3D-Scanning and Computer Reverse Engineering Technology to Preserve Inscriptions at Beihai Park

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***Abstract* —The rapid development of computer reverse engineering and 3D scanning technologies has changed working practices in many different traditional industries, some in cultural heritage preservation. To document and preserve cultural heritage digitally is widely recognized and implemented today. However, seldom researchers have been involved in preserving stone inscriptions with these technologies. Stone rubbing is still a regular method of preserving calligraphies carvings but it can cause more damage to stone inscriptions. In this paper, we considered preserving fourteen important stone inscriptions of the YueGuLou, located at Beihai Park in Beijing. The YueGuLou has preserved more than 300 pieces of world-famous calligraphy from 135 calligraphers, and more than 500 stone inscriptions. These inscriptions are currently facing deformation, damage and even permanent loss due to physical and environmental factors. In our work here, the geometrical information is acquired with Breuckmann high-precision structured light 3D scanner for documentation and preservation purposes. Then we process with reverse engineering technology. Finally, some analysis is performed to demonstrate efficiency and accuracy advantages gained by this technology. The contribution of this research is: i) it verifies the feasibility of applying computer reverse engineering and 3D scanning technologies to stone inscriptions, and ii) it proves the superiority of efficiency and accuracy. This non-contact technology maximizes the importance of the subject while minimizing damage.**

Keywords-3d Scan; Reverse Engineering; Stone Inscription; Heritage Preservation; Data Accuracy

I. INTRODUCTION

A. Introduction of YueGuLou

The YueGuLou in Fig.1 is also translated to "The Chamber for Reading the Classics", which represents the importance in traditional culture. It is located in Beihai Park- an ancient royal garden built up for 900 years. YueGuLou was built in 1747 and located at the northwest of QiongHua Island. The emperor Qianlong built this chamber for collecting calligraphic arts and paintings from Wei dynasty to the end of Ming dynasty. There are 495 stone inscriptions of famous calligrapher were inlaid on walls of this chamber. These inscriptions are all priceless cultural treasure of Chinese traditional calligraphy.

In these inscriptions, the famous calligraphers, such as Wang Xizhi and Wang Xianzhi, whose calligraphies were collected, including "Kuai Xue Shi Qing Tie" (aka "Timely cleaning after snowfall"), "Zhong Qiu Tie" (aka "Mid-autumn Festival greeting") and many top calligraphy in Chinese history. Emperor Qianlong cherished them as his own life and appreciated them with joy. YueGuLou has already opened up to the public for visit and appreciation after hundreds of years have passed.

Figure 1. YueFuLou in Beihai Park

B. Current Damage Status of Stone Tablets

Despite the priceless value of these calligraphies, stone tablets are somehow damaged through baptism of time, some of them are broken and some of them have large cracks. The most terrible threat comes from the air. With the development of modern industry, the environmental pollution is becoming serious day by day, and this pollution can never be avoided even in the protection of glasses box. Fig.2 shows some terrible cracks and brokenness of stone tablet.

Figure 2. Cracks and brokenness of stone tablet.

The fatal damage of these inscriptions is from weathering. Due to the technical conditions at that time, all tablets are all exposed in air till 20th century. Some inscriptions are indiscernible, and even worse, some inscriptions are vanished. The erosion process is unfortunately irreversible. Fig.3 shows the terribly loss of an inscription.

Figure 3. Vanished inscription.

There is still one terrible but not only factor will accelerate the damage of stones, and this factor is exactly a regular and conventional procedure of inscription preserving, which is stone rubbing. Although several people will put plastic film on stones before brush water and Chinese ink on stone tablet, most of them are still eroded by traditional-unprotected procedure.

These "normal" and "regular" procedure are already in a vicious cycle, which is: the more famous and precious an inscription is, the more frequently be preserved and protected by rubbing procedure; the more rubbing an inscription have made, the more damage it will suffer, the more damage of an inscription, the more famous and precious an inscription is.

In order to jump out of this "protection-damage" circle, we have to find out some method to preserve these stone tablets fast, harmless, and convenient. Not only convenient to fetch geometric information, but also convenient to transport, to research , and to share.

II. SOLUTION OF 3D SCAN IMPLEMENTATION

A. Options of 3D-Scanning Devices

The 3d-scanning technology has developed for military purpose at first, and then is widely used in Aerospace, Automotive, Bridge, Education, Heritage and many fields. Due to the maximized fidelity,[1] and high accuracy requirement, this technology have already be recognized and implemented in many projects of cultural heritage preservation. [2]In general, 3D scanning technologies are classified as two types: contact and non-contact. For the purpose of maximum protection, contact scanners are out of consideration, however there are still 3 types of devices we could perform 3d scan: Time-of-flight scanner, Hand-held laser scanner, and Structured light scanner.

In beginning of this project, our team has developed several basic principles for protection and preservation:

- Absolutely non-contact with stone tablets
- High-powered laser is not permitted for avoiding damage
- To reduce air-exposure time, high efficiency should be seriously considered
- High-fidelity 3d models should be processed to fulfill present and future research needs

Thanks to the strongly support of our institute-institute of architecture and urban planning. There are four scanners we could use in this project. In table 1 listed parameters of these scanners, we have to decide which one is suitable for stone inscription preserving in the next step.

TABLE 1. THREE TYPES OF DEVICES ACCURACY COMPARISON

Model	**Faro Focus3D X330**	**Z+F IMAGER® 5010C**	**Handy Scan EXAct**	**smartSCAN C5**
Manufacturer	Faro	Z+F	Creaform	breuckmann
Scanning principle	Time-of-flight	Time-of-flight	Hand-held	Structured light
Working distance(range)	0.3m-187.3m	0.6m-330m	0.5m	1m
*Surface accuracy	±2mm @ 10m	±1mm @ 10m	±0.2mm	±0.02mm
Z-Noise	0.4mm rms	0.3mm rms	0.08mm rms	0.01mm rms
***Time-of-flight scanners are station-based scanning, the accuracy is correlated to scan diameter; Hand-held and Structured light scanners are fixed-focal lens, the accuracy is fixed too.**				

Scale, diameter and accuracy requirement is the first factor we need identify. Efficiency is important either during this project. YueGuLou is a public park, it still serve tourists in scanning process. Due to the high precision demand, a very slight vibration will cause accuracy lost, so that YueGuLou have to close during scanning. Considering of this will cause inconvenience of both tourists and the park , the work of 3d data collecting ought to be finished in 7 to 9 days.

All stone inscriptions are taken photos, then characters will be measured using empirical measurement[3] to figure out which is the smallest character. The breuckmann smartSCAN C5 of our institute have configured 2 types of cameras corresponding different requirements. More details are showing under Table 2.

TABLE 2. TWO TYPES OF CAMERAS ACCURACY COMPARISON

Field of view [mm]	M-125	M-300
Field of view size [mm]	105×90	240×200
Measuring depth [mm]	60	150
x, y resolution [µm]	45	100
Resolution limit (z) [µm]	2	5
Noise (z) [µm]	±5	±11
Feature accuracy [µm]	±10	±26

For efficiency consideration, the measurement need to determine two following requirements :

- To testify whether the M-125 Fov can fulfill accuracy requirements
- To determine areas which needs high precision scanning

In these inscriptions, the smallest character and the average sized character are happens to appear on a same inscription, that makes us convenient to illustrate with screenshot. Fig 4 shows the area we have measured in this inscription, which is one of the famous “Kuai Xue SHINee Qing Tie” (aka “Timely cleaning after snowfall”) preserved in YueGuLou (“Kuai Xue Shi Qing Tie” have two inscriptions, one is maintained in YueGuLou, the other is maintained in KuaiXueTang)

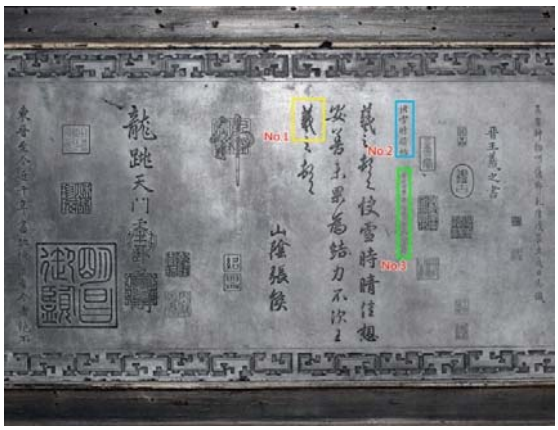

Figure 4. Measurement of Characters in different sizes

In “Kuai Xue Shi Qing Tie”, our team chooses 3 different sizes of characters to measure and analyze their accuracy requirement:

- No.1 character with a yellow box is the Chinese character “Xi”. It’s approximately 30mm high, 15mm wide, and 1.1mm depth
- No.2 characters with a blue box are the title of this inscription, the average size of these characters are approximately 8.4mm high, 7.9mm wide, and 0.3mm depth
- No.3 characters with a green box are a brief introduction of this inscription, which is the smallest character in this scanning project. The average size of these characters is approximately 3.4mm high, 4.9mm wide, and 0.23 mm depth.

Measurement results approved that the structured light 3d scanner is precise enough to control the scanning quality. The M-125 Fov then will be used in consideration of high demands from research purpose and demands of Beihai Park officials.

B. 3-D Data Collection

For the purpose of efficiency, most of inscriptions are performed 3d scanning with M-300 Fov. Every scan we implemented takes 30% overlapping area [4]to ensure the precision at the registration work. The stone tablet is 95CM wide and 30CM high, which needs around 20 scans to complete. A single scan can be finished in 5 minutes, including process of scanning, rough aligning, white balance adjusting, and color acquiring. After the calculation, a tablet will be completely scanned in 2 hours, and 3 tablets will be recorded per day. This can work out the finish date of this whole project, which would be five days.

After the time schedule, there are still 2 days left. Two tablets with “Kuai Xue Shi Qing Tie” are rescanned with M-125 Fov under the consideration of their importance. While the workload has increased more than tenfold but accuracy is also increased by several times.

Structured-light 3D scanners project a pattern of light on the subject and calculate the distance and deformation through cameras. Fig.5 shows the process of projecting patterns on stone tablet, this process needs only few seconds, but with high demand of stability, vibration from people walking will lead to errors.

Figure 5. continues on next page

Figure 5. Structured-light scanner project a pattern of light on stone tablet, then calculate 3D data.

III. DATA PROCESSING AND ANALYSING

A. Data Processing

After seven days of scanning, the raw data was brought back to the data processing centre of our institute. There still are several procedures to transform the raw data to high precision 3d model:

- **Fine alignment**: for most situations, a single scan will not produce a complete model of the subject. In this case, one stone tablet was merged from 20 plus scans. [5]The rough alignment on the operation site is only a basically alignment which have many tiny errors of the accuracy. Fine alignment will calculate the whole model considering every scans to adjust their position and rotation. The adjustment calculation will ease these errors according to overlapping data.[6]

- **Surface reconstruction and fill holes**: The principle of structured-light 3D scanner is triangulation theory combined with image recognition technology, which can produce very high precision and fidelity data. But all image-based algorithms have a limitation- the exposure problem. A strong contrast image will lead losing data, and these data loss will cause very small holes hide in 3D models. Fig.6 shows these small holes [7](generally less than 0.1mm) with red highlighted wires. This procedure is to fill holes using a curvature-based algorithm for minimize manual intervention, and maximum the fidelity of 3D scanning data. Fig.7 shows the comparison between raw data and final data.

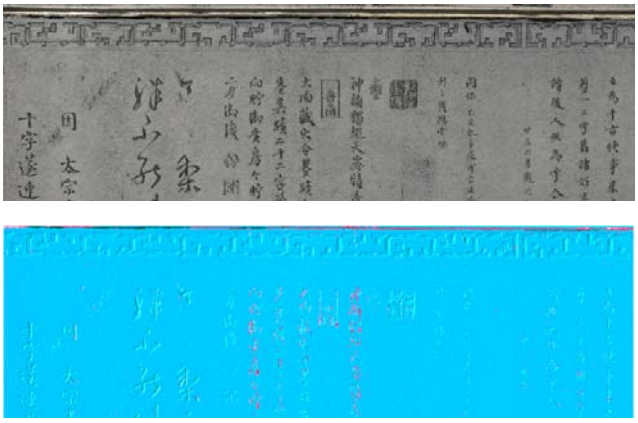

Figure 6.Small holes are hard to recognized in raw data but can be highlighted after wiped off color information.

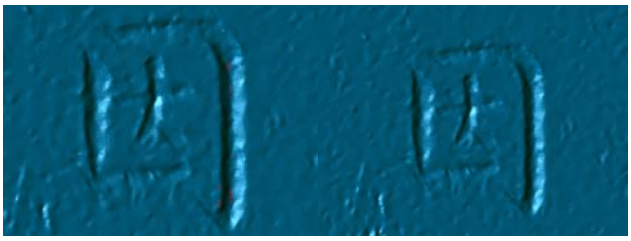

Figure 7.Before (left image) and after fill holes calculation.

- **Texture from point color**: General 3D applications can only display a polygon with textures so that we can see colors in 3D space. UV mapping or UV coordinate is an essential technology when texturing a 3D model. Just several years before, this process needs a lot of artificial operation and rich experience. However the smartSCAN C5 provided an alternative method of 3D model coloring, the vertex color. [8]This technology attaches color information based on vertex or points of polygons, but not on surfaces. The advantage of this technology is the model can display colors without considering UV coordinate or other operations, the disadvantage is that high quality color information requires huge amount of polygons such as pixels to pictures. Thanks to the advanced development of computer reverse engineering technology, the vertex color can now be baked from a high-density polygon to a simplified, low polygon. UV coordinates could be calculated automatically by many 3D applications today, thereby greatly reduced needs of processing time.

- **Retopo and decimat**: Massive polygons support high fidelity, however it suffer limitations too. It demands very high performance computing power can survey or browse these models. All of these 3D models are between 40 million to 200 million polygons that cannot browse or open using ordinary computers. Cultural heritage digitization will lose its value and significance

if it's not convenient to use. The retopo algorithm produces a new reasonable mesh to a more uniform tessellation. After this procedure, a decimate process will be implemented to simplify complex meshes[9]. The final result of digitized heritage can easily be published to research, web communication, and virtual representation. Fig.8 shows the result of retopo and decimate procedure.

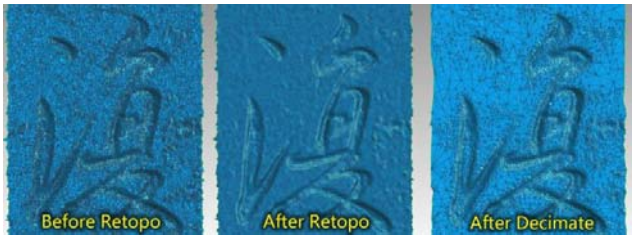

Figure 8. Retopo produces a uniform tessellation of mesh, and decimate will make data convenient to use.

B. Data Analyses

Unlike traditional documents of photos, the 3D documents have very high precision,[10] and avoid problems of lens distortion and problems of perspective[11]. With the proper applications, this digitized document could support many academic research from different directions. Due to the separation of color information and geometry information, it could perform many researches which are difficult to implement before.

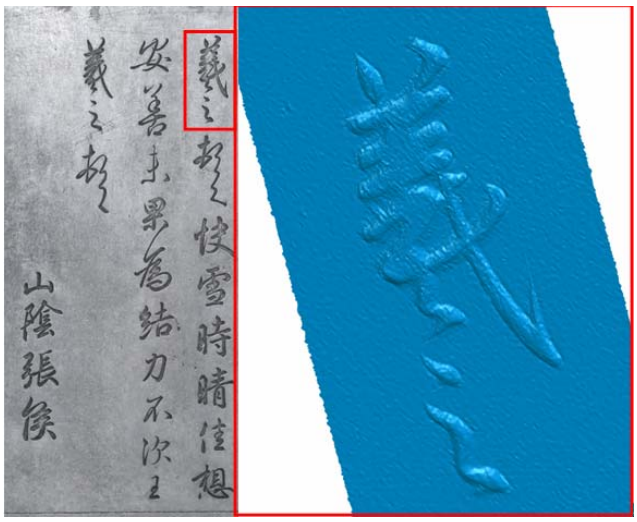

Figure 9. From high precision model, hand-carved trace are easily visualized.

For many years, the best way of preserving stone inscriptions are stone rubbing and photo taking. Stone rubbing will hide the problem of stone tablet deformation, and colors of photo will hide tiny damage of inscriptions. The 3D model could record geometry information with high precision, and remove disturbances from color. Examples like Fig.9, the trace of the hand-carved are hard to recognize in photos, but are easily visualized in color-removed models. In Fig.10, the depth information are totally lost in the photo, but very clearly shown in the model.[12]

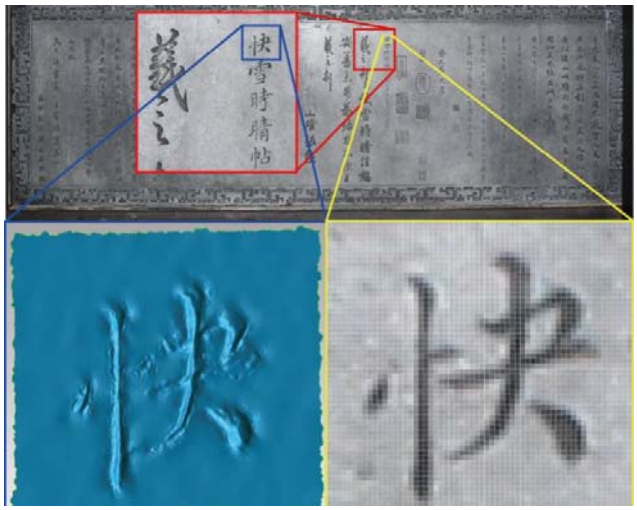

Figure 10. Depth information are very clear even it's just 0.2mm, however in the photo, was hide in black color.

C. Convenience of Digital Document

The "Kuai Xue Shi Qing Tie" have two stone inscriptions, as the paper mentioned before, are stored in different places for many years. Researchers of Beihai Park are always wish to make a compare between these inscriptions, but the comparison are not so convincing cause the lens distortion, and the distance of picturing. Furthermore moving the inscriptions are strictly prohibit, so in many years the researchers can't figure out how much the differences of these two inscriptions. With the 3D scanned data, problem solved.

Scanning data have absolute size information, [13]which could easily be transferred, be merged and be compared. In this case, we selected the part from two inscriptions both including "Kuai Xue Shi Qing Tie", and put them together in Fig.11, then remove color information. Subtle differences are already showed in Fig.12.

Figure 11. Two inscriptions are selected and extracted in the same space to make comparison

Figure 12. Differences are very obvious to identify, the left image come from KuaiXueTang, which was built-up in Ming Dynasty, hundreds of years earlier than the right image, which comes from YueGuLou..

Comparison of color-removed data have obviously visualized the effect of erosion. [14]Hundreds of years by exposure in oxygen and rain makes the edge of carving much thinner and much softer. The inscription carving of YueGuLou is powerful and vigorous on the contrary. This result has never been clearly demonstrated before due to the rapid development of computer reverse engineering technology.

D. Detailed Correlation of Inscriptions

Respecting the request of Beihai Park researchers, the two "Kuai Xue Shi Qing Tie" were performed a deviation analysis in Geomagic Wrap, which is generally be used for quality control in industrial domain. The analysis results are visualized with a spectrum map, which makes the deviations evidently. Figure 13 shows the analysis.

This analysis astonished researchers cause the differences of text-alignment and the word-spacing are more than their imagine, and this is an experiment that they can hardly performed with traditional methods of heritage research. With the contribute of computer technology, we found a brand new way of cultural heritage preserve research.

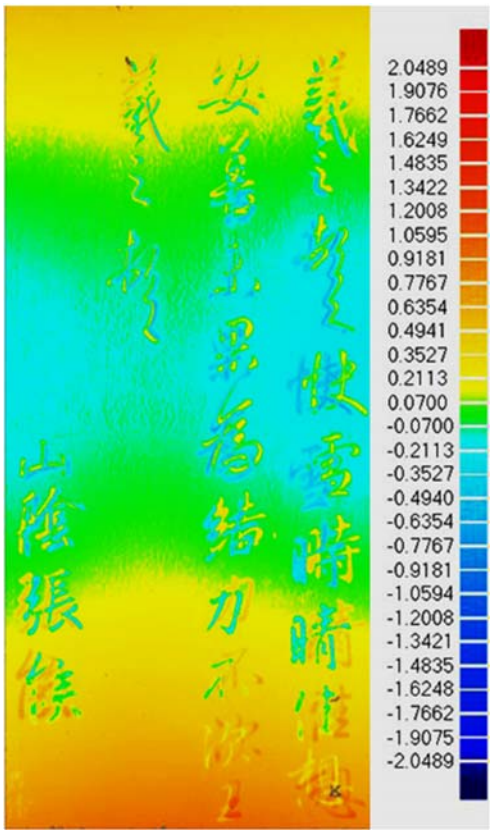

Figure 13. Deviation analysis of inscriptions shows differences in spectrum map.

IV. CONCLUSIONS

This project is a part of CHCI (Cultural Heritage Computer Information) program, which is advocated and dominant by The Beijing municipal administration of cultural heritage. It is the first time that computer reverse engineering and 3D scanning technology was applied on inscription and calligraphy research. Thanks to seven years' experience of practical project and experiments, out laboratory have finished this work in very short time limit with high quality control. The main contribution of this project are:

- Verified the superiority of precision on structured-light 3D scanning than traditional method of document.

- Verified that new technology of 3D scanning and computer reverse engineering can greatly improve efficiency and fidelity of preserving and documenting cultural heritages.
- With this high accuracy and precision data, these inscriptions will be re-scaned per year to monitor deformations and erosions.
- Fourteen important inscriptions will be well-preserved in digital formation, and never will be damaged.

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