

# Easy and cost-effective cuneiform digitizing

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## Abstract

*Modern researchers in the field of ancient Mesopotamian studies read their primary sources, cuneiform tablets, either manually, by moving lights around the tablet to maximize readability, or by studying photographs (or drawn copies) when the actual tablet is not at hand. Although the latter method only holds partial information, and is therefore less desirable, it is often the only available resource due to the inaccessibility of tablet collections. Recently, several digitizing projects have been proposed to provide accurate 2D+ and 3D models of these tablets for digital preservation. However, these methods require manual interaction or are not available to many research groups due to their cost. Furthermore, the digitizing device should be quickly deployable on-site, have an easy calibration procedure and should not have any moving parts which could be problematic in difficult circumstances. We therefore present a new fully automated cuneiform tablet digitizing solution that is relatively inexpensive and easily field-deployable. The solution consists of a small, light-weight dome of light sources and a digital camera. 2D+ representations of the tablets are created by use of photometric stereo. The obtained information allows for photorealistic virtual re-lighting and non-photorealistic rendering of the tablets in real-time through the use of programmable graphics hardware.*

Categories and Subject Descriptors (according to ACM CCS): I.3.3 [Picture/Image Generation]: Digitizing and scanning I.3.7 [Three-Dimensional Graphics and Realism]: Color, shading, shadowing, and texture I.4.1 [Digitization and Image Capture]: Reflectance d

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## 1. Introduction

Since mankind developed writing, record keeping emerged. One of the earliest manifestations of writing is found in ancient Mesopotamia, circa 3200 B.C. These texts used the so-called cuneiform writing system, wedged syllabic signs impressed with the bottom of a reed stylus in a shaped clump of wet clay (tablets). Beside religious, lexical, mathematical and literary texts, large amounts of administrative transactions were recorded and kept in archives. Thanks to excavations, conducted since the mid 19<sup>th</sup> century, hundreds of thousands of these texts were unearthed; today they are mainly kept in museums or university collections around the world. Like the tablets, researchers who can read and work with these texts are spread over four continents. A major problem for their research is the inaccessibility of the tablet collections because of restrictions or geographic location. Worldwide some 200 scholars are sufficiently trained to

read and translate these texts. Only a small percentage of the known cuneiform texts are published and open for general study. Consulting an actual tablet in a collection and making a hand copy of it is a time-consuming process. Conservation of cuneiform tablets is an expensive matter as they are, in many cases, fragile and fragmentally preserved due to their age and history.

Several institutions have started to register their cuneiform collections decades ago, using conventional photography [CDP, ED]. But as a cuneiform tablet is a 3D object with impressed wedges, a static view can never tell all. To read a cuneiform tablet, a trained cuneiformist has to interact with each sign on the tablet separately to gather all available information. In practice the tablet is tilted in all directions to catch different lighting and viewing angles on the cuneiform sign. From some light angles textual features will be illuminated, but others will drop shadows and make other signs

invisible. Even normal digital photography can not resolve this problem.

To make these cuneiform collections, containing several hundreds of thousands of tablets, accessible around the world, digitizing is needed. But this has to be done with respect to the specific properties of their surface. 2D+ images of the tablets, allowing researchers to study every detail, are therefore suggested. Each tablet application also has to be guided by a list of annotations which is connected to a database.

## 2. Related work

Vast digitizing projects can be found throughout the last decade, but none have encountered the above sketched problem. The best known is the CDLI (Cuneiform Digital Library Initiative) [ED], a joint project of the University of California at Los Angeles and the Max Planck Institute for the History of Science. Their goal is to make all cuneiform texts available on the Internet through transliteration and images. In many cases the image is a 2D scan of the hand copy or a digital flatbed scan of the tablet. Based on the scans manual drawings with software packets as Adobe Illustrator can be made. Another digital database containing high resolution photos of Ancient Near Eastern texts is *Inscriptifactor* of the West Semitic Research Program [HLZ05]. For the cuneiform tablets they also use conventional photographic techniques resulting in typical 2D images, with their inherent restrictions. Toward the future they are experimenting with the so-called image-based re-lighting concept.

In [AL02], Sean Eron Anderson and Marc Levoy of the Stanford University were the first to take the special shape of the cuneiform tablet into account. As a tablet is a 3D object, writing can occur on all its sides. Therefore they developed an unwrapping model, so all texts can be visualized on one 2D image. Their pipeline requires however a great deal of user interaction and the combined use of several software packages.

Recently, Cohen et al. [CDS\*04] have presented a hardware solution within the *iClay/Digital Hammurabi* project, which combines structured light with photometric stereo from a sparse set of images, using a DLP projector, a turntable and a CMOS camera, to obtain a 2D+ and 3D model of tablets. Their set-up however requires moving parts and may therefore be unsuitable in some out-of-lab situations. Furthermore, their goal is quite different from ours as they aim for a very high resolution 3D surface scanner [WS] for cuneiform tablets. The approach presented in this paper is geared towards an easy-to-use, relatively inexpensive solution for virtually inspection of tablets, without focusing too much on the 3D aspect (although 3D information can also be extracted).

Some research centers [CHI] have opted for a 2D+ representation of tablet by way of *Polynomial Texture Maps*

(PTM) [MGW01]. The tablets are put inside a dome containing flashbulbs with a digital camera mounted on top. A series of images illuminated each time by one flash light are captured and used to compute the PTMs. These maps store a set of six coefficients at each pixel that can be used for re-lighting and image enhancements via the evaluation of a biquadratic polynomial.

## 3. Overview

This paper describes a fully automated pipeline for the digitizing of cuneiform tablets. Their obtained virtual counterparts allow them to be studied by researchers around the world, without having physical access to the tablet itself.

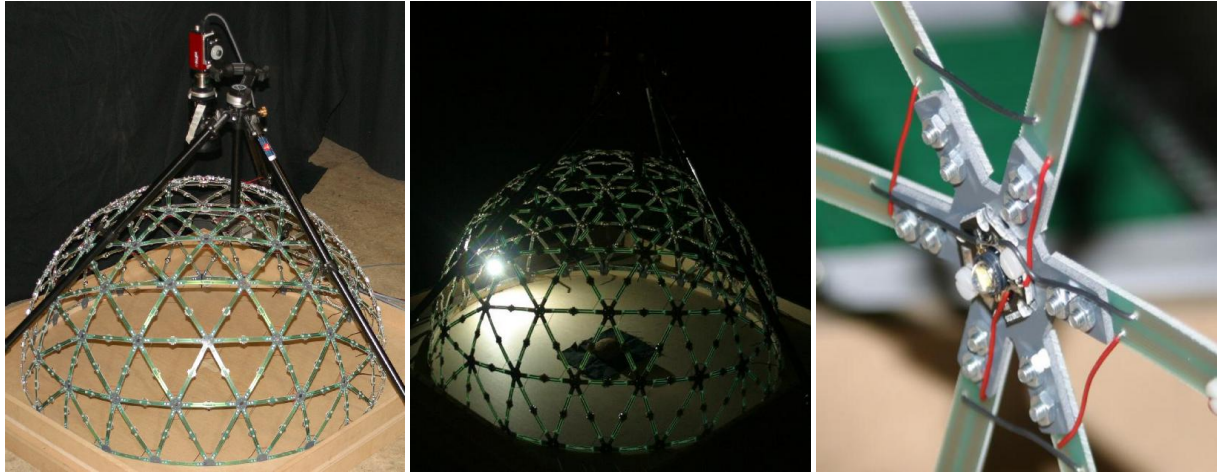
As acquisition device, a dome structure containing many light sources, not unlike [MGW01], has been chosen. A digital camera is mounted on top of the dome, facing downwards at the object to be digitized. As all light sources (LEDs) are incorporated into the dome, no tedious calibration is needed. Given that the camera is mounted correctly on to the dome, the relative position of all lights becomes known. Its dimension and weight allow portability, while the used materials keep the cost down (the most expensive parts being the LEDs). Section 4 discusses the acquisition device in more detail.

As in [MGW01], the recording consists of sequentially illuminating the object by each light source separately. However, instead of fitting polynomials through the captured set of images, we apply a photometric stereo algorithm, from which a normal and albedo map can be obtained. These two maps are sufficient for the generation of novel views through virtual re-lighting or other image enhancements. Examples of a normal and albedo map can be respectively seen in figure 5(d) and 4(a). The robust photometric stereo algorithm used here is described further in section 5.

Section 6 introduces the four tablets which are used as an example and discusses the client application which allows cuneiformists to handle these high-resolution *virtual tablets* in real-time. One or several lights can be positioned around the virtual object to enhance readability, alleviating the restriction of conventional photographs. Furthermore, several non-photorealistic visualizations can be envisioned which could help in studying the tablet. Both type of renderings are shown using the four tablets. Finally, the conclusion and future work are discussed in section 7.

## 4. Digitizing setup

The portable dome has a radius of 50 cm and is a discrete illumination hemisphere consisting of 256 white power LEDs positioned both on the knots and in the center of the edges. The LEDs are 5W Lambertian emitters (over a 120° angle), resulting in homogeneous illumination. The bare dome, without the camera mount, is shown in figure 1.



**Figure 1:** *Left: The portable dome (prototype without camera mount) contains LEDs at both the knots and the center of the edges. Middle: Dome during recording. Right: Close-up view of a LED.*

Each LED can be individually lit and the corresponding images can be recorded by the camera mounted on top. The entire recording procedure is programmable and fully automatic.

A variation to the standard geodesation was applied in order to spread the vertex positions more evenly across the sphere's surface. This results in smaller angles between adjacent light sources. (Minimum and maximum angle between adjacent lamps is  $7.5^\circ$  and  $10.5^\circ$  respectively.)

Through the use of PVC, PCB (printed circuit board) and LEDs for the construction of the dome, the overall structure is very sturdy yet weights in below 10 kg, allowing for a portable and cost-effective solution.

## 5. Photometric stereo

When studying tablets, the cuneiformist uses different lighting and viewing angles to study the wedges in a tablet. The most important property in conveying these indentations to a user are the surface normals. For a fixed viewpoint, these normals can be extracted from images recorded with different known lighting conditions. Given enough of these images, sampled over the hemisphere, robust methods can estimate both the normals and albedo of the surface despite the possible presence of shadows and specular reflections. These properties are stored in maps which can then be used to interactively re-light the object.

Next, section 5.1 deals with the calibration of the light sources. In section 5.2, the robust extraction of surface properties is discussed. Section 5.3 finally discusses the computation of a 3D surface by integrating over the normal map.

### 5.1. Light source calibration

For distant point light sources, only the direction and intensity are considered in image formation. By construction the directions are known, however the color and intensity of each LED needs to be measured. Factoring out these differences is important to obtain accurate results further on. Images of a diffuse white sheet of paper, separately illuminated by each LED, are recorded. The average image intensity within a specified bounding box, corrected by the light source direction, will give the color and intensity of each light source.

### 5.2. Robust extraction of surface properties

Photometric stereo, first introduced by [Woo89], allows the estimation of local surface orientation by using several images of the same surface taken from the same viewpoint but under illumination coming from different directions. The light sources are ideally point sources located at a far enough distance from the object. This means that in each case there is a well-defined light source direction from which to measure surface orientation. Therefore, the change of the intensities in the images depends on local surface orientation, illumination direction, illumination intensity and albedo for Lambertian surfaces. This is expressed by the following equation,

$$I_j = \rho L_j \cos \theta_j$$

with  $I_j$  the pixel intensity for illumination direction  $j$ ,  $\rho$  is the albedo or reflectivity of the surface point,  $L_j$  the intensity of the illumination and  $\cos \theta_j$  is the cosine of the angle the normal makes with the illumination direction or simply the dot-product  $\mathbf{l}_j \cdot \mathbf{n}$  between the unit direction vector of illumination and the surface normal. Usually this is rewritten



**Figure 2:** Samples of the recorded set of images from each tablet. The light in each shown image is positioned at  $(\frac{1}{\sqrt{2}}, 0, \frac{1}{\sqrt{2}})$  on the unit hemisphere. (a) replica of a letter from the El Amarna era (86mm×73mm) (b) replica of a late Ugaritic tablet (95mm×75mm) (c) Neo Sumerian offer receipt (30mm×27mm) (d) Neo Sumerian receipt for reeds (30mm×30mm)

as follows,

$$I_j = \mathbf{h}_j \cdot \mathbf{s} \quad (1)$$

where the albedo  $\rho$  is absorbed in the normal  $\mathbf{n}$  to give a scaled normal  $\mathbf{s}$ , and similarly  $L_j$  is absorbed in  $\mathbf{l}_j$  to give  $\mathbf{h}_j$ . Considering the problem we are facing, the only unknown in this equation is the scaled normal  $\mathbf{s}$  since, by construction of the dome and calibration of the lights, we know the different  $\mathbf{h}_j$  and  $I_j$  is what we measure by recording images. So, for grey-scale images, every image with a different illumination direction gives a linear equation in the scaled normal for each pixel. A minimum of 3 of these equations allows

for the computation of the scaled normal. Extraction of the actual normal and albedo from this is straightforward.

In reality, however, the presence of shadows and the specular behavior exhibited by some surfaces render this Lambertian assumption invalid and force us to resort to a method which is robust against such complicating effects. Observing the intensities measured for a single pixel under different illumination directions, we see that still most of these exhibit a purely Lambertian behavior. If enough measurements are available this fact can be exploited to determine the normal and albedo map, by iteratively trying to find a consensus around the Lambertian model.

As a first step, we only consider those measurements (di-

rections)  $M$  with intensities in the interval  $[I_{low}, I_{high}]$  discarding measurements with a high probability of shadow or specularities. In practice we use a value of 10 and 240 for  $I_{low}$  and  $I_{high}$  respectively. This is not strictly necessary, but can speed up the remainder of the algorithm. Using the measurements  $M$  and equation 1 we can calculate an initial scaled normal. Based on the current estimate of the scaled normal, we calculate error residuals for all directions in  $M$ . Only those directions with small residuals are used to update the scaled normal, again by using equation 1. Now, we keep iterating until convergence over the two previous steps, namely, calculating the residuals and updating the scaled normal. This finally results in the desired scaled normal.

### 5.3. 3D surface reconstruction

A 3D surface can be obtained by calculating a depth map, which for each pixel gives the distance of the corresponding scene point with respect to the camera center. Given a normal map and under the assumption of an orthographic camera model, a depth map can be calculated by what is called normal map integration [ZCHS03]. An example of a reconstructed 3D surface can be seen in figure 7(c).

## 6. Results

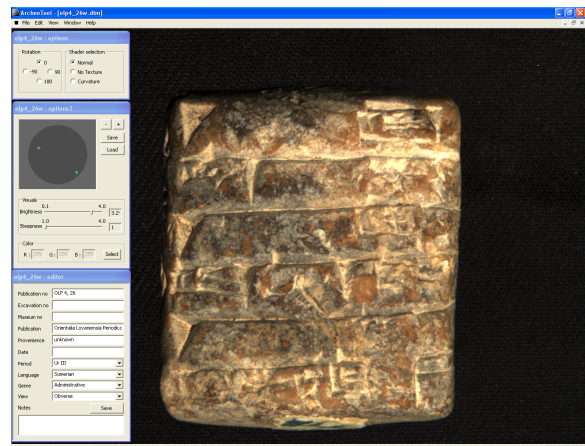
In this paper, the digitizing results of four tablets (two replicas, two originals) are being presented. One image out of the full set of recorded photographs is shown for each tablet in figure 2. Tablet (a) is a letter from Abdi-hiba, king of Jerusalem (El Amarna era). Tablet (b) is an economic treaty by king Ini-Teshub of Carchemish (13<sup>th</sup> century B.C.) with his seal in the center. The bottom two tablets are Neo Sumerian accounts: (c) is a receipt for offertory sheep (OLP 4,26), (d) is a receipt for reeds (OLP 4,57).

All recordings were shot with an exposure time of 1 second, resulting in an acquisition time of 5 minutes for 256 images. The computation of the normal and albedo map takes 15 minutes on average for an image dimension of 1600x1200 on a P4 2.4 GHz.

Both a 1600x1200 CCD and a 2588x1958 CCD camera have been used in the experiments. For the former camera, this results in an average resolution of 350dpi for a 10x10cm object or 700dpi for a working volume of 5x5cm. The latter camera allows for a resolution increase of 60%.

### 6.1. Client application

In this section, we describe an application that can aid the cuneiformists with interpreting tablets using the obtained albedo and normal maps as inputs. The application allows for the generation of realistic novel views by using up to four virtual lights simultaneously. The direction, light intensity and color of each light source can be adjusted in real-time. Useful light configurations can be saved and re-used at a



**Figure 3:** Screen-shot of the client application containing the main visualization window together with a visualization selection window, light manipulation window and annotation area. In this session, two virtual light sources have been set up.

later stage with other tablets. At any time, full-resolution images of the current view can be saved. For reading along the edges, multiple sides of a tablet (if recorded) can be shown simultaneously. The annotation of each tablet is also visible within the application. A screen-shot of the application is shown in figure 3.

### 6.2. Photorealistic rendering

One way of using the application is to render tablets under realistic lighting conditions. The resulting images could, for example, be used in publications. Further, virtual materials can be applied to the tablets. Examples can be seen in figure 4(b-c) where tablet (c) is rendered with a dry look, using a pure diffuse material, and a wet look, by adding a specular component. For the specular contribution, the Torrance-Sparrow model was used.

Sometimes, when studying a tablet, not one but two or more raking or overhead lights are used simultaneously. The current client application can render up to four virtual light sources together in real-time. An example of multiple virtual lights is shown in figure 3.

Further, it is important to notice that, contrary to PTMs, this method does not capture variations due to surface self-shadowing and inter-reflections. PTMs can recreate those variations as they are more geared toward reproducing (and exaggerating) appearance. In our method, we focus less on appearance but more on the underlying surface. A comparison between the obtained normals by both methods is depicted in figure 6. For this, we implemented the PTM fitting algorithm and checked the computed results with the results



**Figure 4:** Photorealistic renderings of tablet (c). (a) recovered albedo map (b) tablet virtually lit by one raking light source using only a diffuse component (c) tablet lit by same light source as (b), with added specular component.

obtained from the freely available PTM software. Although not much can be said about the accuracy of both methods without ground-truth, we feel that the normals from photometric stereo divulge more information about the surface.

### 6.3. Non-photorealistic rendering

Additionally, several non-photorealistic (NPR) visualizations, commonly used in other projects, are also available.

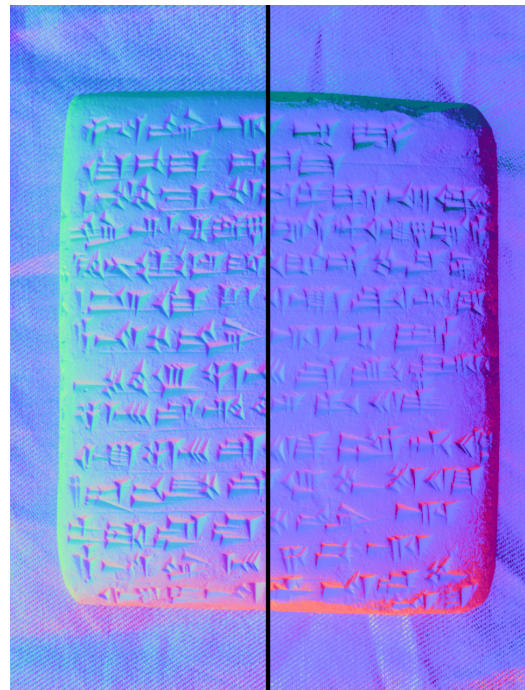
One NPR effect which proved quite interesting is *slope exaggeration*. In this visualization mode, the angle between each normal  $\mathbf{n}$  and the Z-axis is enlarged while keeping the direction within the XY-plane.

$$\mathbf{n}^* = \frac{\mathbf{n}_s = (n_x, n_y, n_z/s)^T}{\|\mathbf{n}_s\|} \quad \text{with } s \geq 1$$

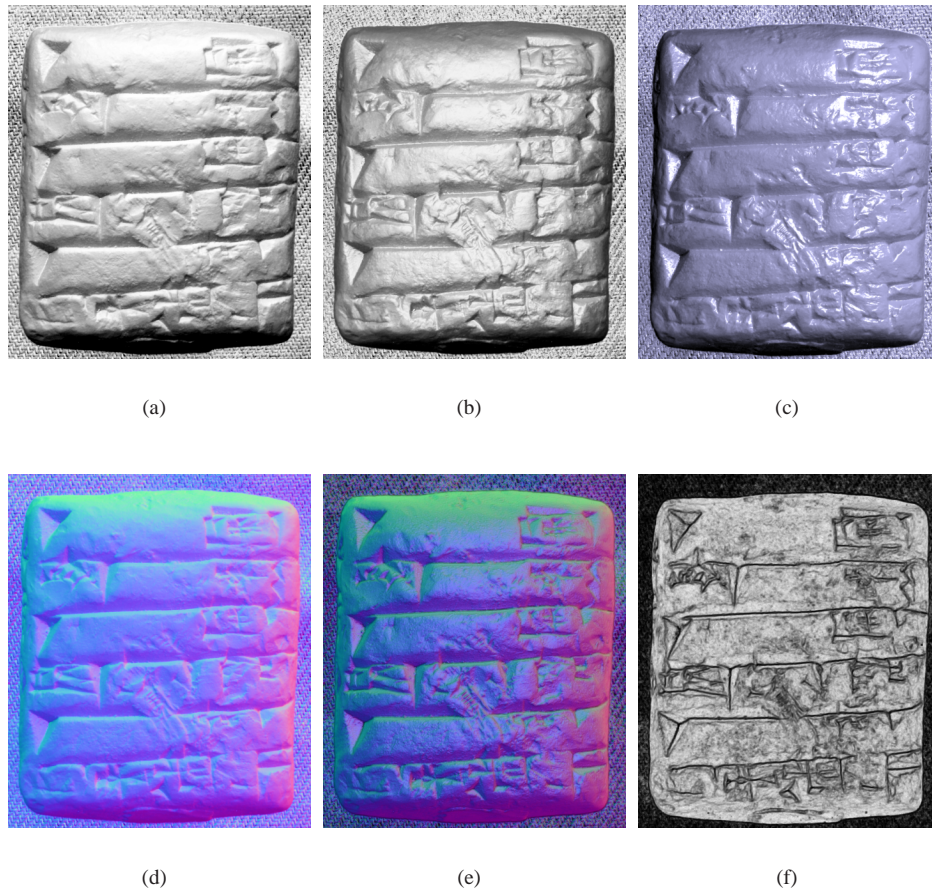
It can be seen that by creating a *caricature* of the tablet in this way, wedges become more outspoken. This effect can obviously be combined with some of the other visualization styles.

A few examples of NPR renderings, such as shading, curvature coloring [AL02], slope exaggeration and a combination of these are shown in figure 5.

All re-lighting algorithms are implemented efficiently on the GPU via fragment shaders using OpenGL 2.0 and the OpenGL Shading Language [RKLO04]. This allows for real-time rendering of novel views at high resolution.



**Figure 6:** Comparison of acquired normals of tablet (a) using our photometric stereo approach (left) and compute normals obtained from PTM coefficients (right). The same set of input images has been used for both methods.



**Figure 5:** *Non-photorealistic renderings of tablet (c). (a) shaded version using one virtual light source (b) shaded version with exaggerated slopes (c) uniform albedo with added specular component (d) obtained normal from photometric stereo (e) rendering with exaggerated slopes, combining normal and curvature coloring. (f) curvature coloring.*

As shown on figure 7, not only the cuneiform signs benefit from a 2D+ representation. Seal impressions, which occur frequently on tablets, or other clay surfaces are often not very visible on conventional photos. With this application their visibility becomes very explicit.

## 7. Conclusions and future work

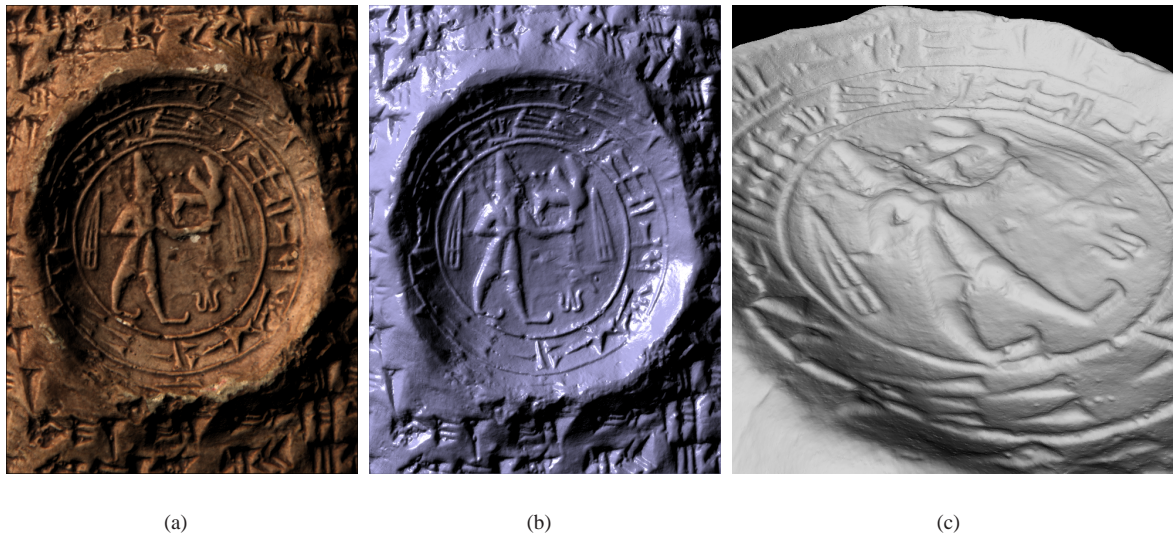
We have presented a cost-effective, light-weight, easy-deployable hardware for fully-automatic tablet digitizing. This allows cuneiformists to digitize tablets on-site without the need of specialized acquisition knowledge. Once a set of images is taken (roughly within 5 minutes), the software automatically extracts the normal and albedo maps.

A client application allows for the generation of novel high-resolution views which are rendered in real-time using commodity graphics hardware. Several photorealistic and

non-photorealistic effects can be used to aid the researcher with his study of the (virtual) tablet.

At this moment only the normal and albedo map are reconstructed from the recorded set of images. We are currently studying ways to utilize a reflectance model in order to also extract the per-pixel specularity of an object.

In the current version of the application, the user can select several sides of a certain tablet, allowing him to read across different sides. Since we have an approximation of the 3D structure of the tablet to our disposal, a future extension could consist in combining image-based re-lighting (virtual light, fixed view) with image-based rendering [WVVV05] (fixed light, virtual camera). This could be an alternative to the geometric solution where first a full 360° 3D scan of the object is created.



**Figure 7:** Close-up of Seal of Ini-Teshub (60mm×50mm). (a) textured re-lighting, (b) shaded re-lighting with added specular component (a&b are lit by the same virtual light) (c) 3D view of reconstructed surface

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