceed values which can be handled by means of conventional manual research methods in a reasonable amount of time, the use of computer aided research methods is an obvious choice. In this paper, we present a novel unified approach for integrating methods of computer graphics into the process of analyzing and joining cuneiform tablet fragments. We will cover a selection of essential research scenarios and identify aspects where those methods can be applied to enhance and extend traditional philological research processes or even help to access formerly unavailable layers of information. This is achieved by integrating methods for visualization, interactive 3D script feature extraction, script analysis, virtual fragment joining and intuitive measurement and annotation tools in our fast and easy to use software framework CuneiformAnalyser, designed for large data sets. Unlike other approaches, our solution integrates for the first time methods to support every aspect of the manuscript analysis and reconstruction process in a single system.

Categories and Subject Descriptors (according to ACM CCS): I.3.8 [Computer Graphics]: Applications—

1. Introduction

Cuneiform writing is characterized by the use of wedge-shaped impressions, which are combined together into meaningful signs. At present, more than 500.000 fragments of clay tablets inscribed in cuneiform script like shown in figure 1 have been discovered [Str10]. Their provenience and dating range over more than three millennia and the entire geographical area labeled 'Ancient Near East'. A major task for scholars active in this field is to document, interpret and make accessible the manuscripts to the scientific community as well as to a broader public. In order to do this, it is essential to reconstruct the original tablets by identifying fragments which belong together, also called 'joins', based on the content as well as on other features, such as paleography, handwriting, layout and clay composition. Reading the signs on the manuscripts is further complicated by the often poorly preserved state of the tablet surface.

Figure 1: Photographic documentation of the reconstructed cuneiform tablet Bo 594(left), a magnified section of a cuneiform tablet Bo 595(middle) and a 3D-scanned fragment join of cuneiform tablet 126/p++(right). (Source: Hethitologie Portal Mainz)

This work presents a novel software framework, called *CuneiformAnalyser*, which allows an unified and effective three-dimensional approach of analyzing and reconstructing manuscripts in the field of philological research. For a selected set of objectives, collation of fragments, script feature analysis and 3D reconstruction, (semi-) automatic and interactive computer aided approaches are conducted.

In the following we will give an overview on related work, describe traditional philological research methods related to the reconstruction of cuneiform manuscripts including

DOI: 10.2312/gch.20141314

their shortcomings and present computer assisted methods to overcome or mitigate them in a substantial way.

2. Related work

Since 3D capable hardware became available, the intention to use 3D technology in the field of philology was to overcome the shortcomings of the traditional subjective hand copies and photographs in order to provide a more accurate documentation and reproduction of the ancient written documents. The idea was to create realistic models that could be disseminated over the internet and allow inspection of texts online all over the world. Already in 2000, the Steinbichler Optotechnik GmbH (http://www.steinbichler.de) produced 3D scanners capable of acquiring detailed 3D scans of cuneiform tablets [Mül00]. However the main memory size and processing capabilities of the computers available in these days, as well as the bandwidth for data transfer via the internet, did not meet the requirements to process large data sets of big tablets with high resolution.

Most projects focused on new ways of documentation of cuneiform tablets, either by replacing laborious hand copies by computer generated 'line drawings' like curvature maps or by the imitation of photographs generated from 3D data like [AL02]. The Leuven Camera Dome System (LCDS) [WVM*05] is based on the principles of Polynomial Texture Mapping (PTM) [MGW01] and Reflection Transformation Imaging (RTI) [DCCS06] to generate a photometric stereo reconstruction and is available at relatively low cost. It represents only one view of the object consisting of flat surfaces with different lighting. While offering sufficient resolution, 3D objects generated from LCDS picture sets usually exhibit large global distortions on the computed depth components and bad accuracy towards the border areas of the digitized objects.

In 2003, the Digital Hammurabi project aimed beyond the development of new visualization techniques also at the transfer via the Internet [WS03] [CDS*04]. The most closely related projects are the Cuneiform Digital Forensic Project (CDFP), later Cuneiform Digital Paleography Project (CDP) [WDF*02], which intended to establish a large cuneiform sign database and experimented with - insufficient - 3D scanners finally using photographs of single cuneiform signs and the GigaMesh project, which introduced methods based on multiscale integral invariants [MKJB10] [Mar12] to compute enhanced visualizations and extract cuneiform signs from 3D scanned artifacts. The results of the GigaMesh project were focused on an efficient computation of the integral invariants and generating a vector based representation of the cuneiform signs on single fragments.

Current research on the reconstruction of fractured documents like [DKS10] and [WLM*11] almost entirely targets the reconstruction of 2D documents. Existing methods for joining fractured 3D geometry are mostly based on combining local pairwise geometry matching with a global optimization approach. The joining algorithm described in [HFG*06] uses only the geometry of fracture face surface geometry to identify matching parts. Approaches like [KTN*06] rely also on fractured edge geometry matching, but additionally integrate boundary incision matching, which accounts for manually annotated feature information on the fragments. [KK01] reduces the surface matching aspect to extracting 2D or 3D boundary curves and performs curve matching for 2 or 3 candidates at a time. All mentioned methods usually require a set of fragments of a specific object to be reconstructed with well preserved fracture faces and matching contact surfaces.

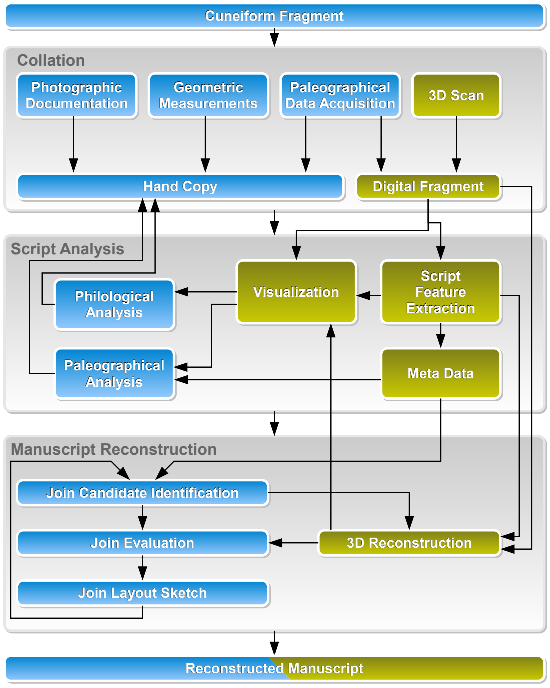


Figure 2: A possible cuneiform fragment analysis and reconstruction pipeline. Blue elements visualize traditional research methods, whereas yellow elements represent computer aided research methods.

3. Traditional cuneiform manuscript analysis

The established approach for a philological study contains the underlying script analysis and the collation of the fragments. Besides, in many cases is it necessary or advisable for a sustainable study to reassemble the fragments (reconstruction). To conduct the different substeps computer-based methods are increasingly used. This is because they allow both more efficient analysis and fundamentally new approaches. Figure 2 represents this concatenation of traditional research methods and computer aided research

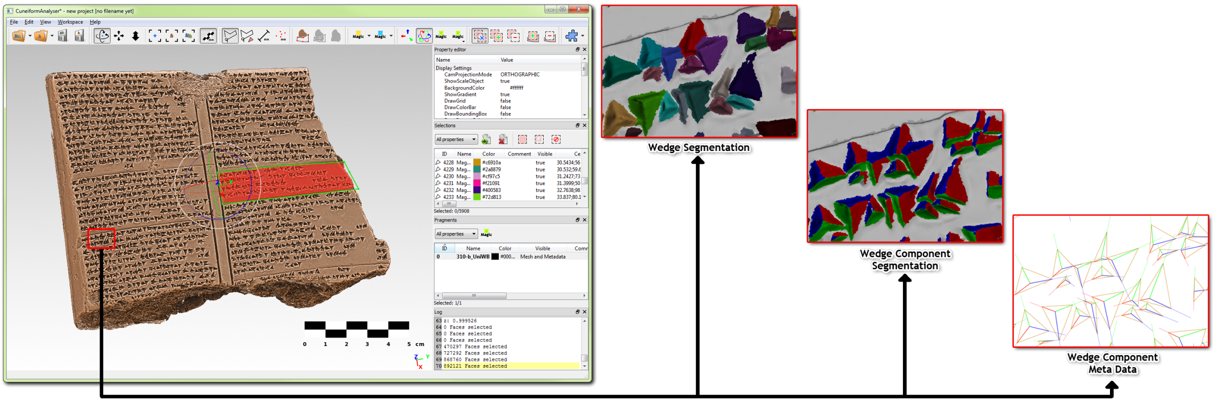


Figure 3: User interface of the software framework *CuneiformAnalyser* with realistic visualization, scale object and segmented wedges on a cuneiform fragment.

methods. It is shown, that an essential step in cuneiform manuscript reconstruction and the primary task of philological study is collation, which addresses the direct examination of an inscribed fragment in order to decipher its content, take geometric measurements and collect any other available information about the manuscript. Collating a manuscript is subject to major restraints because of the necessity of accessing the original fragments. This requires obtaining permits and funding as well as planning a research journey, which is not rarely complicated by geopolitical problems. Access to original fragments is further affected by time limitation and restraints related to museum policies. Collation is typically associated with two further tasks, namely the photographic documentation of the fragment and the drawing of so-called hand copies of the inscribed surface. It is worth stressing that the necessity of collating a manuscript does in no way disappear after hand copies and photographs are published. A hand copy is highly subject to the expertise and interpretation of the particular philologist who drew it; moreover, the surface of cuneiform tablets is often badly damaged or abrased, so that not even high resolution photographs dispense from the necessity of collating the original fragment whenever the philologist considers it worth in order to improve the reading of a specific passage.

Traditional documentation of a cuneiform tablet implies taking multiple photographs of the fragment. Problems related to this process are well-known [HW11]. In order to achieve the best possible reproduction of the script and surface details a custom lighting setup has to be created for each photograph, as some details only become visible by using optimized shadow casting. However on significantly curved fragments it is not always possible to produce a globally optimal shadow direction. In addition to that, a visual scale indicator has to be included to facilitate taking measurements on the photographs later. Taking accurate measurements using photographs may also be complicated or rendered impossible on fragments with a prominent surface texture or in the case of significantly curved tablet surfaces as the reproduction does not only contain spatial distortions caused by the camera lens but also projective errors due to the curved fragment surface. On the other hand taking direct surface geometry measurements of a fragment using traditional hand operated measuring tools may be inaccurate due to the small size of cuneiform wedges or even impossible, when physical contact of the measuring tools with the original artifact is not allowed. Furthermore, traditional measurement techniques based on photographic reproductions and hand copies are not able to account for the complex geometry of fractured portions of the fragment, which is often indispensable in order to verify the match with join candidates.

Before a custom hand copy of a cuneiform manuscript can be created, its textual content has to be deciphered. This task is part of paleographical studies, that include deciphering, reconstructing and interpreting manuscripts. Traditionally, paleographical studies deal with the analysis and classification of sign forms and variants [Lab48] [RN89] as a base for classifying script into known paleographical frameworks. Script features related to the inherent three-dimensional character of the cuneiform script, however, remain unexploited in traditional studies, due to the two-dimensional nature of photographs and to the fact that manual measurement of wedge components on original tablets does not represent a viable option. Especially in the case of abrased fragment surfaces this task may be impossible by only using photographic references and requires extended access to the original artifact.

As many preserved cuneiform texts are available in the form of fractured clay tablets, joining individual fragments to reconstruct the original tablets represents an essential task of philological research. The first step in this process is the identification of possible join candidates, which is usually a difficult task, as philologists are often confronted with a high number of possible join candidates and the exact find spots of the fragments are often undocumented. Additional difficulties arise from the fact, that potential join candidates are often stored at different locations and a direct physical comparison in the same place is not always possible. Identified joins are documented in form of join layout sketches like shown in figure 5, based on hand copies or photographic documentation. The creation of accurate join layout sketches is often difficult, as it requires a scale matched set of photographs all taken from the same angle of view, which is, in many cases, not available. Thus, the resulting sketches exhibit distortions and a general poor reproduction of the structures on the fracture faces. Based on this traditional approach for cuneiform manuscript analysis as described above the following section will focus on the integration of computer aided methods within the philological research.

4. Computer assisted philology

In view of the extensive data of cultural heritage, the availability of an efficient approach for analysis is evident. Computer aided methods are able to facilitate the mentioned philological research in a substantial way, thus improving our understanding of writing techniques and scribal habits. The paper introduces a configurable system, called *CuneiformAnalyser* (cf. figure 3), that allows philological research and analysis in a flexible way. The *CuneiformAnalyser* focuses on intuitive user interfaces, sustaining and enhancing the usual philological workflow and ensuring an inter-research-scenario re-usability of data by combining all methods in an integrated framework. The concept is demonstrated for the cases of collation of cuneiform fragments, script feature analysis and computer assisted 3D reconstruction.

4.1. Collation of fragments

According to the restrictions described in section 3, the target is to record as much and as precise information as possible in the short amount of time available with an original manuscript. To address this, we use a Breuckmann optoTOP structured light scanner (AICON 3D Systems GmbH, http://www.aicon3d.de) to digitize cuneiform fragments. The time required to take a full 3D-scan of a fragment suitable for philological research varies depending on the size of the fragment and the required resolution. Scanning big fragments with a size much larger than the scanning area can require more than 80 scans of different artifact regions at multiple angles and exposure times, which may result in a total scanning time of several hours. Scanning small fragments takes around the same amount of time as a traditional photographic documentation. As the scanner contains a calibrated camera and carries its own optimized lighting setup, the calibration costs per scan are insignificant. It is worth mentioning that for philological research even a high resolution 3D-scan of a fragment can not fully replace access to the original manuscript, but it provides amongst others the huge advantage of being able to view and measure the fragment geometry in 3D any time later by an arbitrary number of researchers. This increases the accessibility of the manuscripts in a substantial way and has relevant implications for philological research, as a 3D model can be examined at any time and location without the restraints discussed in section 3. In most cases, the possibility of investigating the 3D geometry of the manuscript eliminates the need to access the original fragment, which eventually in most cases is able to amortize the additional time required to take the scans.

Aside from improving accessibility, the availability of a 3D surface model offers new options for visualization, which we integrated into our software framework *CuneiformAnalyser*. By using advanced visualization methods like litsphere rendering- [SMGG01], ambient occlusion [PG04] and radiance scaling [VPB*10] on the 3D-data obtained by the scanner, it is not only possible to mimic the visual appearance of the original clay fragment, but also to visually enhance barely visible geometric features on specific scales as is shown in figure 4. The option to view the fragment surface using a uniform surface texture represents another advantage over traditional photographic documentation, insofar as disturbing factors related to color variations on the surface are overcome. In addition to that, the arbitrary magnification of the 3D-visualization has proven to be a good substitute for using magnifying optical instruments for the analysis of the original artifact. Insofar as the decipherment of damaged signs is concerned, on-site experiments have shown, that the visualization tools available within *CuneiformAnalyser* are in some cases even able to improve the results obtained through collation of the original fragment. Using the *CuneiformAnalyser*, intermediate results of the deciphering process can then be annotated directly on the 3D-scanned geometry for review by other philologists. In order to achieve a seamless integration into traditional philological methods the *CuneiformAnalyser* provides several stylized output methods with the possibility to create readable real world sized 2D copies of the fragment surface including a dynamic scale object as can be seen in figures 4 and 3. As an additional advantage the use of 3D scans provides access to highly accurate non-destructive geometric measurements, including distance measurements on curved surfaces and depth measurements on individual wedges. The accuracy of the flexible and intuitive measurement tools integrated into the *CuneiformAnalyser* is limited by the available scanner resolution, which in case of the Breuckmann optoTOP scanner is $30\mu m$. Besides the actual measurement results, the *CuneiformAnalyser* is also able to store and visualize how the measurements were taken on the geometry. This is especially useful when dealing with different measuring conventions, e.g. how to measure the length of a wedge.

In conclusion, the computer aided collation has a more time consuming recording process than traditional methods, but amortizes through many advantages by increasing accessibility and readability during the deciphering process and

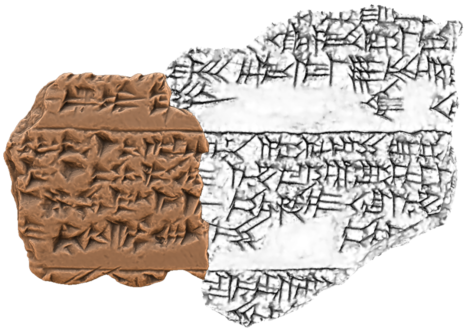


Figure 4: Stylized visualization of cuneiform fragments Bo 59/331 (left, ambient occlusion with radiance scaling and lit-sphere lighting) and Bo 8060 (right, sketch mode) in CuneiformAnalyser.

later research. Additional benefits arise from a combined data storage and the use of geometry attached annotation methods. This includes layers of custom annotations to specific parts of the geometry, which do not corrupt the data storage, as their display is optional.

4.2. Script feature analysis

The exploration of three dimensional script features, which is, as mentioned in section 3, not a part of traditional philological research, represents a new challenge for computer aided research methods and philological research. Transferring traditional philological methods to describe and deal with script characteristics into a new nomenclature, that allows interdisciplinary handling of relevant script features, establishes the necessary base for further research. Our efforts to develop an appropriate nomenclature are not part of this publication, but described in [CMFW14]. Since script features like wedge width, angles, and face curvature provide important pieces of information for the analysis and classification of script, the use of computer aided methods to search for and to analyze those components represents a big advantage over traditional methods based on 2D(+) reproductions. The extended measuring capabilities provide access to formerly unavailable layers of information by taking the script analysis from sign level, which is based on the analysis of wedge constellations, to wedge level, which aims at analyzing the geometry of individual wedges.

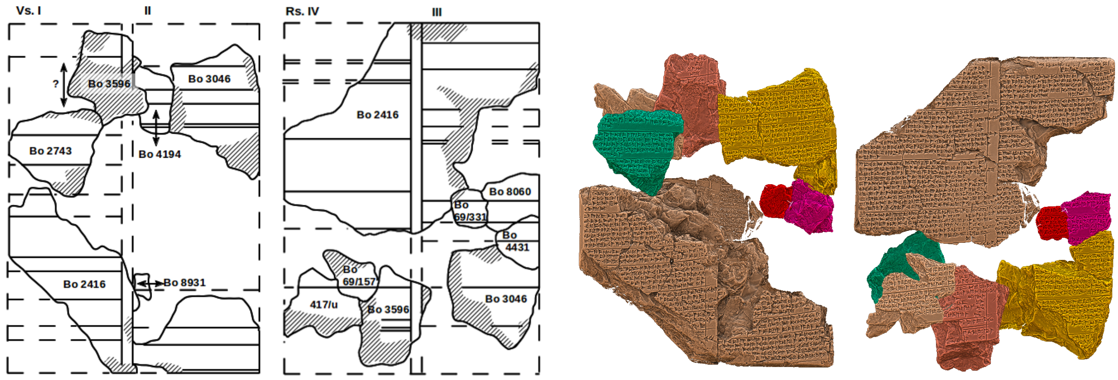
Beyond taking manual measurements, our process oriented approach described in [FWCM13] can automatically extract cuneiform wedge components and their statistical properties using computational geometry and intuitively visualize the segmentation results like shown in figure 3. We use a combination of ambient occlusion filtering, watershed wedge extraction on a Poisson-reconstructed height field and clusting-based wedge-component segmentation with flexible filtering stages to adapt the automatic segmentation methods to different data sets. Our extracted wedge components, as defined in [CMFW14], include feature points, edges and faces, with derived properties like wedge orientation as well as inner-, outer- and aperture-angles. The properties associated with the extracted wedges are pipelined into a direct and intuitive meta data visualization, including amongst others visual representations for wedges, feature points and clustering results, to facilitate manual evaluation of the wedge segmentation. In this process the automatically generated segmentation results can be corrected based on philological expertise using fast and flexible selection and editing methods for geometry and meta data, provided by the *CuneiformAnalyser*. This way, philological knowledge and 3D imaging techniques are combined into a novel approach which opens up new perspectives for paleographical research. A typical result of our wedge extraction preprocessing with enabled wedge component visualization is shown on the right hand side of figure 3. The novel methodology allows to carry out metrological analysis of cuneiform script on large data sets, which constitute the essential premise for the identification and scientific description of scribal tradition and individual hands. The computer assisted analysis of the geometry of individual wedges also constitutes the essential precondition to investigate scribal habits, writing techniques and writing tools.

Another problem in paleographical studies is represented by the fact, that a single cuneiform tablet normally contains hundreds or thousands of signs, which makes the evaluation and classification of the individual signs a time-consuming task. Again, computer aided methods provide a substantial support to such kind of research, insofar as a semi-automated search for similar patterns of wedge components or wedge constellations becomes possible. The *CuneiformAnalyser* includes methods to interactively search for, visually emphasize and annotate similar wedges, which simplifies finding similar wedge constellations on big cuneiform tablets. As the analysis of a cuneiform sign in most cases depends heavily on its context, we also provide semi-automatic methods to extract, compare and analyze the neighborhood of individual wedges.

All computed segmentation data including annotations and visualization options is stored in a machine readable xml-based file format. Except from the mapping of the segmentation results to individual parts of the scanned geometry, all segmentation data can be analyzed and visualized even without access to the original geometry data. This facilitates an exchange of research results, as the original geometry data files may exhibit sizes of more than a gigabyte.

4.3. Computer assisted 3D reconstruction

Concerning the identification of possible join candidates, the results from the metrological approach to the study of cuneiform script, described in section 4.2, represent a great contribution to the search of (in)direct joins, insofar as the



(a) (b)

Figure 5: Traditional join layout sketches **(a)** and virtual join **(b)** for the front and back side of cuneiform tablet 417/u+.

automated analysis of script makes it possible to sort large amounts of fragments according to specific script-related criteria. In contrast to traditional research methods, finding candidates for joining operations this way may not even require the philologist having extended knowledge of all involved fragments. Among script features to be considered are average script density, occurrence of specific sign forms, script declination in respect to the line, line direction, average inner wedge angles and occurrence of text dividers. Features like line spacing and the spacing of text dividers contain valuable information for identifying matching fragments that do not share a mutual fracture face. The obtained pre-sorting of manuscripts can be further combined with other kinds of information, based on annotations or the text content, in order to make the selection of possible join candidates even more efficient.

A typical workflow for identifying new join candidates would start with performing an automated wedge and wedge component segmentation on multiple scanned cuneiform fragments using a batch-segmentation functionality within *CuneiformAnalyser*. The resulting segmentation data not only includes single wedge features, but also wedge quality measures and neighborhood information. At this point the generated meta data may be interactively viewed to add philological annotations e.g. to indicate important wedge constellations, to review the quality of the automated segmentation and to include necessary corrections. Further processing based on the metrological script features depends on the philological question to be solved. In case of a join candidate search, the features can be either used to search for specific similarities in the database of available processed fragments or a cluster analysis can be employed to identify unspecified similarities in a selected batch of fragments. To do so, a fragment descriptor has to be constructed from a set of selected metrological script features to measure the similarity of cuneiform fragments. Generating appropriate fragment descriptors and identifying optimized criteria for automatic join candidate selection is subject to active research.

Once possible join candidates are identified, a virtual join might be conducted without being bound by the restrictions regarding availability and handling applying to original fragments in traditional research methods. However for performing manual virtual joins it is necessary to work with full resolution data sets with millions of vertices and faces, as the contact area for direct joins may be very small but must contain as much geometric detail as possible. As available mesh editing tools usually do not provide support for data sets of this size while maintaining full interactivity and do not integrate any concurrent meta data visualization for script feature based meta data, a custom solution for this task is required. Therefore, our software framework *CuneiformAnalyser* provides a performance optimized environment for interactively working with multiple big data sets at the same time. This is done by using redundancy optimized data structures and parallel data transfer methods in an OpenGL based rendering system while maintaining full visualization capabilities. This way multiple fragments consisting of more than 10 million faces, including all script feature meta data can be visualized with interactive frame rates on a mid range testing platform (Core-i7 2600, 16GB, Geforce GTX 560 Ti).

In addition to that, flexible interaction interfaces for transforming fragments and viewport-based selection mechanisms for all meta data generated during the script feature analysis are available any time. This enables philologists for the first time to interactively evaluate virtual joins on the scans obtained in the computer aided fragment collation process and overcome the accessibility restrictions that are usually connected with bringing multiple fragments together at the same place for a join. In contrast to the join layout sketches mentioned in section 3 the virtual joins do not exhibit large distortions and include structural details of the fracture faces. Moreover, there is no need to transform the components to a matching scale, as everything is already available in real world scale. As a result, it is now possible to evaluate a virtual join, like shown exemplary for cuneiform tablet 417/u+ in figure 5, to verify an existing join layout sketch in less than half an hour, providing that 3D-scans of all involved fragments are available. This poses a big advantage over the traditional joining procedure, which, in some cases, would have even been impossible. The results can then be stored and send to other philologists for peer reviews by either exporting the data in form of aligned high resolution screenshots or, if the original fragment data is already available at the target location, by submitting the join data by means of a small join description file. Like the per fragment meta data storage in script feature analysis the data storage for joins is based on a machine readable xml-based file format, that contains basically fragment transformations and join related annotations.

As our intention is to make the software framework *CuneiformAnalyser* available to the scientific community upon completion, it is build using C++, OpenGL and the Qt library to ensure platform independency. At present it is available for either Windows and Linux based 64-Bit systems. The framework also includes detailed documentation on how to perform specific cuneiform analysis tasks and is already actively used by students at University of Würzburg to assist in philological research tasks.

5. Conclusions

The paper describes the first unified and effective digital approach of 3D analyzing and 3D reconstructing cuneiform manuscripts in the field of philological research. In view of 500.000 fragments of clay tablets, the availability of fast, reliable and automatic methods is urgently necessary. The proposed software framework *CuneiformAnalyser* fulfills these requirements. Computer-aided methods are able to facilitate philological research in a substantial way, thus improving our understanding of writing techniques and scribal habits. The new system allows for the first time to replace impressions and impressionistic descriptions of the script on a fragment by sound, reproducible and comparable data. It provides new enhanced tools to examine details of the text, and it enables the virtual reconstruction and verification of joins proposals even of fragments stored at distant locations. Our optimized software framework provides an interactive visual access to large data sets, including methods for enhanced visualization, feature extraction, statistical evaluation and assisted 3D joining that seamlessly integrate with traditional philological research methods.

In contrast to existing manuscript reconstruction methods, like mentioned in section 2, we focus on the inherent three-dimensional nature of cuneiform script to determine features for automated join candidate selection and to quantify and examine features of cuneiform writing techniques and scribal habits. Basing the join candidate search on script properties and geometric text features instead of geometric fracture face properties accounts for the fact, that matching fracture faces are often bifacially damaged, which complicates the detection of direct joins. Incorporating both automatically extracted script features and philological expertise in form of annotations on wedge and fragment level into our database, ensures a high degree of data usability for both manual and automated research methods. The high quality real time visualization of scan data and segmentation results combined with flexible editing and measurement methods facilitates intuitive quality control and error management.

Further future work includes using methods for an automatic 3D reconstruction of fragments based on conclusions of the script feature analysis, virtual fragment synthesis for missing structures by methods of computer vision and an integrated database-based retrieval of structural and functional information of the analysis of manuscripts. This also leads to evaluating extensive data sets and novel approaches of analysis. Besides that, generality of the method should be investigated with respect to different (non-)philological problems.

6. Acknowledgments

Part of the work on this paper has been supported by the German Federal Ministry of Education and Research within the BMBF project '3D-Joins und Schriftmetrologie'.

References

[AL02] ANDERSON S. E., LEVOY M.: Unwrapping and visualizing cuneiform tablets. *IEEE Computer Graphics and Applications 22*, 6 (2002), 82–88. 2

[CDS*04] COHEN J. D., DUNCAN D., SNYDER D., COOPER J., KUMAR S., HAHN D., CHEN Y., PURNOMO B., GRAETTINGER J.: iclay: Digitizing cuneiform. In *VAST* (2004), Fellner D. W., Spencer S. N., (Eds.), Eurographics Association, pp. 135–143. 2

[CMFW14] CAMMAROSANO M., MÜLLER G. G. W., FISSELER D., WEICHERT F.: Schriftmetrologie des Keils: Dreidimensionale Analyse von Keileindrücken und Handschriften. *Die Welt des Orients 44.1*, 1 (2014), 2–36. 5

[DCCS06] DELLEPIANE M., CORSINI M., CALLIERI M., SCOPIGNO R.: High quality ptm acquisition: Reflection transformation imaging for large objects. In *VAST* (2006), Ioannides M., Arnold D. B., Niccolucci F., Mania K., (Eds.), Eurographics Association, pp. 179–186. 2

[DKS10] DIEM M., KLEBER F., SABLATNIG R.: Document analysis applied to fragments: Feature set for the reconstruction of torn documents. In *Proceedings of the 9th IAPR International Workshop on Document Analysis Systems* (New York, NY, USA, 2010), DAS '10, ACM, pp. 393–400. 2

[FWCM13] FISSELER D., WEICHERT F., CAMMAROSANO M., MÜLLER G. G. W.: Towards an interactive and automated script feature analysis of 3d scanned cuneiform tablets. In *Scientific Computing and Cultural Heritage* (2013). 5

[HFG*06] HUANG Q.-X., FLÖRY S., GELFAND N., HOFER M., POTTMANN H.: Reassembling fractured objects by geometric matching. In *ACM SIGGRAPH 2006 Papers* (New York, NY, USA, 2006), SIGGRAPH '06, ACM, pp. 569–578. 2

[HW11] HAMEEUW H., WILLEMS G.: New visualization techniques for cuneiform texts and sealings. *Akkadica 132/2*, 2 (2011), 163–178. 3

[KK01] KONG W., KIMIA B. B.: On solving 2d and 3d puzzles using curve matching. In *CVPR (2)* (2001), IEEE Computer Society, pp. 583–590. 2

[KTN*06] KOLLER D., TRIMBLE J., NAJBJERG T., GELFAND N., LEVOY M.: Fragments of the City: Stanford's Digital Forma Urbis Romae Project. In *Proceedings of the Third Williams Symposium on Classical Architecture* (2006), pp. 237–252. 2

[Lab48] LABAT R.: *Manuel d'épigraphie akkadienne. Signes, Syllabaire, Idéogrammes*. Librairie orientalisle P. Geuthner, Paris, 1948. 3

[Mar12] MARA H.: *Multi-scale Integral Invariants for Robust Character Extraction from Irregular Polygon Mesh Data*. PhD thesis, Ruprecht-Karls-Universiät Heidelberg, 2012. 2

[MGW01] MALZBENDER T., GELB D., WOLTERS H.: Polynomial texture maps. In *Proceedings of the 28th Annual Conference on Computer Graphics and Interactive Techniques* (New York, NY, USA, 2001), SIGGRAPH '01, ACM, pp. 519–528. 2

[MKJB10] MARA H., KRÖMKER S., JAKOB S., BREUCKMANN B.: Gigamesh and gilgamesh - 3d multiscale integral invariant cuneiform character extraction. In *VAST* (2010), pp. 131–138. 2

[Mül00] MÜLLER G. G. W.: Hethitologie Portal Mainz, 2000. last seen 2014-09-21. URL: http://www.hethiter.net/3d. 2

[PG04] PHARR M., GREEN S.: Ambient occlusion. *GPU Gems 3, Chapter 17* (2004). 4

[RN89] RÜSTER C., NEU E.: *Hethitisches Zeichenlexikon. Inventar und Interpretation der Keilschriftzeichen aus den Boghazköy-Texten*. Harrassowitz, Wiesbaden, 1989. 3

[SMGG01] SLOAN P.-P. J., MARTIN W., GOOCH A., GOOCH B.: The lit sphere: a model for capturing npr shading from art. In *No description on Graphics interface 2001* (2001), GRIN'01, Canadian Information Proc. Society, pp. 143–150. 4

[Str10] STRECK M. P.: GroSSes Fach Altorientalistik. Der Umfang des keilschriftlichen Textkorpus, 2010. 1

[VPB*10] VERGNE R., PACANOWSKI R., BARLA P., GRANIER X., SCHLICK C.: Radiance scaling for versatile surface enhancement. In *I3D '10: Proc. symposium on Interactive 3D graphics and games* (2010), ACM. 4

[WDF*02] WOOLLEY S. I., DAVIS T. R., FLOWERS N. J., PINILLA-DUTOIT J., LIVINGSTONE A., ARVANITIS T. N.: Communicating cuneiform: The evolution of a multimedia cuneiform database, 2002. 2

[WLM*11] WOLF L., LITTMAN R., MAYER N., GERMAN T., DERSHOWITZ N., SHWEKA R., CHOUEKA Y.: Identifying join candidates in the cairo genizah. *International Journal of Computer Vision 94*, 1 (2011), 118–135. 2

[WS03] WATKINS J. L., SNYDER D. A.: The digital hammurabiproject, 2003. last seen 2014-09-21. URL: http://www.museumsandtheweb.com/mw2003/papers/watkins/watkins.html. 2

[WVM*05] WILLEMS G., VERBIEST F., MOREAU W., HAMEEUW H., VAN LERBERGHE K., VAN GOOL L.: Easy and cost-effective cuneiform digitizing. In *Int. Symposium on Virtual Reality, Archaeology, and Cultural Heritage* (2005), Eurographics Association, pp. 73–80. 2