Optical evaluation of heritage silver coin plasma cleaning using statistical methods

B. T. GORAŞ[a*], E. G. IOANID[b], D. RUSU[c], L. GORAŞ[a,d]
[a]*"Gheorghe Asachi" Technical University of Iasi, Romania*
[b]*"Petru Poni" Institute of Macromolecular Chemistry, Romania*
[c]*"Moldova" National Museum Complex, Iasi, Romania*
[d]*Institute of Computer Science, Romanian Academy, Bucharest, Romania*

The paper addresses the problem of optical evaluation of silver coins plasma cleaning quality using statistical methods applied to images - a topic of interest in numismatics as well as in general heritage objects rehabilitation. The purpose of the paper is to present a new low-cost method to quantitatively evaluate the cleaning effect of plasma used for decontamination, conservation and restoration of silver heritage objects.

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1. Introduction

Heritage object restoration and cleaning are delicate and difficult tasks [1-3] since they should usually comply with the contradictory requirements of cleaning without loss of material on the one hand while preserving the specific look and toning on the other hand. For sure the above task is an art that makes use of a plethora of techniques.

Laser-based cleaning methods used in art restoration make use of ultrafast laser pulses that remove dirt and other surface contaminants without touching the object and without using chemicals [4]. The main disadvantage is that the method is not efficiently applicable on surfaces that are not flat.

Among other techniques, *plasma cleaning* using specifically developed equipment for the treatment of cultural heritage objects has been recently reported as an efficient noninvasive method. The method proved to exhibit high cleaning efficiency and low loss of material [5,6].

Regarding the *evaluation* of the cleaning quality so far it has been done by visual inspection or by using the Energy Dispersive X-ray Spectroscopy (EDAX) – an expensive and time consuming analysis [7,8].

The method proposed in this paper comes with a novel point of view for quantifying the quality of heritage silver objects restoration. The method has been confirmed qualitatively by visual inspection and quantitatively by EDAX analysis. Both methods have been applied on multiple areas spread all-over the analyzed objects of interest, namely patches classified according to the surface topography. Moreover, the proposed algorithm is definitely faster, ecological, and non-invasive. Experimental results reveal high sensitivity and easy real-time processing.

The rest of paper is structured as follows: Section 2 describes the plasma cleaning equipment, Section 3 contains a brief review of several statistical concepts the method is based on, Section 4 describes the data acquisition setup, the data processing (image analysis) and the experimental results and the last section is devoted to concluding remarks.

2. The plasma cleaning equipment

Fig. 1 shows the experimental setup the cleaning of the silver coins was done. It has been developed for plasma treatment of cultural heritage objects [5] and consists of a reactor (1), a liquid nitrogen trap (2), a vacuum pump (3) the whole set being monitored by a block (4) that controls the gas temperature, pressure and flow within the reactor. The pressure in the reactor is adjusted by means of a needle valve (5) and is measured by a pressure gauge (6). The reactor is made of a Pyrex glass vessel having inside two plan parallel electrodes (7). The silver coins (8) to be cleaned in plasma were placed between the electrodes on the positive column area. The HF discharge in the reactor is ignited and maintained at the frequency of 13.5 MHz by a power HF generator.

The experiments have been carried out under the following conditions: temperature 35–40°C, pressure 3.5 10^{-4}–7 10^{-4} bar, frequency 13.5 MHz, electric field intensity 20–50 V/cm, the gas used was air, and the treatment period 30 minutes.

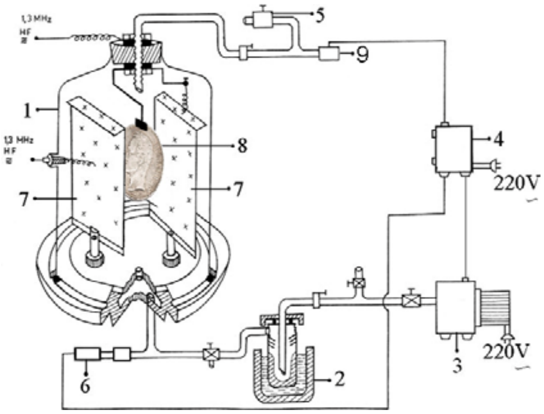


Fig. 1. Plasma cleaning equipment (see text).

3. Images and statistical descriptions

The main idea of the method is to use several statistical parameters of the images before and after plasma treatment to evaluate the cleaning process.

Before presenting the method and the results we first quickly recall several concepts regarding colored images and several statistical descriptions.

The first aspect concerns the type of color space used for the image acquisition and/or representation. In our case the adopted space was RGB (Red, Green, and Blue) [9,10].

For a given color space an image can be considered as a combination of three functions of two spatial variables, i and j (pixel position) one function for each intensity of the color space component, $I_R(i,j)$, $I_G(i,j)$ and $I_B(i,j)$ defined on the (rectangular) domain of the image or image patch considered for analysis. In other words, an image can be considered as the combination of three "reliefs" represented by the color pixel intensities (values) as a function of the pixel position (Fig. 2).

The RGB to grayscale conversion has been made by the typical weighted average [11]:

$$I_{gray}(i,j) = 0.2989 * \mathrm{I_R}(\mathrm{i,j}) + \\ + 0.5870 * \mathrm{I_G}(\mathrm{i,j}) + 0.1140 *_{\mathrm{B}} (\mathrm{i,j})$$

The combination of the three components, together with the properties of the color space determines a unique value in the visible color space.

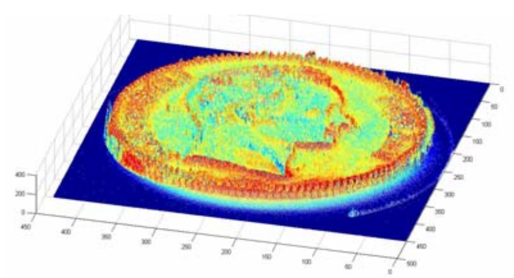


Fig. 2. "Relief" representing a coin.

The above functions can be statistically characterized by the probability of occurrence of pixels with intensities within a prescribed interval called bin for each color or gray level. Histograms are plots of the density of data situated in the bins. For a specified number of bins their width depends on the range of the pixels values within the chosen patch.

$$bin_{c\ width} = \frac{\max I_c(i,j) - \min I_c(i,j)}{number\ of\ bins}$$

where $I_c(i,j)$ is the intensity of the pixels for each color or for the gray scale (c=R,G,B or gray) in the patch. The statistical parameters considered in our approach are the mean, the standard deviation, the skewness and the kurtosis.

In the following we will refer to images represented by images/patches of dimension M×N pixels.

The mean of a patch for a given color c is determined by the arithmetic average of all the pixels values within the area of the image:

$$\mu_c = \frac{\sum_{i=1}^{M}\sum_{j=1}^{N} I_c(i,j)}{M \times N}$$

where Ic (i,j) is the intensity of the (i,j) pixel of color c (c=R,G,B or gray).

The significance of the mean is related to the degree of brightness of the object. For a silver coin, a lower/higher mean reflects a higher degree of dirtiness/cleanliness.

The standard deviation of the pixels in a patch is defined as.

$$\sigma_c = \sqrt{\frac{1}{M \times N} \times \left(\sum_{i=1}^{M}\sum_{j=1}^{N} (I_c(i,j) - \mu_c)^2 \right)}$$

where Ic(i,j) has the same meaning as above. It is a measure of the pixel values spread in an image – high/low values correspond to higher/lower contrast.

The skewness of the histogram of the pixels for the component c (c=R,G,B or gray), defined as

$$skewness_c = \frac{\sum_{i=1}^{M}\sum_{j=1}^{N} (I_c(i,j) - \mu_c)^3}{M \times N \times \sigma_c^3}$$

is a measure of the symmetry of the pixel level distribution – symmetric distributions have zero skewness, negative/positive values show the data are skewed right/left i.e., the left/right "tail" is longer. Images having many pixels with high values are usually skewed right which suggests a tendency to saturation of the bright pixels. This leaning towards the highest values correspond to a clean and shiny surface.

Finally, the kurtosis defined as:

$$kurtosis_c = \frac{\sum_{i=1}^{M}\sum_{j=1}^{N}(I_c(i,j)-\mu_c)^4}{M \times N \times \sigma_c^4}$$

It represents the deviation of the histogram from a standard normal distribution – a kurtosis smaller/higher than 3 characterizes a flat/peaked distribution.

4. Data acquisition and experimental results

The coin image acquisition system consisted of an Olympus E-400 digital camera with 35 mm f/3.5 macro lens and four halogen lamps all placed in a dark room. The positions and orientation of the coin, camera and lamps were the same during all experiments.

-The **white balance of the camera [10]** has been manually adjusted, and kept unchanged during the images acquisition;

- Identical **shutter time** and **aperture** have been used for every pair of images (before and after plasma treatment)

- The appropriate settings for image acquisition were cross-checked by digitally comparing identical areas from the background.

Even though the coins before and after cleaning were placed in the same position in the acquisition system, there were slight unalignements that have been digitally removed.

Three pairs of coins images before and after cleaning are shown in Fig. 3.

Fig. 3 Pairs of initial (first row) and plasma cleaned (second row) coin images.

The study focused on measuring how various types of regions have been cleaned after plasma treatment. The regions have been selected from all over the coin surface as shown in Fig. 4.

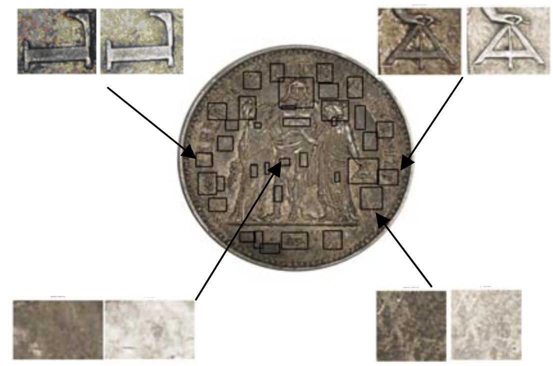


Fig. 4. Initial coin image with patches used for statistical analysis and several pairs before and after cleaning.

The patches have been divided into 2 classes, according to the topography of the areas: “flat” and “bumpy”. The flat areas have been further divided into other 2 subclasses: “higher flat” and “lower flat”, according to their “altitude” in the coin relief.

12-14 patches were extracted from each of the above classes/subclasses for each of the 3 sides of the coins (since a side of one coin was already cleaned mechanically before applying the treatment, it has not been considered as significant and has been discarded from the database).

For a number of about 40 patches for each set statistical analysis made on the histograms for the three colors as well as the gray scale it has been found that, in a first approximation, the gray scale histograms reveal significant information regarding the cleaning process. The most significant parameters are the mean, the standard deviation and the skewness variation before and after cleaning. It has been observed that for all patches the mean of the histograms increased with values of the order of 70 to 90 units on a scale of 256 gray levels. It is interesting to note that the above increase was the same for either blackened initial patches as well as for cleaner ones which showed that the plasma cleaning proved to be rather homogeneous with respect to the degree of blackness. The standard deviation showed an average increase of about 3 units. Several exceptions will be discussed in what follows. The initial standard deviation for “bumpy” patches was higher than for flat ones. The skewness decreased in all cases as a consequence of cleaning which moved the pixel values toward higher levels the histogram of the cleaned surfaces exhibiting a longer tail towards left. Finally, the kurtosis showed a small general tendency of decrease indicating a somehow more peaked histogram.

In the following we will present and comment several examples of typical patches with their histograms together with their individualities. For each patch the histograms for the three colors as well as for the gray scale images have been computed. As already shown, it has been observed that the gray scale histogram were significant enough for evaluating the cleaning.

A sample data describing upper flat type patches before and after cleaning are shown in Table 1.

Table 1. Statistical data for upper flat patches.

	Mean		STD		Skew		Kurt	
	before	after	before	after	before	after	before	after
1	114.82	200.41	9.54	19.316	0.01	-0.39	2.94	2.81
2	129.87	224.97	18.42	15.44	1.04	-0.89	4.29	3.73
...	...	...	...	...	...	...	...	...
7	131.71	210.96	21.38	19.6	1.26	-0.74	6.73	3.42
8	119.13	202.02	11.75	24.51	0.35	-0.50	3.04	2.10
9	117.00	213.77	13.38	16.34	1.68	-1.26	9.51	5.79
10	111.27	207.57	12.01	19.61	0.26	-0.19	3.95	2.72
…	…	…	…	…	…	…	…	…
Avg	118.47	210.86	14.1	17.36	0.58	-0.75	4.67	4.22
Differences:		92.39		3.25		-1.33		-0.45
DIFF_AVG_STD:		10.05		5.49		0.86		3.64

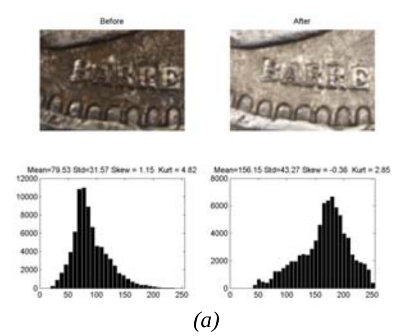
It can be noticed that patch no. 9 is the closest to the average values, while patches 7 and 2 represent extreme exceptions from the point of view of the mean. Moreover, patch number 2 exhibits a high increase of the standard deviation reflecting cleaning and an increase of contrast since the pixel values are more spread.

The general trend of increase of the standard deviation reflect the idea that a narrow range of pixel values has turned into a wider range, i.e. the large amount of homogeneous dirt over the silver regions is eliminated, revealing a bright high definition and more contrasted side. This trend of cleaning is confirmed by the skewness values as well. An asymmetrical tendency of the histogram towards brightness reflects a high degree of cleaning.

Let's make the following assumptions to describe better the impact of the cleaning degree over skewness:

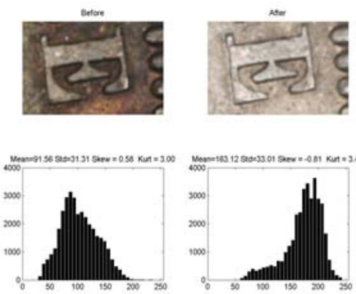
- The cleaning process is uniform
- One can select two regions A and B (A twice as dirty as B)
- The amount of time necessary for region B to become as clean as possible is T_B

Keeping the coin under plasma treatment for T_B minutes, would clean region B completely. This means that the pixel values in region B would increase considerably towards 255, to a saturation value V_{SAT}. In the mean while, region A would experience the same process of cleaning, and will lose 50% of dirt, becoming as region B was before treatment. Now, after another T_B minutes spent under plasma treatment, region B will remain the same, while region A will become as clean as region B is, with the pixel values around the same V_{SAT}.



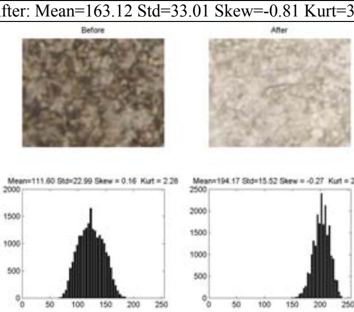
(a)

Before: Mean=79.53 Std=31.57 Skew=1.15 Kurt=4.82
After: Mean=156.15 Std=43.27 Skew=-0.36 Kurt=2.85



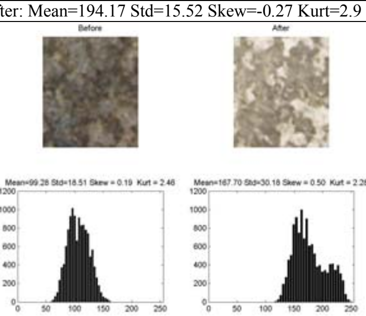
(b)

Before: Mean=91.56 Std=31.31 Skew=0.58 Kurt=3
After: Mean=163.12 Std=33.01 Skew=-0.81 Kurt=3.47



(c)

Before: Mean=111.6 Std=22.99 Skew=0.16 Kurt=2.28
After: Mean=194.17 Std=15.52 Skew=-0.27 Kurt=2.9



(d)

Before: Mean=99.28 Std=18.51 Skew=0.19 Kurt=2.46
After: Mean=167.70 Std=30.18 Skew=0.5 Kurt=2.28

Fig. 4. Pairs of significant patches before and after cleaning together with their corresponding histograms and statistical parameters.

In the following we will comment several results, significant for the illustration of the method, shown in Fig. 4. The patch shown in Fig. 4a was initially very dirty, a fact seen from the low value of the initial histogram mean. Moreover, the patch had initially a high standard deviation since it represented a “bumpy” region. The standard deviation increased reflecting an increase of the contrast in the cleaned image. The skewness naturally decreased and the kurtosis decreased over 3 showing a good cleaning. The patch shown in Fig. 4b refers to a “bumpy” region as well but initially less dirty, with a higher mean and a similar standard deviation compared to the previous patch. However, the standard deviation increased only slightly showing a rather similar shape of the histogram which however got a negative skewness reflecting cleanness while the kurtosis shows a slightly flatter shape.

The next two patches are belong to the “flat” class and have been chosen in order to show the connection between the decrease/increase of standard deviation and decrease/increase of contrast. Indeed in the case of the patch of Fig. 4c the standard deviation decreased reflecting a decrease of the contrast together with the negativation of the skewness and an almost normal kurtosis. The patch shown in Fig. 4d is described by a significant increase of the standard deviation, corresponding to a visible increase in the contrast, together with an increase of the skewness showing nonhomogeneities of the patch and a kurtosis almost constant.

5. Concluding remarks

The proposed method of plasma cleaning evaluation has been tested for two silver coins which have been photographed before and after the plasma treatment in similar conditions with respect to position and illumination. The main idea was to investigate the statistical properties of several specific local patches within the coin images before and after cleaning and to correlate them with the type of region (bumpy or flat) they were extracted from.

The increase of the mean values of a patch before and after cleaning is the most significant measure of the cleaning quality i.e., the increase of the mean reveals a better cleaning. This fact was confirmed by all tests and could be easily associated to the translation of the histograms of the cleaned patches towards brightness.

The increase/decrease of the standard deviation shows an increase/decrease of contrast.

The decrease of the skewness reflects a significant cleaning while its increase reveals the existence of nonhomogeneities in the patch. Last, the increase of the kurtosis reflects for a homogeneous patch a high degree of cleaning leading to pixels with almost equal values.

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*Corresponding author: bgoras@etti.tuiasi.ro