Seal Rotation Device – an Automated System for documenting Cylinder Seals

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Abstract
Cylinder seals are complex artifacts used in many early administrative systems especially in the Near East and Egypt. They are also linked to religious practices and concepts of identity. Several classical methods can be applied to document these objects, like photography, drawing and molding in plaster or plasticine. In addition to more recent methods like structured light scanning, we present an alternative method for 3D data acquisition. By combining existing technologies in a particular way, seals can be documented fast, cost efficiently and safe from a conservation viewpoint. This method developed at the Interdisciplinary Center for Scientific Computing (IWR) at Heidelberg University is a two-step procedure: first several series of images are obtained with a digital reflex camera in an automated way. The seal is mounted between two soft silicone buffers. An Arduino-based control unit rotates the seal using a stepper motor and triggers the camera. In the second step a 3D reconstruction of the seal is computed with the photogrammetric structure-from-motion approach. We will show first results acquired with this method both at the Petrie Museum of Egyptian Archaeology and the British Museum in London.

1. Introduction

Cylinder seals are important artifacts in archeology and play an important part in current research. To date different techniques for their documentation are available. Beside classical methods like ink drawings or rollouts on plasticine, 3D scanning as an emerging technology has already proven to show promising results[15, 2].

In this paper we introduce a new and cost-effective procedure to obtain 3D models from cylinder seals. The individual methods this process is based on are already well established in other fields. But by combining those methods and automating them we present a new approach, which is time and cost effective and to our knowledge has not been done before in this manner[1]. The basic idea of this

[1]There are some similar approaches in other research areas, but usually using expensive software, see for example [13]. Many other approaches are using similar setups to develop, improve or evaluate the SfM methods or results by rotating objects on a turntable, see [4] for example.

method is to rotate a cylindric seal around its roll axis with a predefined number of steps taking a photo each time.

We use a rotation device we developed specifically to automate this task and a SLR camera. The device triggers the camera and rotates the seal incrementally by a predefined angle. This allows us to gain a huge benefit in time and accuracy compared to manual operation. The requirements in hardware and software are kept to a minimum, encouraging others to copy or adapt our design to their individual fields of application. The next step of our procedure is the reconstruction of the three dimensional model. Analysis can then be performed based on the mesh using software like GigaMesh [12] for a virtual rollout of the seal. This procedure has successfully been applied to 14 seals that were digitized at the *Petrie Museum of Egyptian Archaeology* and the *British Museum* in London.

The objective of this paper is to give an overview on the procedure we developed for documenting cylinder seals. Our intention is to present an alternative to expensive 3D scanning equipment without having to sacrifice accuracy. Section 2. explains the important role of cylinder seals in archaeology as well as the advantages of using 3D models in contrast to classical methods. Section 3. elaborates on the procedure to obtain those models and provides detailed information about the device itself (section 3.1.). In section 4. we demonstrate the success of our method by showing cylinder seals that have been processed in the way described in this paper.

2. Cylinder seals in archaeological research

Cylinder seals are rolled over wet clay stoppers of all kind to imprint their inscriptions and consequently seal the objects that were closed by the clay stoppers. The imprint is to be considered the positive of the image, mostly appearing in raised relief. The cylinder seal however is inscribed with the mirror image using the intaglio technique. According to the current state of research cylinder seals were a Mesopotamian invention of the end of the 4th Millennium B.C. [16, 36]. From Mesopotamia the concept of small inscribed cylinders spread to neighboring early states in the Near East, North Africa and the Eastern Mediterranean region (Levante). There they became significant parts of early administrative systems.

The importance of the cylinder seal as a complex artifact spans several areas of archaeological research. To date cylinder seals have often been documented and published as ink drawings of a (virtual) rollout, plaster casts taken off an imprint in plasticine or single photographs. Those methods cannot illustrate all aspects of cylinder seals, as they either lack information on form and material or are only able to present one view of the seal. This is especially problematic since the seals are usually quite small, ranging from 1cm to 4cm in height with completely differing diameters.

In contrast to classical documentation methods the 3D-model is a high quality image of the original cylinder seal. Also the 3D-model can be made available to a large number of expert researchers. It already contains every information that can be captured from an actual object by the eye of the researcher. This instance offers the possibility to view the different aspects of the cylinder seal, form material and inscription in one. Consequently a better picture about the usage, wearing and ideas encompassed in a cylinder seal can be obtained by applying our method. It is also possible to create virtual rollouts from 3D-models as templates and complements to (the time consuming) drawings by archaeologists. A research interest on 3D-models of especially soft stone cylinder seals are for example the tracing of wear on the inscribed surfaces and the boreholes. The former could testify continuous rolling on clay and the latter shows the fashion of every day wearing.

Today there exist several methods to document seals directly in 3D. There are for example scanners based on the structured light method, like the one also used at the IWR. On one hand it can document objects with very high precision, but on the other hand the scanner also is very expensive. Similar are laser-based methods which are very precise, but also costly.

3. Method proposed

The method we propose combines Structure-from-Motion (SfM) photogrammetry with a special rotation device developed by us for that purpose. Since our method is based solely on photography, the equipment therefore is comparatively cheap, since good photographic equipment is usually already available. As we will show, the results provide enough details to document objects like the presented seals.

3.1. The rotation device

The SfM algorithm needs a large number of pictures covering an object from lots of different angles in order to produce an accurate and gap-free 3D representation. This can be very time consuming if repositioning the camera and/or the object is done by hand. Cylinder seals were handmade commodities in constant use. Because of their material, manufacture and wear they can't be treated as perfect cylinders. In the case of cylinder seals we propose a device that rotates the seals in predefined steps around their main axis. Furthermore, after each increment the camera is triggered automatically allowing to record a complete revolution of the seal unattended in only a few minutes, depending on the shutter speed and the number of steps.

The targeted users for the seal rotation device are archaeologists and cultural historians who do not necessarily posses a profound technical background. Therefore the main objective while designing was to keep the hardware and software requirements as low as possible allowing for an easy reproduction and adaptation of the device. We focus on robustness and practicality of the system in environments like museums where space and time is naturally scarce.

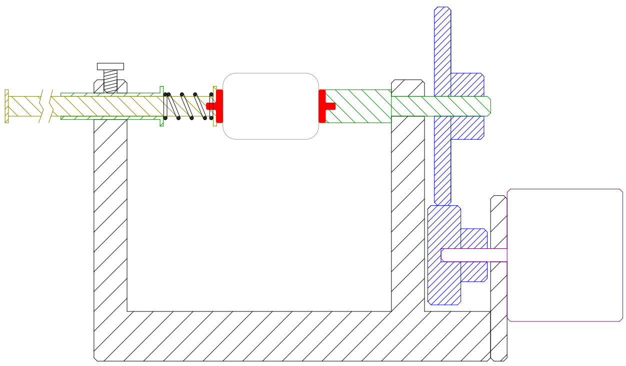

Figure 1. Mechanics of the seal rotation device

In our device the seal is clamped between two coaxial mounted axes and held in place by a coil spring. Buffers made of soft silicone protect the seal and make the procedure safe from a conservation viewpoint. The spring force is adjustable to adapt to different dimensions and weights of the seal by changing the spring bias. The axis is driven by a 2-phase stepper motor over a $2:1$ reduction gear (Figure 1). Due to this reduction and the use of micro stepping we can achieve a theoretical resolution

Arduino Uno	25€
Stepper motor driver	10€
Stepper motor	20€
Remote controller	5€
Additional electronic parts (LEDs, case, switches)	20€
Mechanical parts	30€
Sum	110€

Table 1. Costs of the seal rotation device

of 3200 steps per revolution (approx. 0.11 degree), limited only by the mechanical precision of the gears.

Three main electronic components can be identified: the motor driver, the camera triggering device and the microcontroller.

The stepper motor driver we use is a *Pololu A4988* stepper driver. This board and similar compatible clones became very popular in the rapid prototyping scene [21] and can therefore be obtained easily around the world at very low prices.

The camera we use is a Nikon D800 with a 60mm fixed-focal-length lens. This model provides a proprietary ten-pin remote terminal for triggering the capturing mechanism. By inserting two relais, a simple remote control for that camera was modified to be triggered by the microcontroller. It is also possible to connect an infrared transmitter to the control unit instead to emulate IR-based remote controls. This enables the device to trigger a wide range of other camera models from different manufacturers.

The controller is an off-the-shelf *Arduino Uno* board equipped with an Atmega328 microcontroller. The Arduino project has gained high popularity in recent years. A free and open source development software is available for every major operating system enabling everyone with a USB port to start using Arduino boards. [1]

The software consists of two parts: a firmware for the Arduino microcontroller written in C++ and a PC frontend. The frontend is based on the Qt5 library and focuses on portability and intuitive use. It runs on MS Windows, MacOS X and Linux. All software parts are open source and published under the Creative Commons license. We developed the firmware using the Arduino IDE. This allows for an easy adjustment to individual needs by the users themselves. The communication protocol between PC and device is kept simple and human-readable. An integration into other software projects can therefore be done without much effort. In addition to being directly controlled by a PC the device can also be used in stand-alone mode, eliminating the need for a big setup in places where there is limited time or space available.

Depending on the camera's shutter speed and the time needed to store the image to the flash memory, a capture can be triggered approximately every 2 or 3 seconds. The time needed for the stepper to advance is almost negligible compared to that. With the current configuration it takes about 5.2 seconds for a complete revolution. Assuming 50 steps per revolution, the process for taking one series takes about 2.5 minutes.

3.2. Photogrammetry

We used the Structure-from-Motion (SfM) approach to reconstruct 3D models from the series of images obtained in the first step. A large number of SfM implementations is available, some are open source or free to use. The program we choose is *VisualSFM* by C. Wu [22, 23], since it is used at the IWR for a while and its usage and results are very convincing[20, 19]. It is a challenging task to use SfM on such small objects as the cylinder seals. They are the smallest objects we documented with this method at the IWR so far. We had to try different tools to get the necessary pictures for the computations. We established a best practice for the seals: the momentary setup consists of a tripod with a slide for macro photography to adjust the camera, a ring light for proper illumination, and of course the rotation device itself. The camera is a Nikon D800 with a full-frame sensor and a resolution of 36 MPx combined with a 60 mm macro lens and a spacer to reduce the distance to the focus point. The images were taken with large apertures of 20 to provide as much depth of sharpness as possible without aperture distortion. To provide a sufficient number of photos, the seal has to be photographed from different positions and angles. At each position, the seal rotates one full revolution creating a series of photos. We move the camera using the slide but also the tripod in a hemispheric way around the rotation device. Additional photos of the top and the bottom of the seal were taken manually. For each seal we did 6-7 series of photos, each containing 50 photos.

The procedure of computing a 3D model from these photos consists of several steps, which are mostly automated and easy to use. The first step is to find points of interest in each image using scale-invariant feature transform (SIFT) [11]. In the next step, each photo is compared with every other by the interest points to find similarities. If there are images of high similarity, it is possible to compute the position of the camera from where the photo was taken, creating a sparse point cloud of the object. This step is repeated until every camera is found. Now that it is known where each camera is located, a dense point cloud is computed by tracing points visible on the photos. We tested two different approaches for this step. The first one the one integrated in *VisualSFM* is *CMVS*[5] and the second one is the software *SURE* of the German company NFrames, a University of Stuttgart spinoff. SURE is using redundant depth-maps for the triangulation, resulting in very dense and precise points[18]. After each photo has been processed, the result is a dense and colored point cloud of the object. We then can calculate a surface using the Poisson Surface Reconstruction algorithm implemented in MeshLab [3] and color the surface by the corresponding point colors. In the end we obtain a colored 3D mesh of about 2-3 million vertices and more, as shown in figure 2.

We started recently to use *PhotoScan* by Agisoft LLC, which seems to be the state-of-the-art SFM software in Archaeology. This software offers the integration of own python scripts to include the informations of our tools. There are many possible improvements open for future work, especially in creating more comparison data. Dealing with small seals is difficult sometimes. Especially the matching and camera reconstruction algorithms have problems with near-black seals. Sometimes the friction between the buffers and the seal is to small so the seal is not rotating. Also surface reflections on the seals can result in errors.

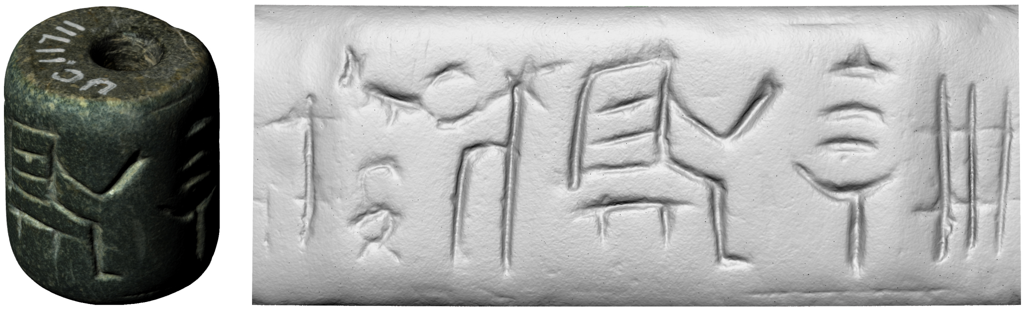

Figure 2. The 3D model of seal UC11711 (Petrie Museum). Left a colored view, right the unrolled and uncolored model.

4. Results

4.1. Comparison to Structured-Light-Scan

To check the accuracy of the new method we acquired an Assyrian seal of the Egyptian collection at Heidelberg University with our method and also with an Breuckmann structured-light-scanner owned by the IWR. We used a tele lens on the scanner, which has a resolution of 20µm.

Figure 3. Comparing SFM to structured-light-scan. Left PhotoScan (RMS 0.028 mm), center the scan and right the VisualSFM (RMS 0.044 mm) model. The accuracy range is $\pm$0.1 mm visualized by a morgenstemning colorramp.

The comparison shows clearly the small error between the models. It can thus be stated that this precision is sufficient for any 3D documentation in Archaeology.

4.2. Analysis of the 3D model

To improve the visibility of carvings on seals we use the GigaMesh software-framework developed by Dr. H. Mara at the IWR [12]. It provides tools for character extractions and unwrapping of objects[17]. In this case a virtual cylinder is fitted to the seal manually. By unwrapping this cylinder's surface to a plane we obtain a full overview of the seal maintaining encarvings with their correct heights. With this roll-out it is possible to analyze differences in the surface or even traces of usage. A detailed analysis of the glyphs is done using the Multiscale Integral Invariant Algorithm contained in GigaMesh. Using this algorithm we can detect features and visualize them as shown in figure 4, providing an improved view on the different traces.

Figure 4. The unwrapped 3D model of seal UC11715 with visualized features in a HOT colorramp.

5. Conclusion

Cylinder seals are very small artifacts. At the same time they are rich in detail. Traditionally the cylinder seals comprise some of the greatest works in miniature arts. With our method and the post-processing with Gigamesh we are able to make all these details visible that are lost with the classical documentation methods. All aspects of the inscriptions, stone cutting techniques, conditioning of the seal surface and traces of wear and weathering can be seen clearly. It is even possible to identify small residues of clay inside the grooves of the inscriptions, stuck there for several thousand years.

The detailedness of the results are aspects in our method's favor. Furthermore, the data acquisition is time-saving and easy. All needed equipment can be carried, set up and operated by one person, which is an advantage for work destinations that require traveling. Hence the automated photogrammetry by use of the seal rotation device is ideal for cylinder seal documentation in museum collections and in the field.

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