Precision and Classification of Predynastic Egyptian Stone Vessels: A Metrological Study

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Abstract

I present a numerical method for evaluating archeological artifacts, which allows classifying the objects into quality classes. The distinct quality classes arise from the different tools or different fashioning techniques used to make the objects. As such the developed method can help establish the origins of the archeological finds and thus aid with the cultural attribution and dating of the artifacts. The method is based on the metrological analysis of the 3D scans of round objects where a scan is divided into a set of 2D slices that are evaluated for circularity and concentricity. The classification is accomplished by way of the quality metric, which is a sum of circularity and concentricity errors for the inner and the outer surfaces of the object. The method was tested on a set of 27 3D scans including 22 objects from Matt Beall's predynastic Egyptian stone vessel collection, 3 scans of modern stone vases made on a lathe, and 2 scans of contemporary stone vessels purposefully made using only primitive hand tools consistent with our understanding of the ancient Egyptian stone works. The analysis of the 27 scans revealed that all objects in the data set fall into two distinct categories: the 'imprecise' class, which is consistent with manual fashioning using primitive hand tools, and the 'precise' class, which is consistent with the use of precision machinery. It was surprising to see that 11 out of 22 stone vessels in Matt Beall's collection fell into the 'precise' category, with several of these objects being 10 more precise than the contemporary objects made on a lathe. This result could mean that the 'precise' objects in the collection are modern forgeries, or hitherto unknown precision stone manufacturing tools were available in the past, in which case the 'precise' predynastic vases were not made by the culture they are being attributed to. This determination can be made by scanning and evaluating a larger set of stone vessels from museum collections, although this effort is outside the scope of this paper. To conclude, the developed metrological analysis method can serve as a useful analytical technique for classifying archeological objects. The proposed quality metric can be used to show how the fashioning quality improved over time or how it varied from culture to culture and thus provide a novel tool for dating and attributing various man-made artifacts.

Keywords

Predynastic Egyptian stone vessels; metrology; classification.

Background

Flinders Petrie assembled the world's largest collection of ancient (including predynastic) Egyptian stone vessels, which is now exhibited at the Flinders Petrie Museum in London, UK [1]. Petrie pioneered the classification of these objects based on their shape and material [2]. Lucas subsequently expounded on the origins and attribution of these artifacts [3].

Recently, predynastic and first-dynasty Egyptian basalt vessels were analyzed and classified on the basis of their typology by Mallory-Greenough [4]. Aston [5] studied a vast number of Ancient Egyptian stone vases from museum collections, classified them by material, and attempted to identify potential quarry sights.

Until recently, all such classifications were based predominantly on mineralogy and typology (form, size, material used). Petrie's effort perhaps was the most thorough as he assigned a chronological order to stone vessels based on their shape and suggested that objects of unknown origin that are similar in shape to known vessels ought to be attributed to the same historical period and consequently to the same culture.

However, even a casual visual examination of these stone artifacts exhibited in major museums reveals striking differences in the fashioning quality: some vessels appear crudely made, they are visibly imperfect, lack uniform wall thickness, and are characterized by poor symmetry; while certain other vessels (some in Petrie collection and others on public display at the Egyptian Museum in Cairo) appear astonishingly well-made, they are perfectly symmetric, perfectly balanced, finely polished, and feature uniform wall thickness.

This obvious dichotomy did not go unnoticed, and many casual observers (including Adam Young and Ben van Kerkwyk) pointed out that there appear to be two distinct quality classes of ancient Egyptian stone vessels. Young and van Kerkwyk even presented measurements to support their observations, although they did not publish their findings in peer-reviewed literature.

This motivated me to develop a scientifically accurate method for the automatic classification of round artifacts based on the numerical analysis of their three-dimensional representations.

The main hypothesis that accompanies the method is as follows: different cultures used different fashioning techniques for their artifacts, as such these fashioning techniques are likely to differ in the quality and precision of the stonework. Therefore, if one can develop an automatic metrological analysis method then one can derive an objective conclusion on who and when could have made the object.

The added benefit of the automatic metrological analysis is the possibility of distinguishing genuine historical artifacts from modern forgeries since a modern-tool made object is likely to be characterized by a totally different fashioning quality compared to an ancient artifact.

Metrological Analysis Method

To develop the automatic metrological analysis method I needed to obtain a sufficiently large dataset. Because museums generally do not provide 3D scans of their exhibits, I had to rely on the help of private collectors. Specifically, I was able to obtain high-quality 3D CAT scans of 22 stone vessels purportedly of ancient Egyptian origin from Matt Beall's collection – Fig. 1.

Fig. 1. Twenty-two stone vessels from Matt Beall's collection.

This dataset was supplemented by the 3D CAT scans of 3 modern vases – Fig. 2 – and 2 optical scans of contemporary 'replica' stone vases made by Olga Vdovina using primitive wood, stone, and copper tools consistent with our understanding of the ancient Egyptian stonework – Fig. 3.

Fig. 2. The three modern stone vases: M1 is marble, M2, and M3 is onyx.

Fig. 3. The two contemporary ‘replica’ stone vases made by Olga Vdovina using primitive wood, stone, and copper tools, consistent with our understanding of the stone working technology available to the ancient Egyptians; O1 is diorite, O2 is marble breccia.

The 25 CAT scans and the two optical scans were processed into 3D models that were saved as STL files. The CAT scanning was performed at EMS, Inc. using a Nikon 4M-RTSS scanner, and the two optical scans were captured using a hand-held 3D scanner.

An EMS technician manually aligned each scanned model to ensure maximum axial symmetry. Each model was centered on the origin in the XY plane with the principal axis of symmetry being the Z axis – Fig. 4.

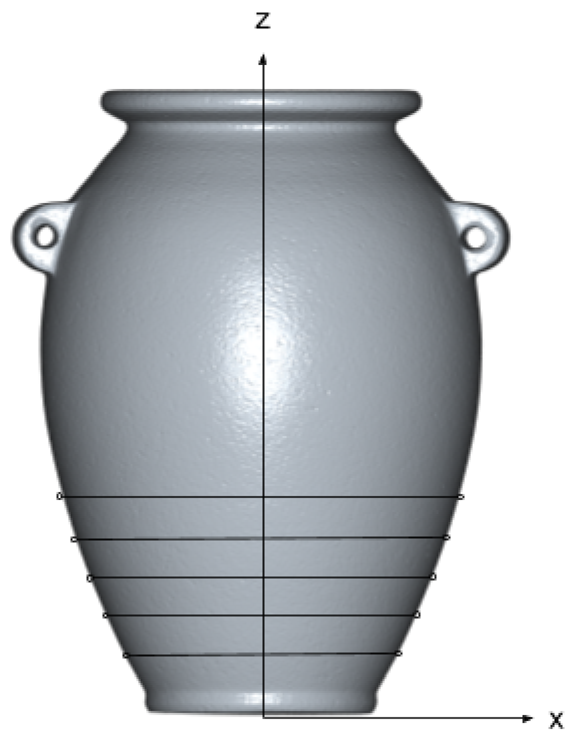

Fig. 4. The alignment of the 3D model of a scanned artifact.

Model Slices

To analyze the models I wrote code in MatLab (using the MatGeom 1.2.8 library) to slice each STL model into 101 slices evenly spaced along the Z-axis – Fig. 5.

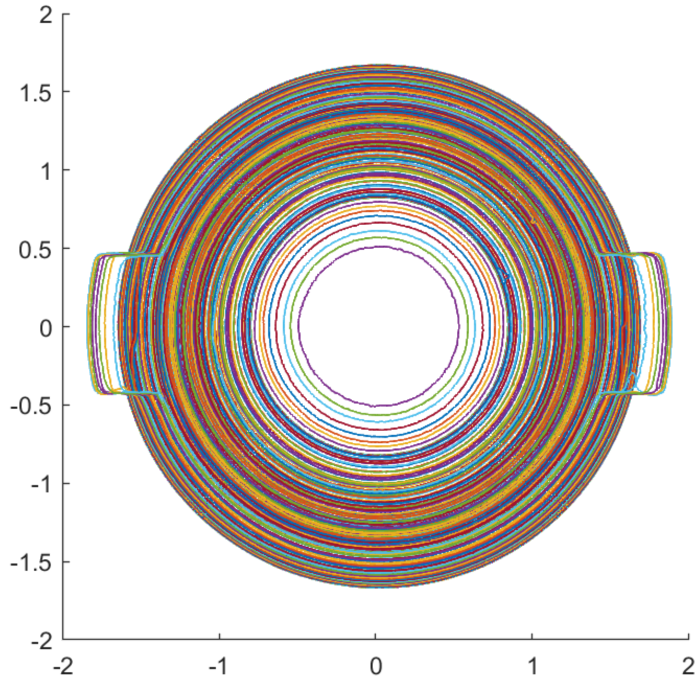

Fig. 5. The contours of the model slices along the Z-axis.

Because most objects exhibited wear along the top and bottom surfaces, the first slice and the last slices were offset 0.040” from the bottom and the top of each object.

Note that the vast majority of the model slices (except those that cut through the handles) are circular. This is expected since the vases are axially symmetric and we are slicing the model across the axis of symmetry (the z-axis).

Quality Metric

First, we must clarify what we mean by ‘precision’. Precision is not an absolute but rather a relative measure characterizing how close an object is to its ideal. For example, when machining a part we use tolerances to specify the maximum allowed deviation of the actual shape of the machined part from its ideal given by a dimensional drawing or a CAD model.

However, in the case of ancient Egyptian vases, we do not have such a priori design documents, which we can use for comparison. Therefore we must abandon the idea of tolerances and define another quality metric.

Since the model slices are approximately circular, I decided to evaluate the quality of each slice’s fit to a perfect circle in the least squares sense. The result of the fit is the best-fit radius R, the root mean square error (RMSE), and the best-fit center (x, y), from which I compute the centering error $dR = \sqrt{(x^2+y^2)}$ – Fig. 6.

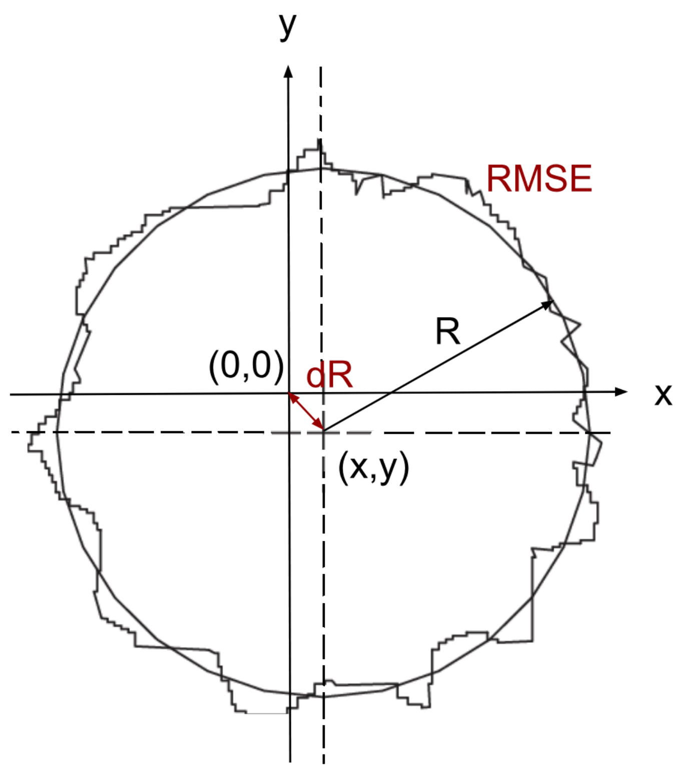

Fig. 6. The circularity error (RMSE) and the centering error (dR) of a circular slice.

Small values of RMSE and dR mean that the slice is ‘very circular’ and ‘well centered’ on the origin, while large values of RMSE and dR mean that the slice has ‘poor circularity’ and is ‘poorly centered’ on the origin.

Combining the results for all slices, we can compute the average RMSE (<RMSE>) and the average dR (<dR>) for the inner and outer surfaces of a model. Then we can define the quality metric M as follows: $M = \langle RMSE_{outer} \rangle + \langle RMSE_{inner} \rangle + \langle dR_{outer} \rangle + \langle dR_{inner} \rangle$.

Slice Filtering

Because slices cutting through the handles are non-circular we ought to exclude them from the analysis. Other slices to be excluded are the slices through badly worn top and bottom surfaces and the slices that are too oblique. For example, slices through the lower portions of the rounded-bottom vases and top and bottom surfaces of the lip of a vase are ‘noisy’ because the oblique slicing angle disproportionally magnifies surface imperfections (this effect is similar to the elongation of shadows that occurs when objects are illuminated from low angles).

Through trial and error I implemented the following slice filtering algorithm: all slices with RMSE greater than twice the <RMSE> are eliminated; this procedure is repeated 3 times to eliminate the noisiest outliers.

An alternative approach is to include only the slices from the bottom portion of a vase up until the handle. Such a procedure requires an operator input to specify the value of z where a handle begins. This is not ideal since manual intervention introduces an operator-dependent degree of subjectivity into the analysis. For the rounded-bottom vessels, this approach requires even more operator input to specify the value of z, below which the slices must be excluded due to the excessively oblique slicing angle.

As such, I settled on the first approach because it allows for complete automation and does not require human participation, which could lead to undesirable selection effects.

Calibration

To ensure the validity of measurements, EMS, Inc. has calibrated the CT scanner by scanning a ruby T-stylus sphericity set (a NIST traceable metrological standard), which contained a small bead with the radius R = 1.99820 mm – Fig. 7.

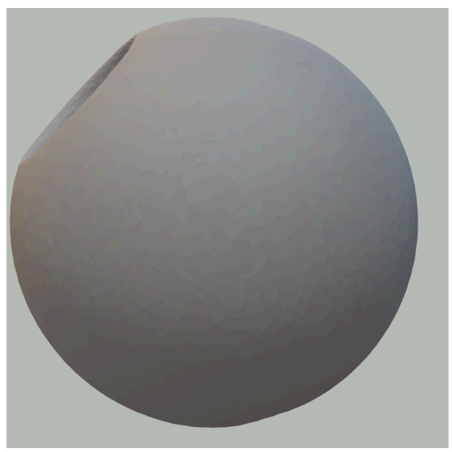

Fig. 7. The metrological standard, a ruby bead with the declared radius R = 1.99820 mm.

I analyzed the resulting STL file using the same MatLab code I used to analyze the stone vases and obtained the following results: <RMSE> = 0.0001”, <dR> = 0.0003”. The measured radius of the standard was R_{max} = 2.0026 mm, which corresponds to the error of 0.0044 mm or 0.00017”.

Thus, I was able to establish that my analysis of the CT scans is accurate to within 0.2 thousandths of an inch.

Sample Results

Below are the examples of the analysis of the two stone vases from Matt Beall’s collection characterized by the vastly different quality metrics: the vase ‘V18’ on the left is a lot more ‘circular’ and ‘well centered’ than the vase ‘V8’ on the right – Fig. 8-17.

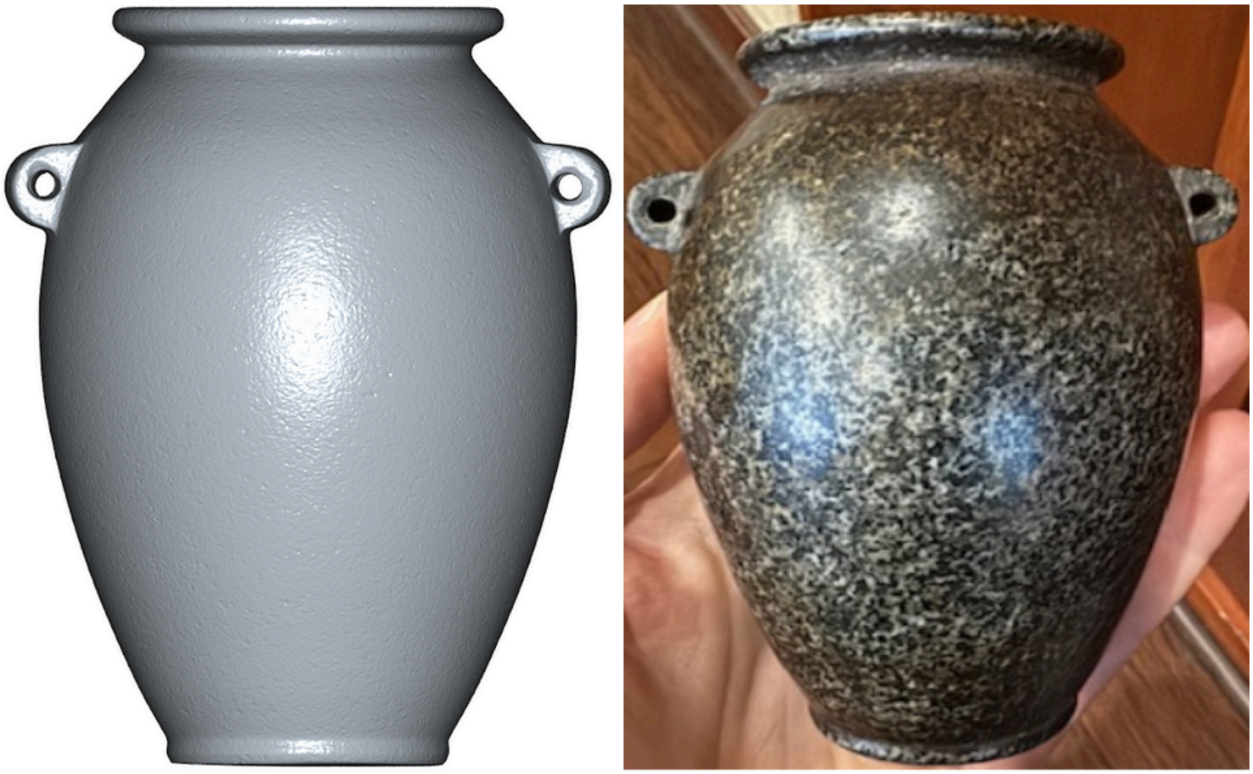

Fig. 8. The STL model (left) and a photo (right) of the vase 'V18' from Matt Beall's collection.

Fig. 9. The STL model (left) and a photo (right) of the vase 'V8' from Matt Beall's collection.

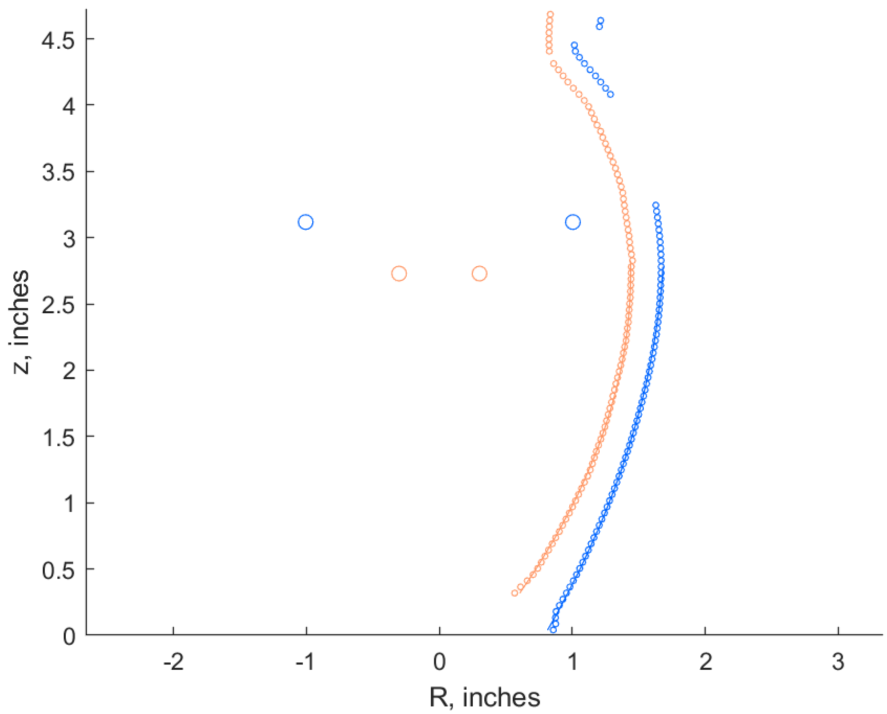

Fig. 10. The inner (red) and the outer (blue) surface slice points for the vase 'V18' with the outer surface slice points corresponding to the handles and the lower surface of the vase removed.

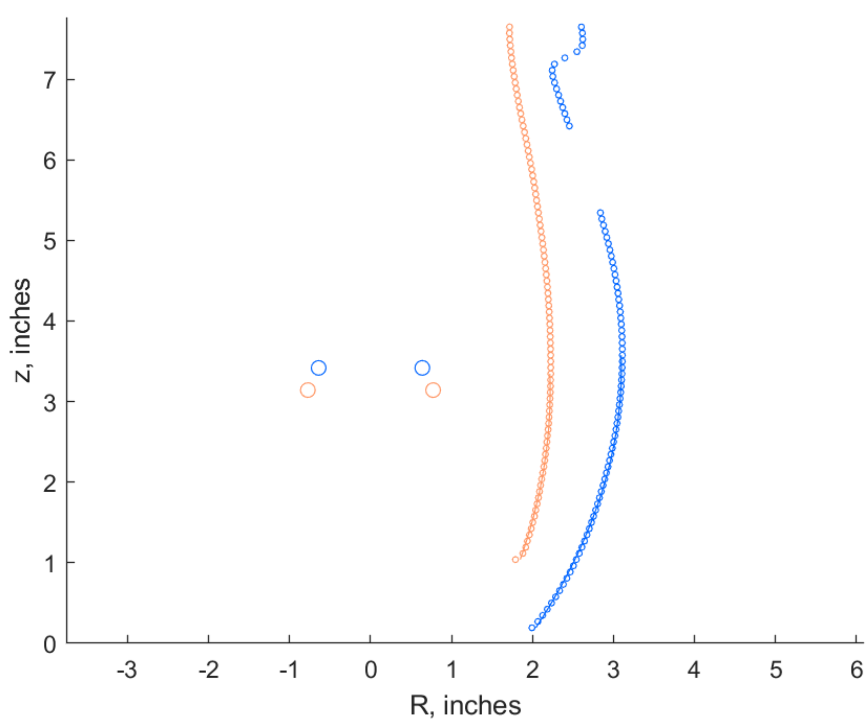

Fig. 11. The inner (red) and the outer (blue) surface slice points for the vase ‘V8’ with the outer surface slice points corresponding to the handles and the lower surface of the vase removed.

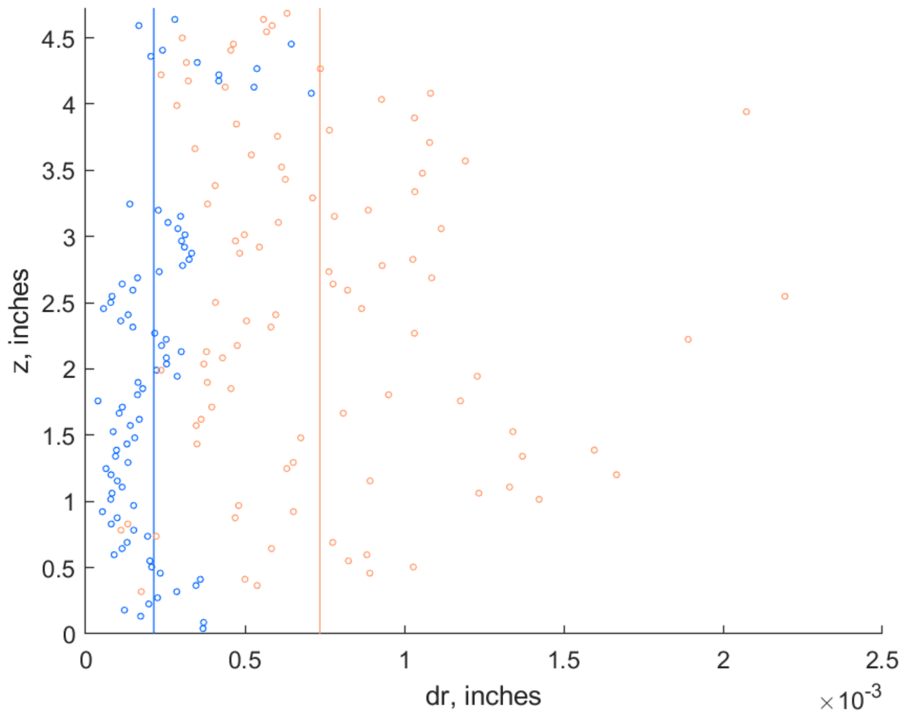

Fig. 12. The inner (red) and the outer (blue) surface slice RMS errors for the vase ‘V18’ and their mean values (vertical lines).

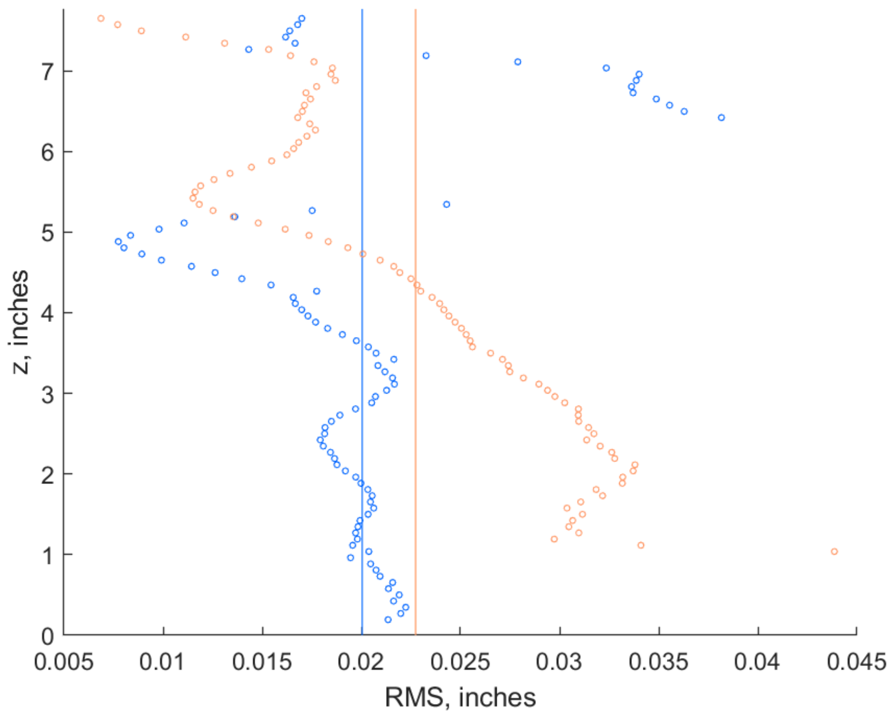

Fig. 13. The inner (red) and the outer (blue) surface slice RMS errors for the vase ‘V8’ and their mean values (vertical lines).

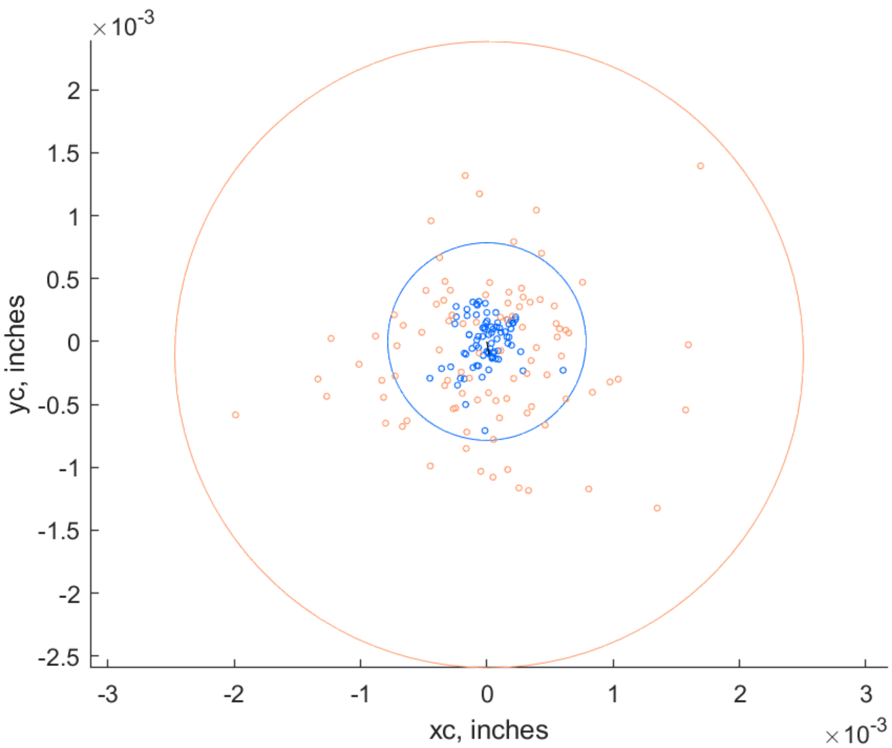

Fig. 14. The Inner (red) and outer (blue) surface slice center points for the vase ‘V18’ and the circles corresponding to the six standard deviations.

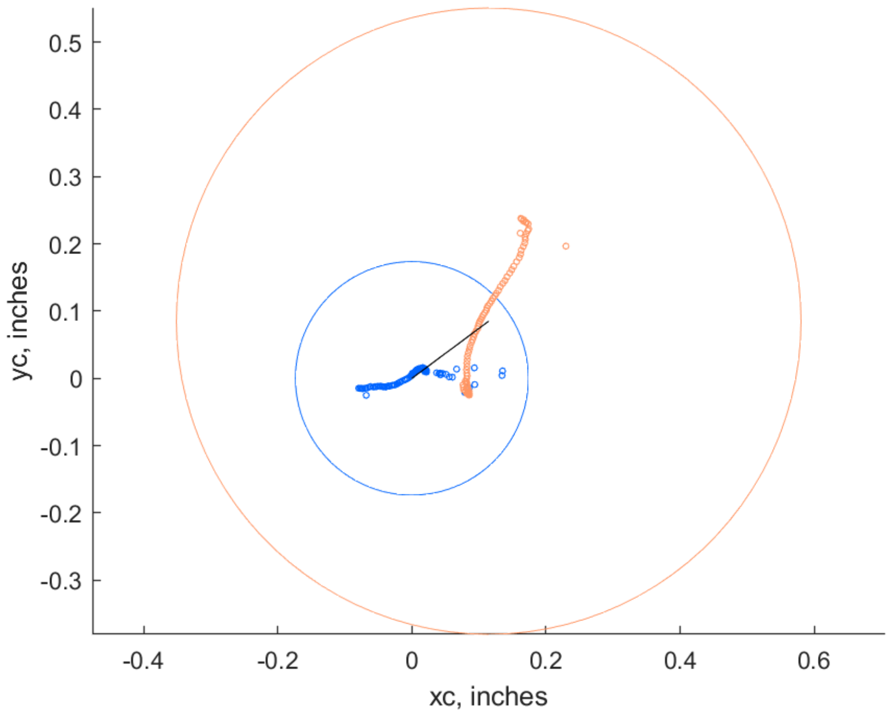

Fig. 15. The Inner (red) and outer (blue) surface slice center points for the vase ‘V8’ and the circles corresponding to the six standard deviations.

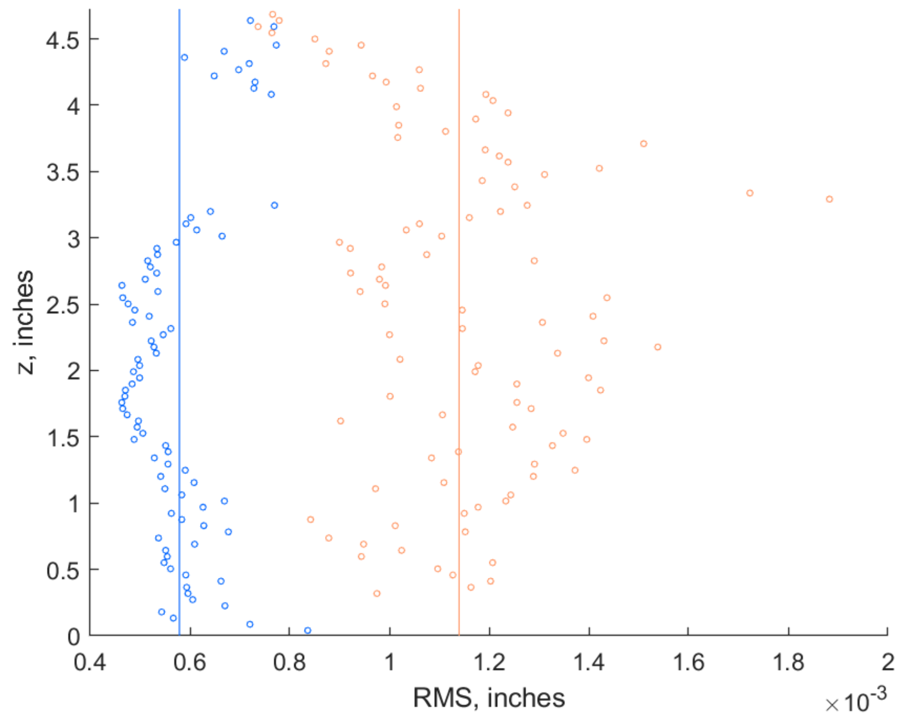

Fig. 16. The inner (red) and the outer (blue) surface centering errors (dR) for the vase 'V8' are their mean values (vertical lines).

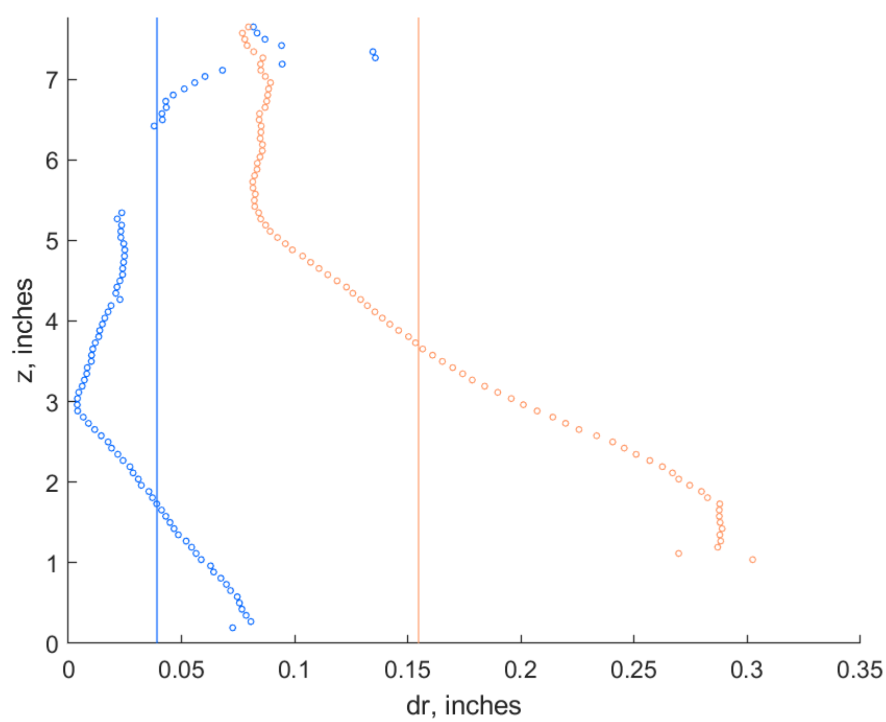

Fig. 17. The inner (red) and the outer (blue) surface centering errors (dR) for the vase ‘V8’ are their mean values (vertical lines).

For convenience, the results of the analysis of the two vases are summarized in Table 1. The vase ‘V18’ is 40 to 100 times more precise than the vase ‘V8’ in terms of <RMSE> and <dR>.

ID	$\langle RMSE_{outer} \rangle$	$\langle RMSE_{inner} \rangle$	$\langle dR_{outer} \rangle$	$\langle dR_{inner} \rangle$	σ_{outer}	σ_{inner}	Center Error	Total Error
V18	0.5	0.9	0.2	0.7	0.1	0.4	0.1	2.9
V8	20.5	22.8	21.6	151.2	13.6	99.4	133.3	462.4

Table 1. The summary of the metrics for the vessels ‘V18’ and ‘V8’; all values are in thousandths of an inch.

The ‘Total Error’ in the last column of the table, which is a sum of all metrics listed in the table, paints an even starker picture since it amplifies the gap between the ‘precise’ and the ‘imprecise’ artifacts.

The Findings: Two Classes of Objects

A scatter plot of <RMSE> vs <dR> for all objects in this study is shown in Fig. 18 and a bar plot of the quality metric M is shown in Fig. 19.

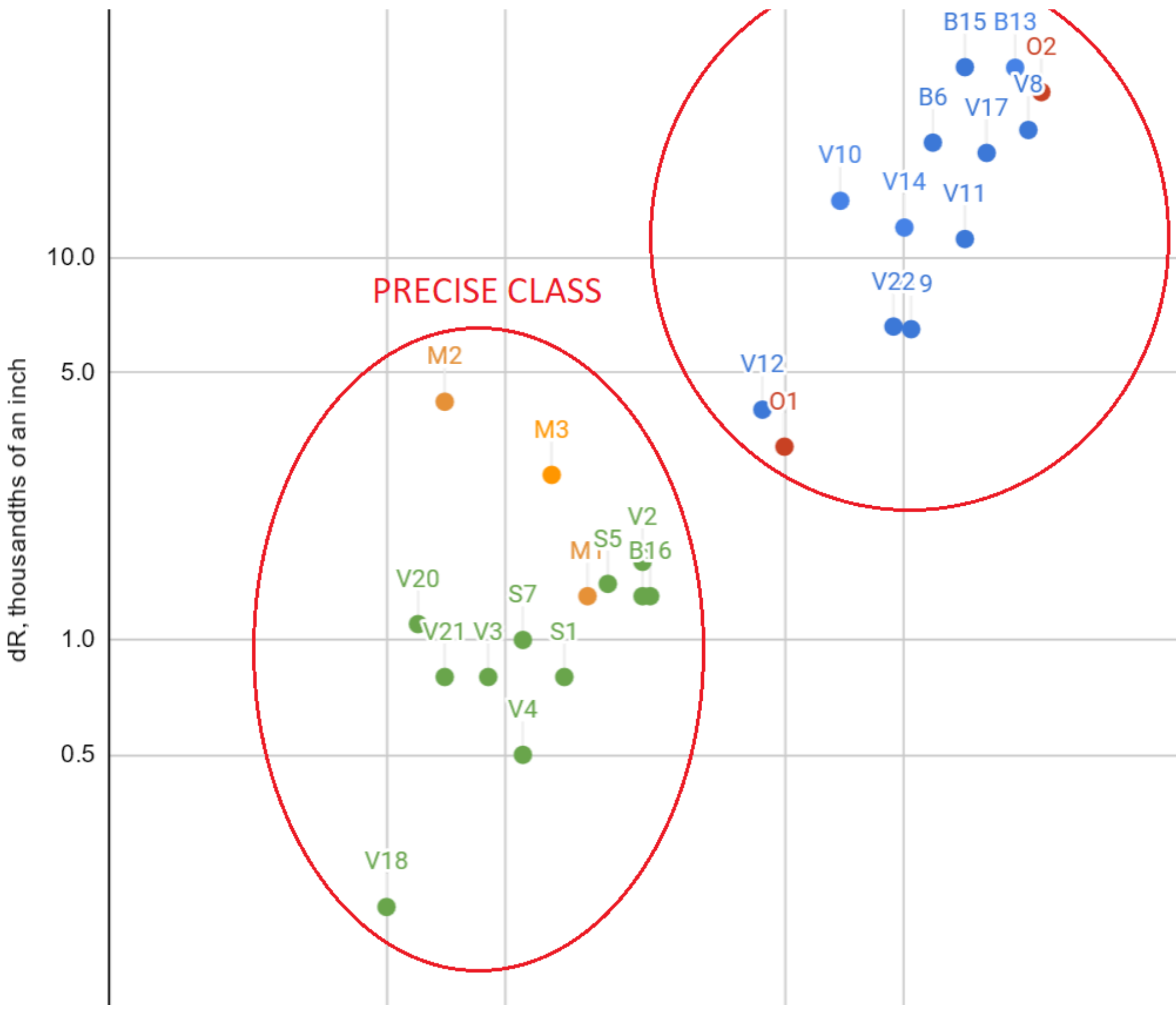

Fig. 18. The scatter plot of <dR> vs. <RMSE> for the objects in this study illustrating the two classes of objects; note the logarithmic scale: without the logarithmic scales the individual points in the two clusters are too difficult to distinguish.

Fig. 19. The bar plot of the quality metric M for all objects in this study; note the logarithmic scale for the vertical axis (which is the quality metric).

The scatter plot in Fig. 18 illustrates how the objects in this study cluster into two classes. The bar chart in Fig. 19 allows precisely define the two classes as follows:

- **THE PRECISE CLASS:** M < 25 thousandths of an inch;
- **THE IMPRECISE CLASS:** M > 25 thousandths of an inch.

Class Averages

The ‘PRECISE’ class average errors are as follows:

- <<RMSE>> = 1.3 thousandths of an inch (0.03 mm);
- <<dR>> = 1.3 thousandths of an inch (0.03 mm).

Such surprising precision indicates a highly advanced manufacturing technique consistent with machining on a lathe as the modern lathe-made vases ‘M1’, ‘M2’, and ‘M3’ fall into this class.

On the other hand, the ‘IMPRECISE’ vases in Matt Beall’s collection are characterized by the following class averages:

- <RMSE> = 12 thousandths of an inch (0.3 mm);
- <<dR>> = 23 thousandths of an inch (0.5 mm).

This manufacturing quality is indicative of a much less advanced manufacturing technique consistent with the ‘stone and stick’ technology, as the vases ‘O1’ and ‘O2’ that were purposefully made using primitive tools fall into this category.

In other words, there is a huge gap in quality between the two classes of artifacts, which spans more than an order of magnitude in precision.

The ‘precise’ class includes the three modern stone vases, which were machined and polished on a lathe, and 11 objects from Matt Beall’s collection.

The ‘imprecise’ class includes the other 11 objects from Matt Beall’s collection and the two contemporary replica vases made using wood, stone, and copper tools consistent with the stoneworking technology known to be used by the ancient Egyptians.

Discussion

It is nothing short of astonishing to find that the most ‘precise’ vases in Matt Beall’s collection (e.g. ‘V18’ and ‘V4’) are characterized by the circularity error <RMSE> = 0.6 thousands of an inch (15 microns) and the centering error <dR> = 0.1 thousandths of an inch (2.5 microns). The centering error of the vase ‘V18’ is actually below the resolving ability of the analysis method used (which is 0.2 thousandths of an inch).

The vases ‘V4’ and ‘V18’ appear to be 10 times more precise (in terms of the quality metric M) compared to the three modern vases. However, the modern ‘gift shop’ vases ‘M1’, ‘M2’, and ‘M3’ were of average rather than exceptional quality as they were purchased on eBay for about $20 each. Such onyx vases are typically made on machine lathes in artisan shops in Asia. Onyx’s hardness on the Moh’s scale is 6.5-7, which is comparable to the hardness of granite. Granite artifacts (such as funerary vases) are also routinely machined on a lathe.

Thus, it appears conceivable that with greater care and/or on a better quality lathe one can probably match the remarkable precision of the ‘V4’ or ‘V18’ vases from Matt Beall’s collection.

At the same time, it appears utterly improbable that such remarkable precision can be achieved using primitive ‘stone and stick’ technology, as the manually made ‘replica’ vases ‘O1’ and ‘O2’ clearly show.

All objects in Matt Beall’s collection appear genuine according to the supplied provenance documentation, although the critical examination of the provenance is outside of the scope of this paper.

Lathe Marks

Given these results (the quality metrics consistent with the modern objects), I conclude that the ‘precise’ vases in Matt Beall’s collection were machined using advanced tools since the lathe marks are clearly visible on the inner surfaces of the vases where they were not polished away completely – Fig. 20.

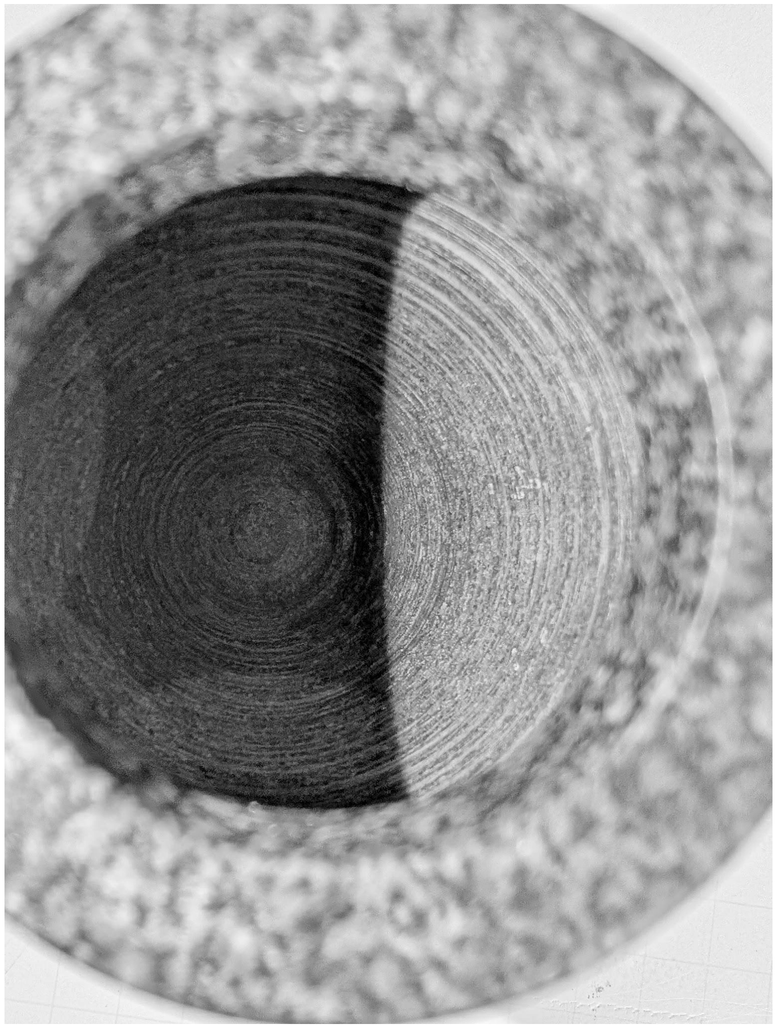

Fig. 20. Lathe marks on the inner surface of the ‘precise’ vase ‘V18’ from Matt Beall’s collection.

Visual Appearance

The ‘precise’ vases are strikingly symmetric and, for lack of a better word, beautiful – Fig. 21-22.

Fig. 21. The ‘precise’ vase ‘S1’ from Matt Beall’s collection.

Fig. 22. The ‘precise’ vase ‘V18’ from Matt Beall’s collection.

The 3D models of CAT scans of the ‘precise’ vases look like CAD models: their symmetry is so perfect that it is difficult to spot any surface profile variability when these models are rotated – Fig. 23-24.

Fig. 23. The 3D model of the CAT scan of the ‘precise’ vase ‘S1’ from Matt Beall’s collection.

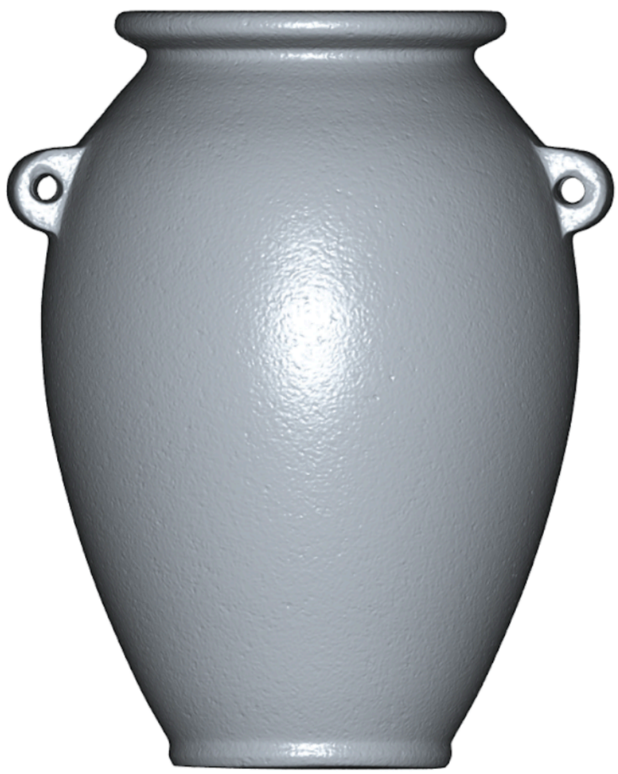

Fig. 24 The 3D model of the CAT scan of the ‘precise’ vase ‘V18’ from Matt Beall’s collection.

At the same time, the ‘IMPRECISE’ vases appear noticeably imperfect to the naked eye, their lopsidedness made particularly clear by the CAT scan – Fig. 25.

Fig. 25. The 3D model of the CAT scan of an 'imprecise' vase V19 from Matt Beall's collection; note the visible asymmetry.

Parabolic Fit

The outer and the inner surfaces of the 'precise' vases exhibit excellent fit to a parabola with RMS error on the order of 0.005" – Fig. 26.

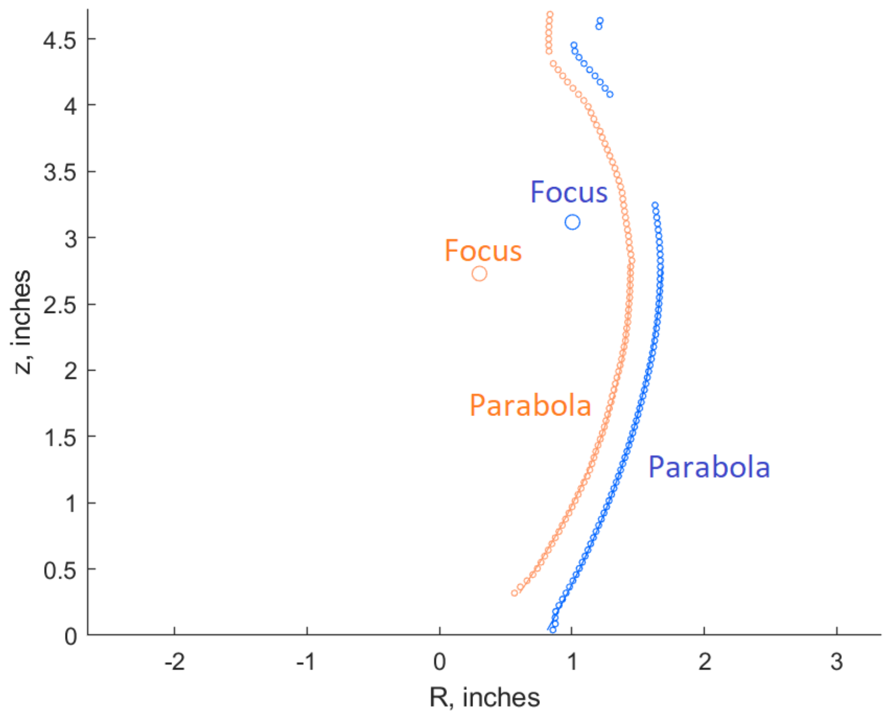

Fig. 26. The parabolic fits of the inner and the outer surfaces of the ‘precise’ vase ‘V18’.

The parabolic fit is evaluated for the slice points beginning from the narrowest slice at the bottom of the vase and ending with the widest slice.

For comparison, parabolic fits of the outer surfaces of the ‘imprecise’ artifacts are on the order of 0.030”.

A Note on the ‘Replica’ Vases

The ‘replica’ vases ‘O1’ and ‘O2’ were made by Olga Vdovina in collaboration with the antropogenez.ru. The objective of the replication effort was to show that it was possible to make stone vases using stone, wood, and copper tools known to ancient Egyptians. The optical scans of the two resulting stone vases are shown in Fig. 27 and 28.

Fig. 27. The optical scan of the marble breccia vase ‘O2’ made by Olga Vdovina.

Fig. 28. The optical scan of the diorite vase ‘O1’ made by Olga Vdovina.

I must point out that Olga Vdovina made the vase ‘O1’ using a plastic rotary table supported by a ball bearing to control the outer surface accuracy through rotation by painting the elevated spots with a Sharpie marker – Fig. 29.

Fig. 29. The rotary table used by Olga Vdovina in the making of the diorite vase ‘O2’.

The use of modern technology in making the ‘O1’ vase represented a significant deviation from the initial objective of antropogenez.ru to use only the tools available to the ancient Egyptians. Nevertheless, both vases are classified as ‘imprecise’ according to the proposed quality metric, despite the impressive outer surface circularity of ‘O1’ on only 5 thousandths of an inch. This remarkable circularity was achieved due to the use of the ball-bearing supported rotary table, which is a contemporary piece of technology that was not available to the ancient Egyptians.

Nevertheless, Olga Vdovina's work proves that one can achieve a remarkable degree of precision when working stone manually. Still, the quality of the resulting objects is clearly distinguishable from the objects that were machined on a lathe (e.g. 'M1', 'M2', and 'M3'). Yet the proposed quality metric can distinguish the use of high technology even on a portion of the vase (e.g. the use of the ball bearing supported rotary table, allowing to perfect the outer surface of the vase).

Conclusion

The developed method for numerically evaluating the 3D scans of archeological artifacts allows for classifying the objects into quality classes. The distinct quality classes arise from the different tools and different fashioning techniques used to make the objects. As such the developed method can help establish the origins of the archeological finds and thus aid with the cultural attribution and dating of the artifacts.

The method was tested on a set of 27 3D scans including the 22 objects from Matt Beall's predynastic Egyptian stone vessel collection, the 3 scans of modern stone vases, and the 2 scans of the contemporary stone 'replica' vessels by Olga Vdovina.

The analysis of the dataset revealed that the 11 stone vases in Matt Beall's collection are consistent in quality with the 3 modern vases that were machined on a lathe. The remaining 11 stone vases are consistent in quality with the 2 contemporary 'replica' stone vases purposefully made using only primitive hand tools consistent with our understanding of the ancient Egyptian stone works.

This result could mean that the 'precise' objects in the collection are modern forgeries, or hitherto unknown precision stone manufacturing tools were available in the past, in which case the 'precise' predynastic vases were not made by the culture they are being attributed to.

The conclusion of forgery, however, is inconsistent with the available provenance of the artifacts in question. Nevertheless, the matter could be conclusively resolved by scanning and evaluating a larger set of stone vessels from major museum collections. Finding stone vessels in the museum collections consistent in quality with machining would strongly indicate the misattribution of these artifacts.

Finally, the developed quality metric can be applied to pottery to show how the fashioning quality improved over time or how it varied from culture to culture and thus provide a novel tool for dating and attributing various man-made objects.

Acknowledgments

I acknowledge Matt Beall’s support in obtaining the 3D CAT scans of the stone vessels used in this study and in publishing this paper.

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