3D Sutra: Processing of Scanned Sutra Inscriptions in China for Analysis, Interpretation and Visualization

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Abstract:
The 8th-century Buddhist stone inscriptions from Sichuan province, China, are important cultural assets, which cast a new light on the history of Buddhism in China, their adaptation to Chinese culture, as well as the confrontation of the Buddhist religion with the secular state. Thus, these stone inscriptions need to be documented, analysed, interpreted and visualized archaeologically, art-historically and text-scientifically. On this basis, new archaeological and art-historical knowledge is gained through technical research which, for the first time, results in innovative techniques of measurement and geoinformatics. Thereby, particularly accurate and objective techniques are of great importance as they document the texts in their spatial context and make them available for transcription and different analysis. In this article, innovative approaches are shown which enable the visualization of the inscriptions and the results of their interpretation, combined with additional 2D/3D maps within an interactive web portal.

Key Words: *Sutra, 3D Scanning, Image Processing, Matching, Web Portal*

Introduction

Buddhism has greatly influenced the historical and cultural development of East Asian countries, especially China, thus its growth and dissemination needs to be investigated. Buddhism was introduced to China at the beginning of the current era, but spread slowly owing to the lack of a written tradition of its teachings. While a variety of Buddhist teachings were passed on by word of mouth at a very early age, the writing down of them began much later. The Diamond Sutra, for example, was created in the first century AD and found a wide dissemination initially by a verbal then written tradition. However, the first reproduced traditions of this sutra, which were created by using wood panel printing, date back to AD 868.

Prior to the conservation and reproduction of the sutras by printing techniques, the inscriptions were carved into stone by Buddhist monks, in order to ensure permanent conservation of the sutras. Such stone inscriptions can be found in Sichuan province (China), where 80 sutras with more than 600,000 characters are located at approximately 6 different sites. The most important archaeological site is Wofoyuan, which contains 400,000 characters spread through 15 caves and a large reclining Buddha figure after which this site is named. All these stone inscriptions, dating from the 8th–12th century AD, are of great importance because they provide profound insights into the history of Buddhism and Buddhist teachings and thus into the cultural development of China (Ledderose 2006).

The research project '3D Sutra' is based on the art-historical, archaeological and linguistic analysis and interpretation of these Buddhist stone inscriptions by sinologists who are supported by the disciplines of geoinformatics and surveying as well as geography. Owing to the mass of inscriptions and characters it is necessary to support and optimize the until now manual interpretation process consisting of documentation, transcription, translation and analysis. Optimization will be realized with high-precision 3D measuring techniques as well as further innovative techniques of documentation which produce visual and geometric data and thus provide a wide base for the support of the transcription and analysis of the inscriptions.

In order to document the Buddhist stone inscriptions high resolution, structured light 3D scanning will be used. Such scanning data provide precise virtual copies and make the texts accessible to computer-based treatments. Additionally, the original 3D data will be processed to optimize their value for the user. This includes some inevitable processing owing to the structure and volume of data, and conversions to specific products, which are necessary to support subsequent interpretation steps. Furthermore, algorithms support and assist the transcription of the Buddhist inscriptions. Each Chinese character within the processed 3D data will then be transformed automatically into a machine-encoded character. The characters will also undergo calligraphic analyses which might allow the sinologists to distinguish different authors and manufacturers.

Finally, all datasets and interpretations will be presented in a web-based information system, so that a wide community gains access to the results of our work. This information system provides 2D/3D maps inside a geographic information system (GIS) (Zipf et al. 2007), which illustrates the dissemination of inscriptions in space and time, and enables the analysis of spatial relationships between the inscriptions. Furthermore, the information system presents the inscriptions within an interactive inscription visualization tool which offers the inscriptions as pictures, rubbings or scans, and allows changes in their visualization. This information is supplemented by details of the different sites and previous interpretations, encouraging a gain of knowledge as a major goal of our research project.

Documentation and Processing

Traditionally, the documentation of carved stone scriptures is based on rubbings (Ledderose 1981). For this purpose, a paper is fixed on a stone's surface and then the paper is rubbed with ink. Thus, the structures and indentations (characters) of the wall are copied on to the paper. As a result, the surface of the wall appears in black, while the engraved inscriptions remain white. The main disadvantage of this method is potential damage to sensitive surfaces by the physical effects of abrasion, hence new and innovative documentation methods have been used, which protect the objects and provide a better base for the interpretation process (Fig.1).

These innovative methods result in various geometrical and visual documentation processes, which are not limited to the documentation of the inscriptions, but are expandable to their local and regional context (Boochs et al. 2006). The inscriptions fringe projection has been established for high precision 3D data acquisition, because it generates precise virtual copies of the inscriptions without making contact with

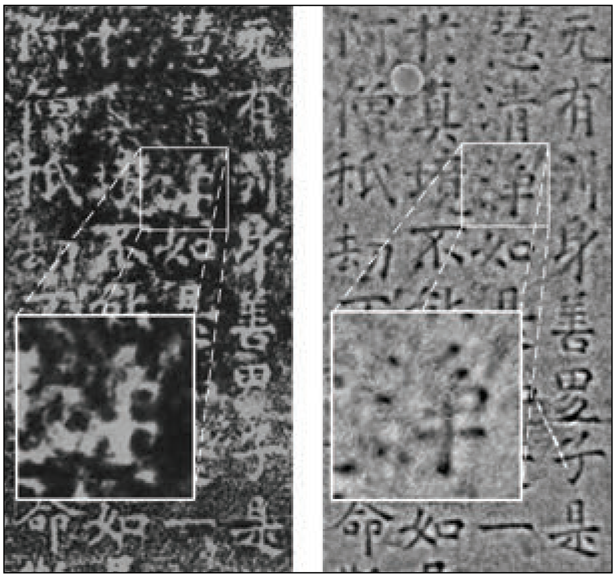

Figure 1. Comparison of rubbing (left) and processed results of the fringe projection (right).

their sensitive surfaces. Within the three-dimensional acquisition of the inscriptions' environment, laser scanning has prevailed owing to the fact that a larger context can be captured and so spatial relationships can be mapped. In addition, stereo-photogrammetry has been used as a geometrical documentation method, with Panorama-Photography and Polynomial Texture Mapping as visual methods (Malzbender et al. 2001). The use and benefits of these techniques are explained below.

Laser scanning

Laser scanning can be used to generate digital terrain models allowing the Buddhist texts and text passages to be placed in a local and regional context. By the use of laser scanning non-accessible objects can be captured with high accuracy, high resolution and high speed. The resulting 3D point clouds lead to 3D models, which describe the topography with a realistic impression of the environment by the use of textures. Beyond the visual advantage, the capabilities of analysis can be extended to the spatial aspect. Based on 3D models, lines of sight could be calculated and visualized, which might allow an analysis of the arrangement of the inscriptions. By complementing the 3D models with additional information, such as historic streets and monasteries, cost-benefit calculations can be performed which might lead to information about possible migration routes of monks.

The historical site of Wofoyuan (dimensions 80×300m) has been captured by a Chinese research team from several scanning points using the laser scanner Leica HDS6000.

Thus, the environment of the inscriptions is represented by a cloud of individual 3D points referenced in a local coordinate system which was constructed for this purpose. The average point spacing of this point cloud is at a distance of 30m, at about 9mm. The derived 3D models are generated by separating the northern and southern areas of the historical site and they are equipped with various generic and original textures, enabling a photorealistic impression of the environment (Fig. 2).

The textured 3D models are complemented by Shuttle Radar Topography Mission (SRTM) data for the province of Sichuan which have a resolution of about 90m, to perform the aforementioned analysis. For high performance presentation via the Internet the entire terrain model is prepared on several levels of detail (LODs) which allows the loading and showing of the parts of the 3D model in the field of view in real time.

Fringe projection

With respect to high resolution and high precision, fringe projection provides an exact geometrical copy of the original inscription (Böhler et al. 2004). Compared to the traditional rubbings, this 3D measuring technique provides very precise digital copies which offer better results in the legibility of

Figure 2. Textured 3D model of the 'Reclining Buddha' at Wofoyuan, Sichuan. In the upper left area caves where inscriptions are located.

each character (Fig. 3), give a more objective base for analysis and reduce the impact on the sometimes sensitive and eroded surfaces. This 3D measuring technique allows the capturing of objects less than 1m² in size and produces 3D data which facilitate many different possibilities of processing and analysis owing to their structure (Hanke & Böhler 2004).

The Buddhist stone inscriptions from Wofoyuan are carved into the cave walls whose expanse is up to 3×4m. A wall is scanned with a lateral resolution in the order of 0.25mm, using the GOM ATOS III, while the point density is higher because of a 50% overlap when scanning individual parts of the wall. With respect to the typical size of characters (~1cm²), this gives more than 1,600 3D points for an individual letter. Given the huge amount of data, the individual scans must be prepared so that they can be handled, analysed and visualized appropriately, and thus contribute to ensuring that the manual interpretation process will be automated. Despite this mass of data for one letter, an acquisition with even higher accuracy for exemplary areas is useful to increase the potential for a structural analysis of a typical character and to extract individual characteristics of these characters. This might help to find correlations with the work of a particular monk or stonemason.

Data processing

The data processing is divided into two main fields: firstly, the real 3D data is simplified into a 2.5D structure; and secondly, this 2.5D data is further transformed by image processing methods in order to reduce the amount of data and improve legibility. An efficient 3D to 2.5D transformation is possible as a result of the flat geometry of the inscriptions. Thus, the walls themselves can be approximated as a two-dimensional plane with inscriptions as height variations relative to that plane. The results of this transformation, the so-called raster-based digital elevation models (DEM), lead to a simplification in the treatment of complex data and enable the application of image processing algorithms. The latter are applied to perform image normalizations, various histogram operations enabling improvement of to improve image contrast and thereby legibility of the inscriptions (Schmidt 2009). Both processing steps can reduce the data volume of an inscription by a factor of one hundred.

The transformation of the 3D data into the 2.5D space needs to have a global surface model. This model has to be derived from all registered scans of a wall. Since all registered scans of an inscription wall form an amount of data that cannot be triangulated with the corresponding

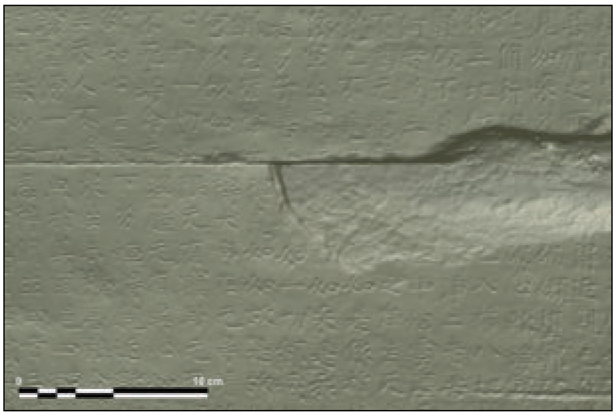

Figure 3. Shaded 3D model of a part of an inscription captured with the fringe projection system (1% of the entire wall)

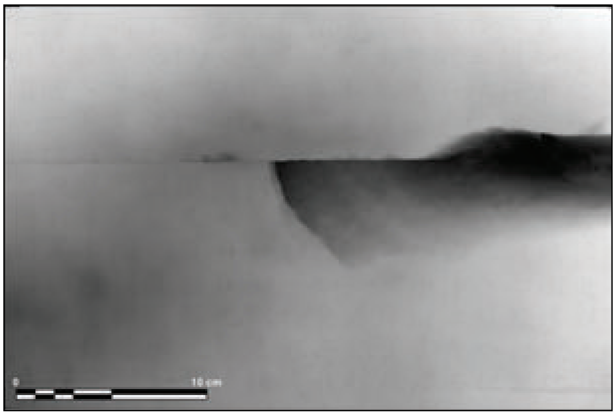

Figure 4. Digital elevation model of an inscription panel (32-bit image visualized in 8 bits).

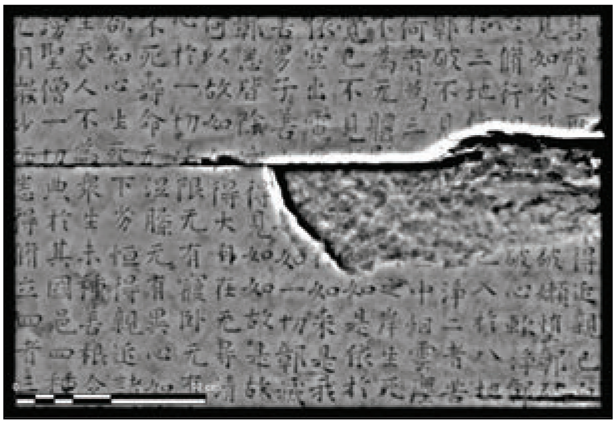

Figure 5. Processed DEM of an inscription panel (8 bit image).

software (GOM ATOS III), the data are split into vertical stripes, which will be triangulated to surface models and then exported together with their georeference. The transformation itself is performed by an ImageJ plug-in XYZ2DEMImporter which fits planes into this model and projects the original 3D points onto this plane. The spatial resolution for each pixel has been fixed at 0.15mm, which retains all relevant information sufficiently. The raster data of each vertical stripe is exported into a 32-bit image file that is subsequently rectified and merged using their georeference. Using the mosaic tool of ERDAS the georeferenced images are merged together into one large image (32 bit) which represents the inscription of an entire wall (Fig. 4).

The resulting raster data is processed further by image normalization, converting the heights of the elevation model into relative heights. These data are used to form the wall's topography which has to be subtracted from the original model in order to separate inscriptions and surface topography. The model of the wall's topography can be derived by smoothing the original raster data. Through a combination of histogram operations, such as histogram clamping and histogram stretching, an increase in image contrast can be achieved and, therefore, the legibility of the characters is improved. Histogram clamping uses limits depending on statistical values as they enable the best adjustment for characteristics of the respective image material. The implementation of histogram stretching is based on the standard function for transferring grey values to the required range from 0 to 255 (8 bit) or 65,536 (16 bit). (Schmidt et al. 2010)

The resulting DEM (Fig. 5) represents a wide and appropriate basis for further use in the interpretation process. While the inscriptions within the processed images are of high contrast, the surface roughness of the wall is also emphasized, especially in the area where the weathered characters less legibile.

Transcription and Analysis of Inscriptions

So far, the transcription of Buddhist inscriptions has been a manual process shaped by reading each individual character, transcribing it into Unicode-characters and comparing it with reference texts. Because of the mass of inscriptions and characters new and innovative approaches need to be found which automate this manual process significantly. There are a variety of algorithms and concepts for the automatic transcription and analysis of image data, which can be used for processing these steps further. Such steps could automate manual interactions, such as the identification of the characters, an automated interpretation of text passages or even a structural analysis of individual characters. All these approaches attempt to simplify and accelerate the process of interpretation by the user and help to obtain information that cannot be generated by a visual inspection.

Basically, offline optical character recognition (OCR) represents the electronic translation of handwritten or printed texts in the form of scanned images as machine-readable encoded texts. With particular regard to Chinese characters, OCR offers a variety of algorithms, which are based mainly on the binarization of the scanned images, then extracting and vectorizing the character's radicals or individual strokes (Cao & Tan 2000, Liu et al. 2001, Solth et al. 2009). The different algorithms provide good results in the identification of the characters. However, the capability of identification depends on a good extraction and vectorization of radicals or strokes which is correlated with the quality of the binarized image. Transferability could be given if comparable databases could be derived from the scanned inscriptions. The inscriptions represented by 2.5D raster data can be considered as orthophotos since the engraved structures are free from geometrical bias, true to scale and, as a result of the preceding processing steps, rich in contrast. In order to apply the algorithms of the OCR the 2.5D raster data need to be binarized which either leads to a loss of information regarding the engraved characters (individual strokes are lost) or misinformation. The data represent a raster-based elevation model of the inscription boards. As these consist of sandstone and are exposed to external influences such as wind and rain the engraved structures and the background are partially eroded. This means that the background in parts has the same height range as individual components of the engraved structures. Thus, a binarization of data, that shows such properties, results in previously mentioned problems, such as loss of information or misinformation.

Since the data of the inscription panels differ significantly from the usual data of automatic character recognition the direct decoding by means of OCR is difficult to realize. However, an identification and localization of a particular character can be useful, and is implemented using simple template matching (Steinke 2009), in order to serve the needs of the transcription process. The strengths of the template matching are 1) its robustness against radiometric influences and 2) its ability to apply any patterns. In contrast, the weakness of the template matching comprises a rotation and scaling invariance and poor performance on large images. Owing to these strengths and weaknesses, the template matching is particularly suitable for the raster-based elevation models. The elevation models feature a great deal of interference resulting from the roughness and unevenness of the wall and its erosion. Moreover, there are a variety of characters that must be localized within a wall. As a result of the fact that the characters vary only slightly — in size, orientation and characteristics within an entire wall — the rotation and scale invariance is of less significance, and is improved by applying an average character. The problems of performance are achieved by simple rasterization, because the characters are applied in a regular grid on the wall.

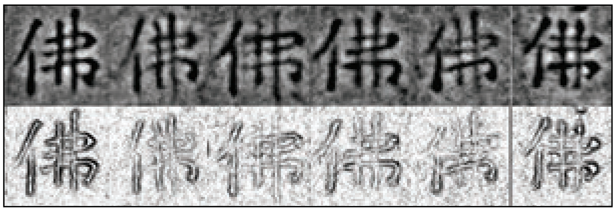

Figure 6. Group of detected character Buddha (佛). Top: original image snippets, Below: the characters visualized as a slope.

The recognition process by means of template matching is based on the selection of an individual character in an inscription panel (natural template) and the subsequent search for similar characters. The tolerance and robustness of the detected character depends on the correlation threshold used in the matching algorithm and on the geometric variations of characters. Figure 6 shows the results for a search of the character Buddha (佛) and gives an impression of the geometric variations that are accepted by the matching.

As shown in figure 7, the results are satisfying even in the case of lower correlation thresholds. In the upper left, an image window is shown which has been selected manually as a representative template for this character. Below the graphical representation of this sign, as derived from the Unicode value is shown. These two representations correspond very well, although small structural differences have to be noted with respect to size and orientation of the graphical elements forming the sign. They express individual characteristics of the handwriting of the person who engraved the signs.

The described recognition process allows the isolation and identification of individual writings. However, this process is still dominated by manual interactions such as the selection of the templates. This selection of templates cannot be improved further. However, the manual interaction can be facilitated considerably by the integration of additional information, located inside a database 'CBETA'

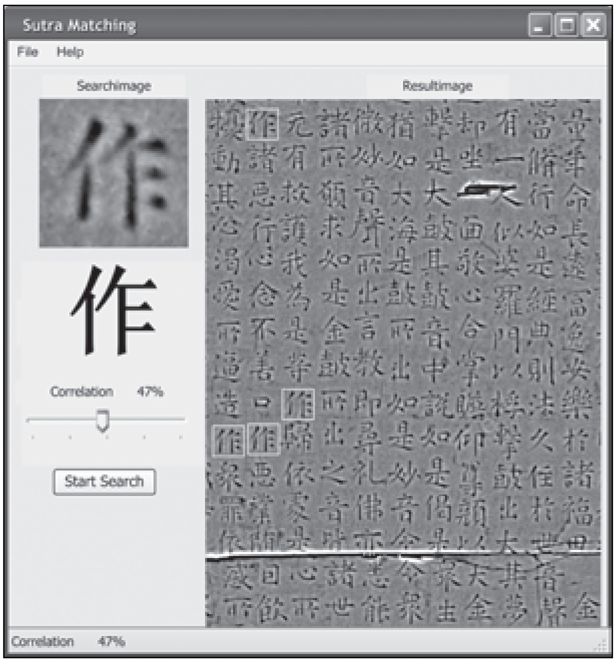

Figure 7. Automatic identification and localization of character in the images using template matching.

(CBETA 1998) which contains a digital library of those sutra texts which have already been found and translated from other sources. As monks generally made use of common Buddhist knowledge and teachings during their missionary work they mainly distributed known texts through their engravings aiming to communicate these texts to foreign regions. Thus, many of the texts found on the walls have their counterpart in libraries.

This leads to a second process which integrates the information from CBETA and is done in an iterative mapping of text sequences found on the wall with those in the libraries. This mapping tries to identify text streams inside the libraries which have been found on the wall. Therefore, the matching process locates, as a first step, some individual characters and searches for their counterparts within the reference library. A comparably small number of connected letters already defines unique text passages which allow them to be found in the reference text section. The aim is to merge the results of matching algorithms with the knowledge

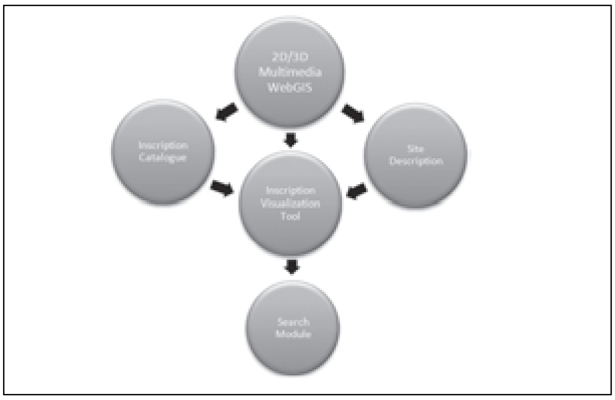

Figure 8. Structure and interaction of components for the Web portal.

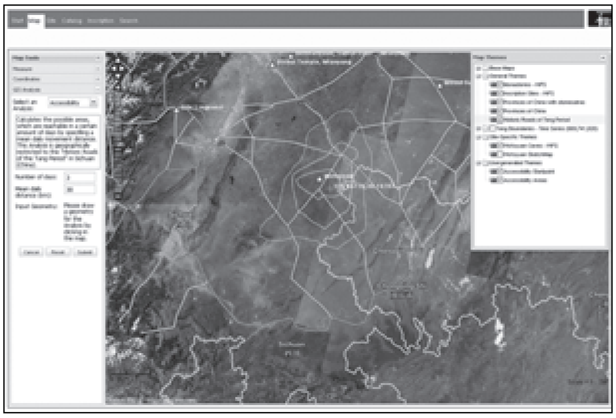

Figure 9. Network analysis of the average travel distance per day based on historical roads.

contained in the reference library. The matching might be based on natural templates extracted from the processed data, or on generic templates provided by Unicode characters defined in the Chinese alphabet. After the right text passage is identified from Chinese Buddhist canon 'Taisho' the comparison continues in order to find differences between the library and the engraved texts. These differences are very important for the interpretation process because they identify particular messages incorporated by the monk, and give a deep view into the changes and/or individual characteristics of Buddhist teachings.

Besides the differences in the inscription texts, for further interpretation the calligraphy of individual characters as well as the calligraphic differences between characters from different sites is of great interest as conclusions about the monk or stonemason can be drawn. The inscriptions were painted after smoothing the inscription panels by the monks and then engraved by specially trained stonemasons. Thus, with calligraphic analysis differentiations can be made concerning not only size and orientation of the characters, but also depth and special characteristics.

Visualization in Web-based Information System

The final goal of the research project is the visualization of the elaborated results by means of the Internet. For this reason, a web portal has been established, which basically consists of five components which comprise: textual descriptions of the sites; catalogues with information about the inscriptions; an application to visualize the inscriptions; a function to find the same characters in all inscriptions; and an innovative multimedia application combining two-and three-dimensional geographical data with pictures, panoramas and GIS functionalities, and acting as central interface between the other components (Fig. 8).

While the multimedia GIS, as well as the inscription visualization tool, offer a large number of manual interactions they also enable further interpretation and conclusions.

2D/3D Multimedia GIS

The multimedia GIS is central within the web portal, not only because it acts as an important interface between the various components mentioned above, but also because it controls the navigation through the web portal. The multimedia GIS guides the user from the spatial and temporal distribution of the sutra texts in East Asia via their numerous sites in Chinese provinces through to their substantive arrangement on the respective archaeological site.

The presentation of the sutra texts in their geographical context is founded on different base maps which are supplemented by thematic overlays, such as, for instance, historical roads, historic-political developments as well as locations of monasteries during the Tang Dynasty. As well as this presentation some spatial and temporal analyses are offered which provide information such as the route a monk took from a monastery to an inscription site. Based on historical roads, digital elevation models and theoretical assumptions, a network analysis can be performed, which calculates and visualizes the average travel distance per day (Fig. 9).

The visualization of the sutra texts in their archaeological sites leans on meta-information, 360° panoramas and 3D models of the sites and their inscription panels. While the 360° panoramas are used for visualization only, the 3D models provide further analysis, such as visibility analysis. This visibility analysis allows verifying the line of sight which can be seen from the current viewpoint (Auer et al. 2011).

Inscription visualization tool

The results of the documented sutra texts and already achieved interpretations of different Buddhist inscriptions are made accessible by means of an inscription visualization tool. With this tool, the different methods of documenting inscriptions, such as pictures, rubbings and scans, are shown. Depending on the type of documentation, various static and interactive visualizations and thematic overlays are provided, which should support the further interpretation and should lead to a lively exchange of knowledge between experts. As a result of its structure, the tool can be used separately from the web portal in the interpretation process and presentations.

In addition to a pure visualization the user can analyse the scans of an entire inscription panel using a web-based procedure of 3D computer graphics and methods of image processing.

The 3D computer graphic procedures allow manipulations of parameters such as texture, lighting and shading, and give a close-to-reality presentation of the inscriptions. Interactive changes of the light source affect the shading of the surface directly which provides a better idea of the inscription's 3D surface (Fig. 10). Dynamic virtual water filling influences the appearance of the 3D surface and thus gives an even better impression of the depth of the characters.

Image processing methods are concerned with image manipulation in order to emphasize special aspects of the characters, and to support the identification of weathered characters. Thereby, the colour functionality reverts to various look-up tables, and the convolution functionality to predefined filters such as edge detecting and blurring filters.

As well as interactive visualization, the tool shows the user the available interpretations of the inscriptions (Fig. 11). This simplifies the process for the inexperienced user or provides

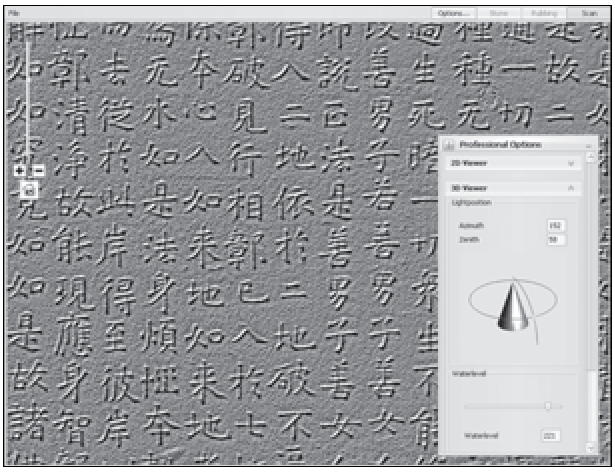

Figure 10. Shading and water filling applied to sutra texts.

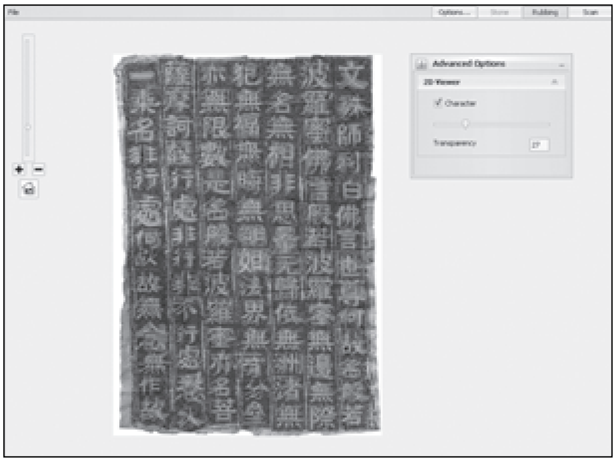

Figure 11. Interactive overlay of achieved interpretations on a historical rubbing.

the experts with an alternative version of interpretation. Technically, this is performed by an interactive overlay of the rubbing or scan with an interpreted text of the sutra. The overlaying information is generated from the matching algorithm and is linked automatically by the coordinates of the inscription catalogue and the character in the referenced rubbing or scan.

Conclusions

Modern precision measuring techniques open up new perspectives for archaeological and art-historical questions. This assumes that the objects are accessible to the equipment and can be captured with high precision. The captured data opens up various processing chains and enables their presentation on the Internet whereby important cultural treasures are made accessible to a wider community.

For the stone inscriptions, fringe projection techniques have been used to document the inscriptions with laser scanning utilized for their environment. Compared to traditional rubbing, high resolution scanner data provide non-destructive virtual copies of the stone inscription. It has been shown that such digital copies offer improved legibility of each character.

However, high resolution measuring techniques produce huge datasets which cannot be handled simply and directly by the user that wants to interpret the sutras. Nor can they be transferred over the Internet without further processing. Therefore, a processing chain has been developed in order to prepare the data for both interpretation and visualization on the Internet. In spite of the good results achieved with processing for interpretation purposes there is still a need for an algorithm to separate the weathered characters from the walls' surface and to emphasize such characters.

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