Image-Based Comparison of Pre-modern Coins and Medals

Jens Hedrich,[1] Dietrich Paulus,[1] Hendrik Mäkeler,[2] Ewert Bengtsson[3]

[1]Universität Koblenz-Landau, Institut für Computervisualitik,
Universitätsstr. 1, 56070 Koblenz
eMail: {jenshedrich, paulus}@uni-koblenz.de,
URL: http://www.uni-koblenz.de/agas

[2]Uppsala universitet, myntkabinett,
URL: http://www.myntkabinettet.uu.se/en/

[3]Uppsala universitet, Centrum för bildanalys,
URL: http://www.cb.uu.se/

Abstract

In Numismatics it is of central importance to find out which dies were used to mint a specific coin. For this purpose, coins have to be compared directly with each other. However, different states of preservation turn a comparison into a challenge. Partly degenerated regions which are caused by abrasion and corrosion present considerable difficulties. Furthermore, within a comparison based on images, different directions of illumination can lead to completely different impressions. In this contribution, it is described how the acquisition of coin images can be enhanced by a Three-Color Selective Stereo Gradient Method. The resulting reflection images can be aligned with each other by a Modified Particle Swarm Optimization Algorithm. This technique helps the numismatist in deciding, and thus decreases the effort of the comparison. So far, the proposed illumination and registration technique has been tested on 14 die-identical coin images of 6 different coin types.

1 Introduction

Numismatics (from 'nómisma', the ancient Greek word for 'coin') is an auxiliary science of history. It is concerned with the study and description of coins as well as with historical, artistic and economic matters related to them. Since the invention of currency, coins have been the most frequently preserved documents throughout all historical periods. A careful study and documentation about a coin type can lead to a new understanding of different history disciplines. Apart from categorization and documentation about where a coin was found and minted, the research is focused on how a coin type has developed over time. With this collected knowledge, numismatics provides other fields of research with information.

In documentations of coins, images are used as additional information besides the written description. Thus, the imaging of coins became an essential part of the documentations. Due to the illumination and reflectance grade of a pre-modern coin, the imaging can be difficult. This effect depends on the material which the coin is made of. For example, silver coins are usually highly reflective. When it comes to imaging of pre-modern coins, numismatics uses incidence of light from the side. This might reduce the reflections on the cluttered surface, but on the profile of the coin it produces a reflection on one side and a shadow on the other. Thus, an image of a coin is one interpretation depending on the viewing angle and illumination angle. For numismatists the work with these images can be very complex and is associated with uncertainties, in particular the decision whether a coin is minted by the same die or is rarely unequivocal. As a consequence of the possibilities provided by information technology, digitalized documentation of this information is increasingly published on the internet [1]. Thus, the exchange of those images becomes easier, but the tremendous effort to analyze the data remains the same. Based on these facts, it is of great importance to numismatics to have tools developed which reduce the effort of the documentation or even more the complexity of identifying die-identical coins.

Die Identity Since the first coinage, pre-modern coins have been produced in a similar way as described in Figure 1. Coins that were minted with the same dies are absolutely identical in their appearance. Hence, there may not even be a single dot or pellet that differs or is even slightly misplaced. Among larger coin finds, it is usually possible to detect coins that were minted by the same coin dies. However, different states of preservation turn this task into a challenge. The modern study of coins, which is concerned to detect die identities, is relatively young. Up to the present day, comparing coins by hand has been common. It is time-consuming and regularly generates discussions between numismatists [2]. Nevertheless, comparing coins by hand provides the foundation for modern numismatic research. For such investigations, it is important to have access to a large amount of coins of the same coin type. Usually, research is only done on major coin finds. If merely a picture of the coin serves as the basis for the investigation, difficulties are bound to occur. Coming up with a definite result is sometimes hardly possible.

1.1 Influences on the State of Preservation of Coins

In the following it is described what is of high influence on the state of preservation of coins and whether this causes problems with data acquisition and the analysis of the data.

Abrasion The abrasion or wear of a coin is caused by external mechanical forces. This leads to an increasing loss of material and can cause a complete destruction of the coin

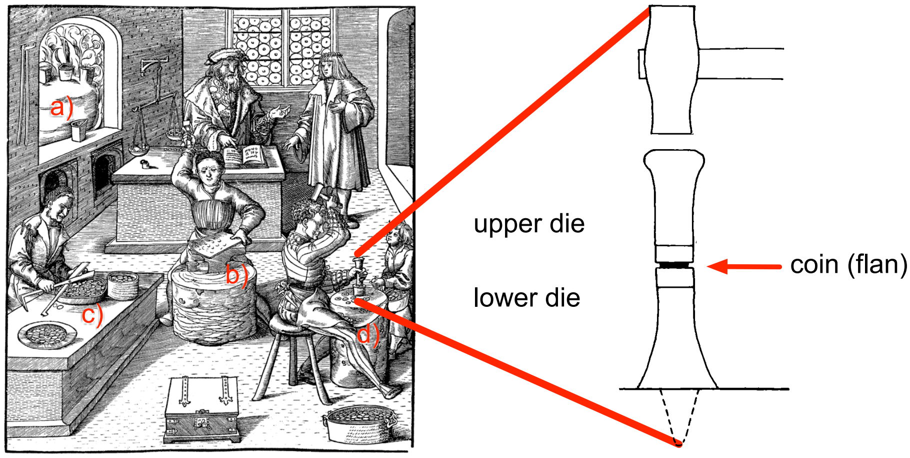

Figure 1: This illustration shows the production stages of pre-modern coins. (a) First the metal is melted in a furnace, (b) after that the cast slabs are placed in shape, (c) the flans are cut out of the sheet metal, (d) the flan is minted with a hammer stroke on the coin die [3]

imprint. Under pressure forces and depending on the material hardness, and the embossing depth, the metal can be moved superficially. This material shift does not always change the overall impression, but it can have a negative influence when it comes to the identification of a coin die.

Corrosion The word 'corrosion' was first used in 1669; in connection with detrimental material alteration caused by hot mineral water of an English spa on silver coins. The corrosion behavior of coins is determined both by the material used and by the external forces and stresses. There is a variety of corrosion phenomena of the same coin, which can appear, depending on whether it was in use, stored or buried in the ground. Copper and bronze are corrosion-resistant under adverse conditions. However, there are conditions that lead to a rapid corrosion of the metals. In terms of coins, the most common corrosion phenomena are fretting as well as the selective corrosion [4]. In connection with imaging units, it has to be noted that this type of material change can also lead to a significant deformation of the coin imprint, and consequently, to a strong change in color and reflectance of light.

Double striking During the manufacture of pre-modern coins, the imprint was embossed with a hammer blow. But during the minting process, it happened that there was not enough strength applied to achieve a degree of embossing depth. In such a case, the upper die was hammered on for a second time which could slightly shift the imprint. This double striking effect, with the associated deformation on a coin, complicates any identification of a die significantly.

2 Origin of the Coin Analysis

Since the introduction of the Euro in 2001, automatic recognition and classification of modern coins have been attracting increasing attention. Within the framework of the

Figure 2: Example of a) abrasion, b) double striking and c) corrosion on a coin

monetary reform, 300 tons of coins had to be sorted into currency and size. This task was given to the Austrian Research Center (ARC) in Seibersdorf by the European Union. The developed recognition system 'Dagobert' [5] was able to separate more than 2000 different coin types from 30 different currencies. Based on the compiled image data (c 60,000 coins), the MUSCLE CIS Coin Recognition Competition was held in 2006 and 2007. For this occasion, 50,000 coins were provided as training data and 10,000 coins as test data. Different approaches to the classification of coins were developed, including eigenspace, edge directions, gradient directions, and neural network algorithms. All approaches had one thing in common; to get rotation invariance by converting the data into a polar-coordinate representation and by taking the center of gravity as the point of origin. However, these algorithms are ineligible for the recognition of pre-modern coins. Apart from abrasion and corrosion, pre-modern coins also suffer huge differences during the manufacturing process. They do not have a perfectly round shape and the center of the imprint is not congruent with the center of gravity.
Another project is the 'Combat On-line Illegal Numismatic Sales'-Project (COINS-Project) which had been financed by the European Union from 2007 until 2009. One of the project's primary objectives was to provide tools for combating illicit trafficking of stolen coins, by pattern recognition and image processing algorithms. For this reason, a coin should be identified by its distinct character based on a photo. The provided tools and the results are described in the project's final report [6]. According to a specially developed segmentation method, a shape analysis is carried out and finally, a comparison is made using SIFT feature descriptors. This results in a 92.57% recognition rate. Beyond the re-identification of a specific coin, some classification tests were made. Therefore, a system was trained with the SIFT descriptors of three ancient coin types. For each type 100 training images were used. Unfortunately, this high number of training images is not practicable in numismatics. It is extremely difficult or even impossible to get such an amount for every type of coins. For most coin types there are less than 100 specimens available world-wide.

3 Three Color Selective Stereo Gradient Method

The Three Color Selective Stereo Gradient Method (Three-Color SSGM) is a special illumination setup to determine complex 3D-structures of objects with highly reflective metallic surfaces. This setup was developed for a real-time coin classification system, whereby minted coins are moving down an inclined plane [7, 8, 9]. To detect three-dimensional contour information, the coins are illuminated from three different directions. The diodes in the setup are mounted on an LED ring, which is divided into three color sectors; red, green and blue (Figure 4). Under this illumination a single image can be captured by a digital color camera, while the coins are passing by fast. Exploiting the spectral properties of the illumination, which correspond to the characteristics of the RGB-camera, three independent sub-images can be extracted and recombined by simply taking the maximum value of each channel at every pixel position in the image:

$$M(x, y) = max[R(x, y), G(x, y)B(x, y)]. \tag{1}$$

To determine the surface orientations based on measuring the reflectance intensities, it has to be proven that the samples are highly reflective and satisfy the reflection condition where the angle of incidence (θ_i) is equal to the angle of reflection (θ_{spec}). These conditions have been proven in Adameck et al. [7] for modern coins in an experimental setup. A region of a Euro coin in minted condition is illuminated with a laser beam on a region of $5 \times 5mm^2$. The laser source is located in a fixed position, while an image sensor measures the reflection intensities for all relevant observed angles θ_r (Figure 3 a). Finally the Phong shading model is used to approximate the measured data (Figure 3b), which show that Euro coins fulfill these conditions.

This method is related to Woodham's photometric stereo method [10]. Its basic idea is to observe a reflective object, while changing the direction of incident light source. Based on the achieved reflectance maps, it is possible to determine the surface orientation. Woodham showed that only three different illumination directions with the same angle of incidence are sufficient to determine the surface orientation of objects with a significant radiance towards the camera. The recovered body reflectance color of a suitable angle of incidence is a convenient model to describe the surface orientations [8]. Thus, all captured absolute values over the coin surface represent the embossed structure. While the Woodham photometric stereo method requires multiple images, the Three-Color SSGM captures three reflectance images at once. The capturing process of multiple images is time-consuming and for most real-time applications inapplicable. As of this and because not all gradients are necessary for the 3D structure of a minted coin, the Three-Color SSGM is limited to a particular angle of incidence (θ_i). In the experimental setup of the Three-Color SSGM, 15 LEDs are mounted on a ring around the measurement field. Due to the inhomogeneous irradiance of the LEDs, planoconvex plastic lenses are used for shading correction.

4 Processing Workflow

In this section a workflow for coin imaging is described which is the basis for further coin analyses. Therefore, a derivative of the Three-Color SSGM setup (Section 3) with two different illumination angles has been developed. Lastly the reflection images of two different coins will be aligned by a Modified Particle Swarm Optimization Algorithm.

The processing workflow can be divided into image acquisition, data detection/selection and registration.

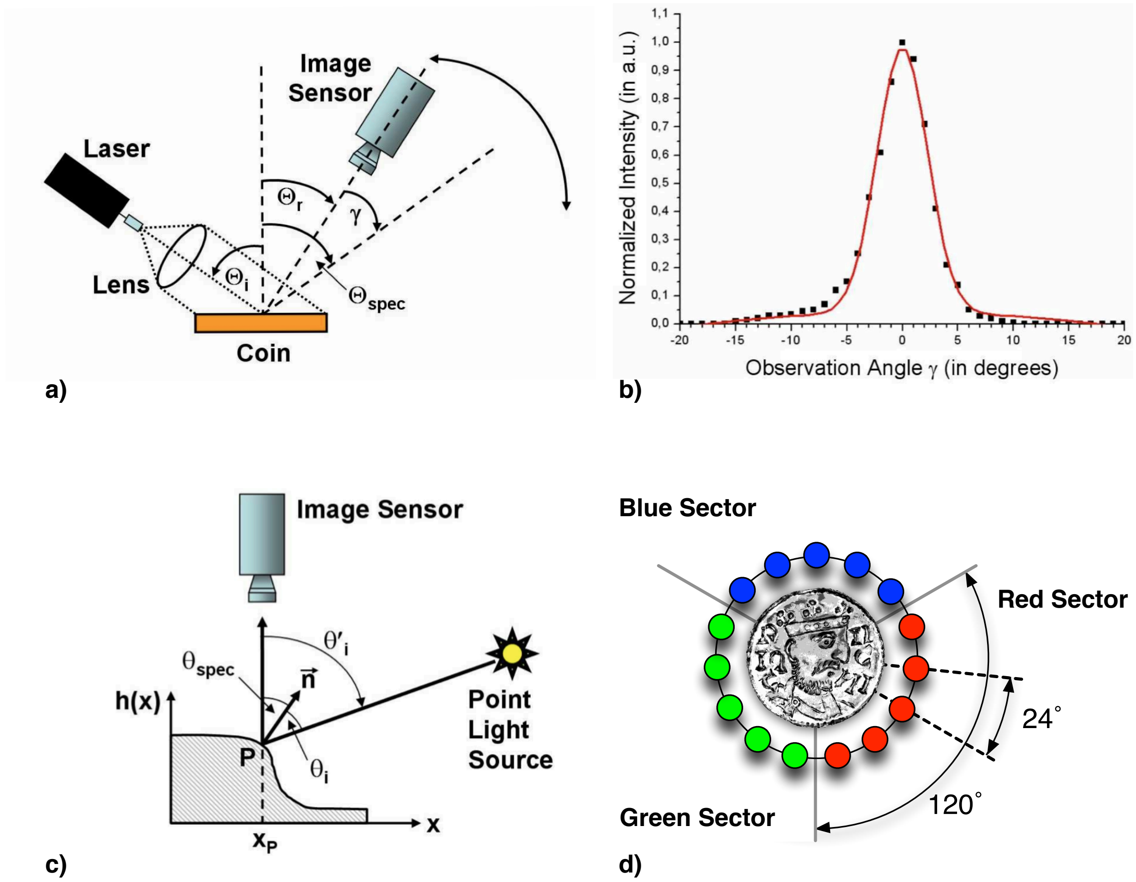

Figure 3: a) Experimental setup for measuring the reflectivity property, the laser beam is fixed, while the image sensor measures the intensities of the observed angles b) Plot with the normalized reflected specular intensities in ratio to the observed angles. The red line is the approximation with the Phong shading model. c) The Three-Color SSGM setup; the reflection angle direction points towards the camera, which results into an absolute reflection value, which can indicate the coin embossing. (image source [8]) d) The diodes are arranged around the measurement field, which is divided into three sectors; red, green and blue. The diodes illuminate the coin with a certain angle of incidence.

1. The image acquisition is essential irrespective of any image analysis application. This part defines which imaging modalities are determined. All images were taken with a NIKON D50 DSLR-camera and with a macro-lens (AF Micro-Nikkor 60mm f/2.8D), which is mounted on a reproduction tripod. This tripod arranging the sensor absolutely parallel to the reference plane with a focus distance of approximately 300mm. Further camera parameters are: exposure time 1/30 and aperture $f/8$.

2. The data detection/selection part defines what kind of data, features or regions are extracted from the raw data for a further processing. For reasons of simplification, it is required that the coin is positioned on a homogeneous background and the coin-center is located in the optical axis of the camera. Occasionally a ruler is placed on the right image margin, to indicate the size.

3. The selected data can be used for further analyses, for example to align the captured images with the help of a Particle Swarm Optimization technique.

4.1 Development of the Imaging Setup

Based on the described Three-Color Selective Stereo Gradient Method in section 3, a low-cost setup was developed to get a better impression of the three-dimensional structure of the coin imprint. Most pre-modern coins are deformed and it cannot be ensured that the material fulfills the reflection condition, given in section 3, where the angle of incidence (θ_i) is equal to the angle of reflection (θ_{spec}). Local corrosion, worn-out regions, and dust on the pre-modern coins affect the structure of the imprint. These effects can deteriorate the complete impression of a coin. Pre-modern coins may have a similar reflection behavior like modern coins, but not necessarily in regions where the coins are affected by corrosion. According to the deformation and the different profile-depth of pre-modern coins, two rows of LEDs with different incidence angles are arranged in a spherically shaped holder (Figure 4)

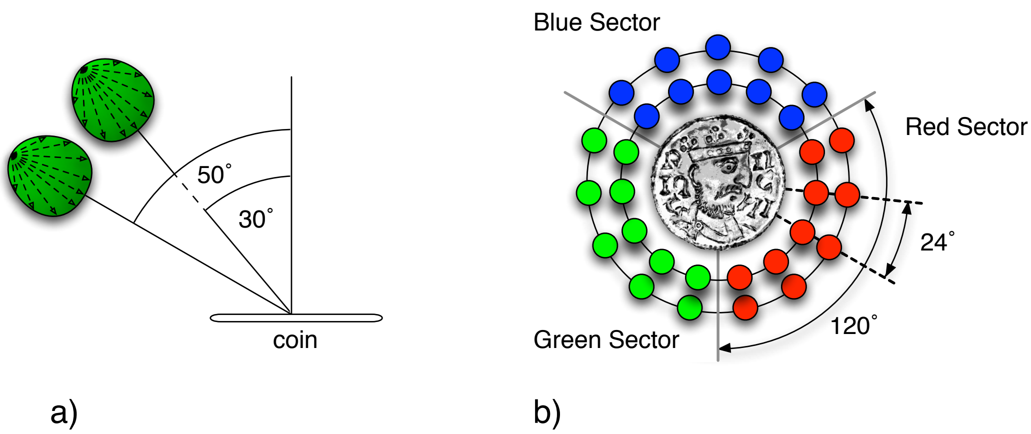

Figure 4: The illumination setup has two LED rings which are equipped with low-cost 120° StrawHat-diodes. The incidence angle of the lower ring is $\theta_i = 50°$, where the upper ring has an angle of $\theta_i = 30°$ a). Both rings are divided into three 120° degree color sectors; red, green and blue b). For each illumination ring, one image is captured, which corresponds to a particular incidence angle.

The mounted LEDs in the illumination dome are low-cost straw-hat LEDs with an angle of radiation of 120° and a luminance between $700 - 1000 cd/m^2$. All diodes have visually a spectral emission characteristic of red, green or blue. A controller is used to change the diodes in their intensities, individually by their channel. This controller is working according to the pulse-width modulation (PWM) principle to change the intensities smoothly.

A white plane is captured while only one color of one row is activated. The histogram of images shows that in each channel the correlated color is dominant. For this reason, a sufficient spectral emission characteristic of the diodes is given. The inhomogeneous irradiance of the LEDs can be recognized as well (Figure 5).

In the original proposed method the LEDs are located next to the measurement field. This short distance leads to a markedly decreasing illumination over the measurement

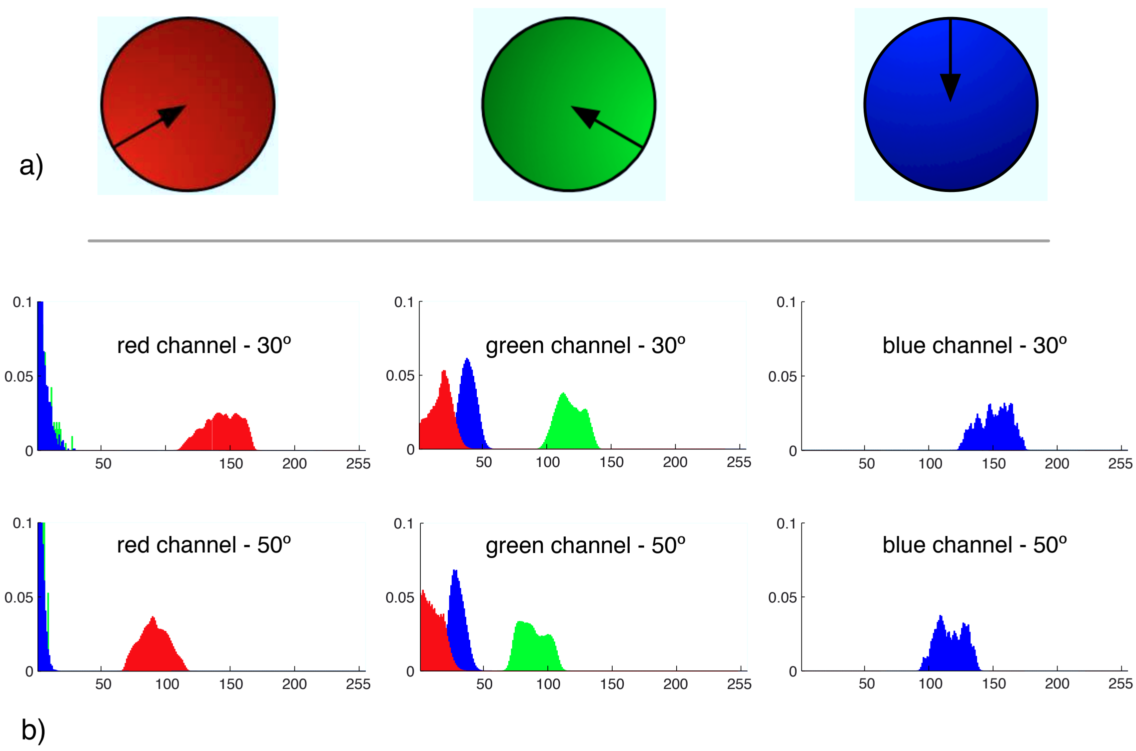

Figure 5: Histograms of the calibration images; the upper row shows the histograms for the angle of incidence $\theta_i = 30°$) and the lower row for the angle of $\theta_i = 50°$

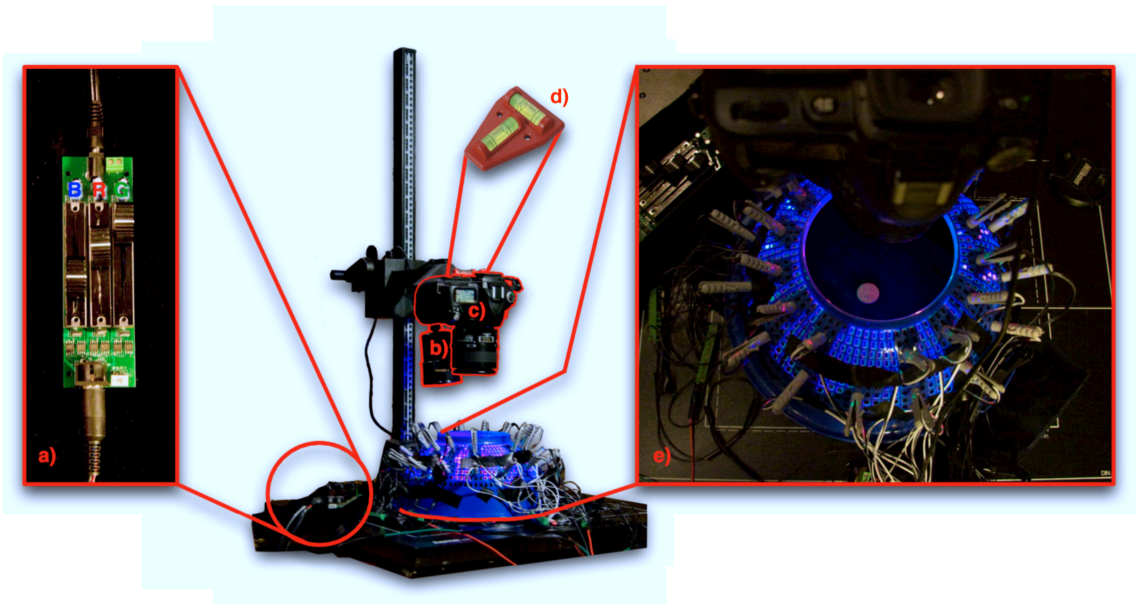

Figure 6: Illumination setup a) controller; each channel can be controlled with the slider in its intensity, this is especially useful for low cost LEDs b) Spotlight; for a third image with a normal light source c) DSLR-camera mounted on a reproduction tripod d) water level for adjusting the camera e) custom-built illumination setup according to [9]

field. To correct this inhomogeneity, planoconvex plastic lenses are placed in front of the LEDs. In this setup the LEDs are located further apart ($15cm$). This reduces the decreasing illumination effect and permits to use a pre-captured calibration image for correction instead of using special lenses. More precisely, for each color channel, one calibration image is captured. These calibration images are normalized and component-wise multiplied with the Three-Color SSGM image. Figure 7 illustrates all major calibration stages. This illumination setup is easy to be embedded in the numismatic photography workflow. A normal light source is extended to the setup. Accordingly, a numismatist has to take only three images for each illumination configuration. Great reflections that eliminate essential information of the coin can be caused by varying deformations of coins. This requires to change the incidence angles.

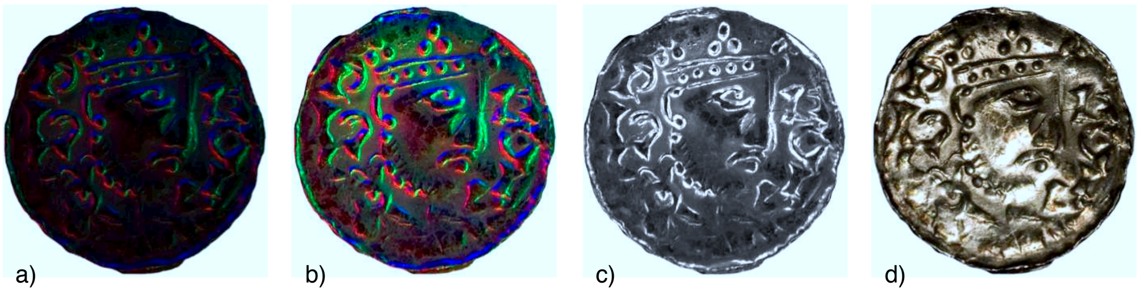

Figure 7: a) The direct output of the camera sensor. b) the shading corrected image; it uses the corresponding RGB-calibration images to correct the inhomogeneous illumination of the LEDs. c) combined image of all three channels by taking the maximum RGB value at each pixel coordinate. d) coin image captured with a 150W defuse spotlight.

4.2 Region of Interest Segmentation

An important step for the coin analysis is to detach the captured coin from the homogeneous background. The segmentation is performed according to Kampel et al. [6]. Within this method the coin images are convolved with a local entropy and a local range gray value filter. Afterwards, the results are summed up to a normalized intensity image and always thresholded with a value of 0.4.

4.3 Image Registration with Modified Particle Swarm Optimization

Particle Swarm Optimization (PSO) is a population-based method and was developed owing to Kennedy and Eberhart [11]. The method is inspired by the movement behavior of a bird flock or shoals. PSO is an optimization method for solving continuous non-linear functions. It has been successfully used for a wide range of applications in varying research disciplines. In PSO, a limited number of particles is randomly placed in the parameter space of problems or functions. After each update of a particle the current position is evaluated by an objective function (fitness-, or cost-function), $O : \mathbb{R}^n \rightarrow \mathbb{R}$. For an N-dimensional problem, one particle can be expressed as a vector with N-components. More precisely, a particle is a particular position in a multidimensional search-space, which is, in terms of image registration, the transformation parameter. Thus, the best position in the search space is given through maximizing/minimizing the objective function.

Finally a recently published modification to the PSO algorithm was used [12, 13]. This PSO version prevents that the algorithm gets stuck in a local extremum, by taking different decisions based on the directions of the cognitive and the social components. The normalized cross correlation is chosen as the objective function. It can be easily replaced by another similarity or dissimilarity function in the used MATLAB implementation. To decrease the effort, the images are reduced to the size of approximately 600×600 pixel. This limitation is necessary to keep the complexity of the search-space low. With an increasing search-space or dimension more particles are required to explore the search-space. This application uses 60-80 particles for the exploration of the search-space. The acceleration coefficients have influence on the acceleration of the particle's cognitive and social term. These coefficients are set to a value of 10. The whole search space is always determined after 50 iterations. The used transformation limitations are:

- $\pm$ 40 pixel for the translation in x and y direction
- $< 180^\circ$ for the rotation (α)
- 0.95 - 1.05 as scale factor (σ)

Additionally, the two rectangular coin images cannot be registered in total. A registration process with the including background pixels from the rectangular image would lead to a highly normalized cross correlation value, but without alignment of the imprints (Table 1). The background and thus the shape of the coins would get aligned. To avoid this effect, only the overlapping regions of the coins are used for a comparison. More precisely, for each particle position, the source image is transformed with the appropriate transformation parameters. Only the pixels for a comparison are taken where the coins are overlapping (Figure 8). The overlapping regions of both images have the same size, which is usually a requirement of the similarity functions. For reasons of simplification, these regions are represented as a one-dimensional vector in the MATLAB implementation.

Within the registration process it can happen that the particles are moving with a high translation value to a position in the search space. This translation would lead to a smaller region for the comparison and if the regions were worn out at this time, a high rating value would be followed by an abortive registration. This is the reason, why the search space in x and y direction is limited.

5 Results

In this section the results of the developed illumination setup as well as the results of the registration with Particle Swarm Optimization are presented.

5.1 Maximum Gray Value Images

Figure 9 shows a comparison between the resulting images of the Three-Color SSGM and the standard illumination with one point light source. The images which were taken with the Three-Color SSGM depict more details, while in the images with the illumination of

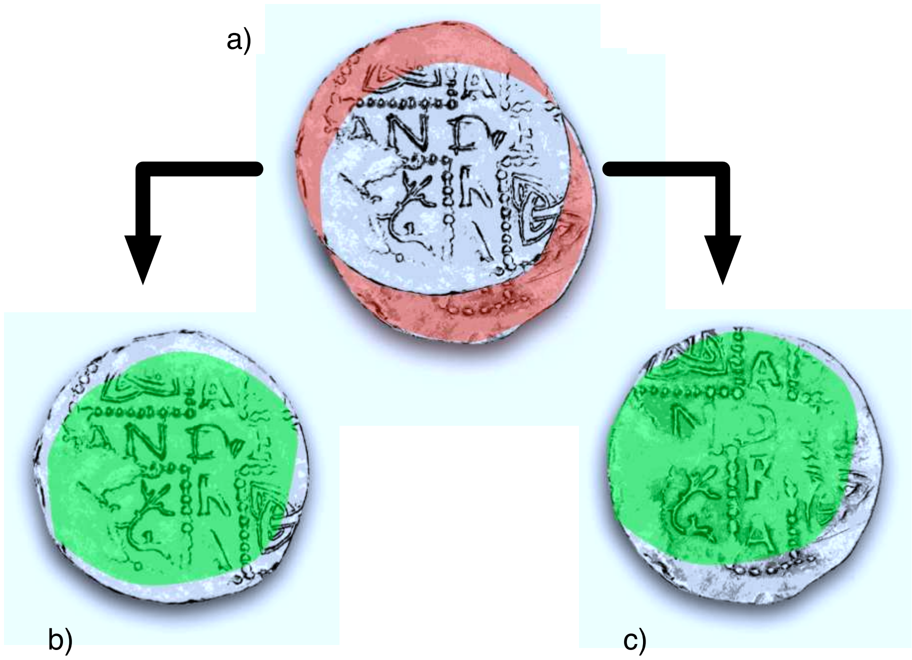

Figure 8: a) at any time step the source image is transformed and only the overlapping regions of the coins are taken for a comparison (b, c)

one point light source, the imprint loses information, caused by the self-shadow. These images are notably of great value for a numismatist. A manual comparison between two coin images is now possible. Especially for those coins, whereby a manual comparison based on the standard illuminated coin image was abandoned. Furthermore, these images are the basis for the comparison of the coin structure. As expected, it could be noticed that the sensed reflections on the coin profiles can be very different between the images with a various angle of incidence (Figure 9a,b). While one image with a certain incidence angle gives a good impression of the profile structure, the impression of another incidence angle image is not as detailed. Overall, it is recommended that at the same time of capturing the normal documentation photo, two additional photos with the Three-Color SSGM are taken. Thereby, either the image with an angle of incidence $\theta_i = 50$ or with $\theta_i = 30$ turn out to result in a more detailed impression of the coins.

5.2 Image Registration

First it was tested how standard illuminated coin images can be automatically aligned. It turned out that the used similarity measurement NCC is not sufficient for the required search space. Dust and corrosion on the coins distort the impression and thus affect the registration results (Figure 10). A registration was only possible for an extremely limited search space ($x, y, < 20$, $\sigma < 5°$). However, experiments have shown that either an additional 30° or 50° image solves this problem in most cases.

Table 1 shows results of the image registration process with NCC as objective function. After the registration it was decided visually if the images are registered, or not.

PSO is a good optimization technique. In theory, it represents all possible solutions. However the whole registration process is dependent on the objective function. It is evident that NCC is not the best function for this application.

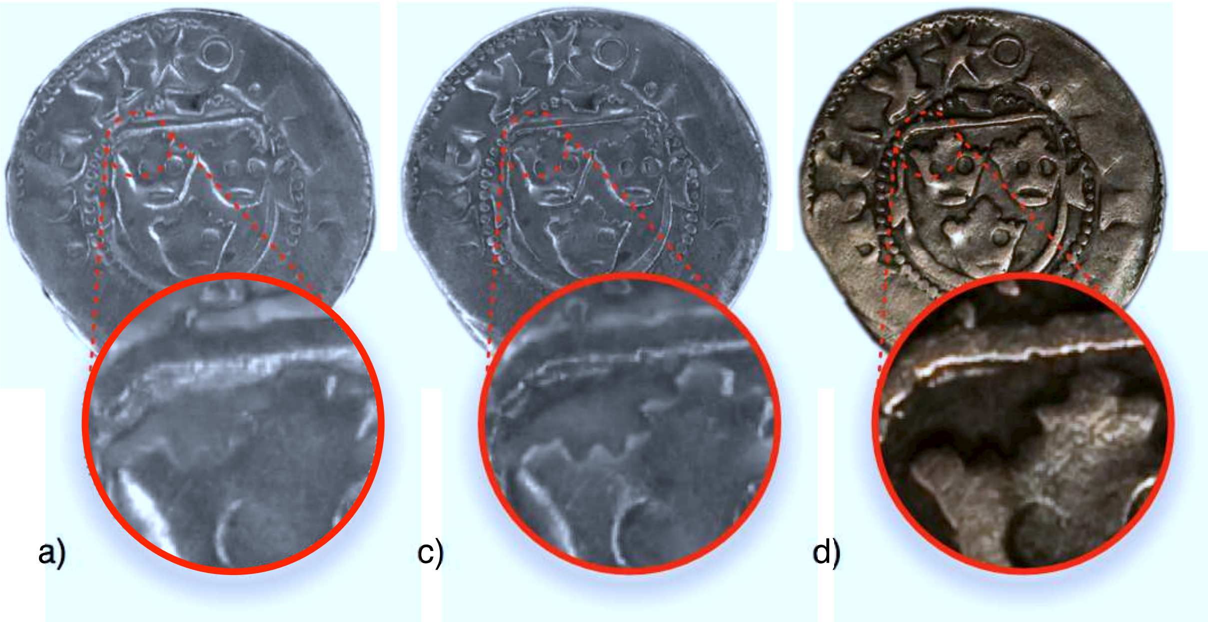

Figure 9: Comparison of the Three-Color SSGM images with different angle of incidence; a) with $\theta_i = 50$ and b) with $\theta_i = 30$, c) shows the normal illuminated coin

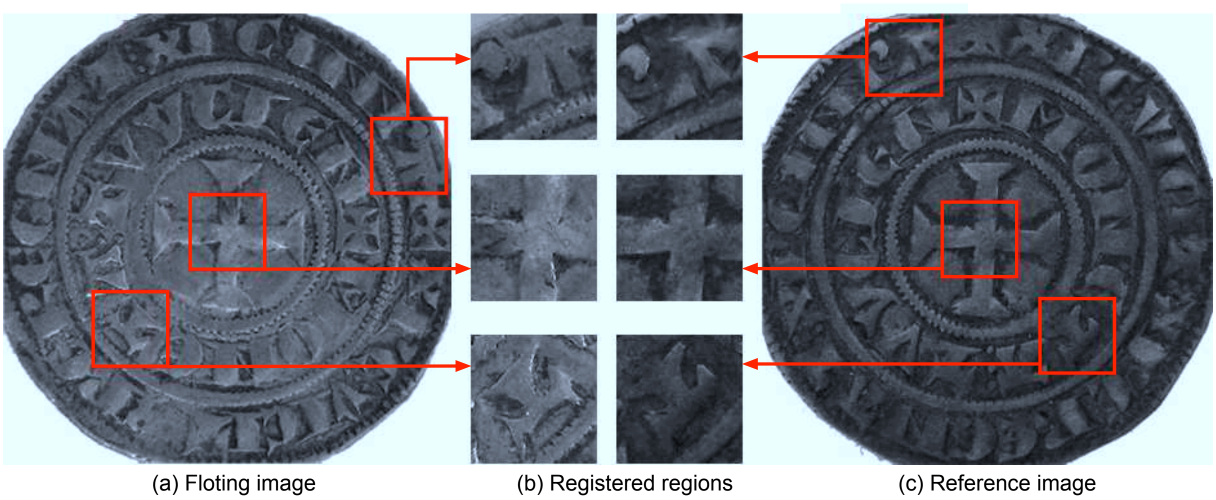

Figure 10: The depicted die-identical coins are different in impression caused by corrosion and dust. The used NCC cannot perform a registration for the fully required search space.

6 Conclusion

The developed derivative of the Three-Color SSGM is a low cost technology, which can be built for less than 60 Euros. It cannot generate a complete 3D documentation of a coin, but the generated maximum gray value images can provide a good impression of the depicted 3D coin structure as long as the material is highly reflective. The images which were taken with the Three-Color SSGM depict more details, while in the images with the standard illumination shape-information of the imprint is lost, due to self-shadowing. This is a major issue, now numismatists are enabled to decide more confidently if two

Reference Image	Source Image	NCC	Registered
SNU2 Nr 20	SNU2 Nr 21	0.2837	Yes
SNU2 Nr 305 U	SNU2 Nr 304 U	0.1685	No (worn out)
SNU2 Nr 584 U	SNU2 Nr 585 U	0.4241	Yes
SNU2 Nr 586 U	SNU2 Nr 587 U	0.2673	Yes
SNU3 Nr 330 U	SNU3 Nr 331 U	0.1785	Yes
SNU3 Nr 330 U	SNU3 Nr 332 U	0.1214	Yes
SNU3 Nr 331 U	SNU3 Nr 332 U	0.282	Yes
SNU3 Nr 333 U	SNU3 Nr 334 U	0.1908	No (double strike)

Table 1: Matching Result with Modified Particle Swarm Optimization and NCC as objective function. (SNU = Studia Numismatica Upsaliensia)

images depict die-identical coins in particular those coin images which could not be judged by the standard illumination technique, beforehand. Nevertheless, it is recommended to document the coins in the presented way; by taking two Three-Color SSGM images with different illumination angles and one image with the standard illumination. The whole setup can be easily integrated in the normal workflow of numismatic photography, which is a further advantage. So far, this illumination- and registration technique has been tested on 14 die-identical coin images of 6 different coin types. The registration failed in the comparison of two coin-pairs, because of abrasion and a strong double striking. Further tests with this system need to be performed to optimize the registration of such coins. Unfortunately there were no additional die-identical coins available. Based on the achieved results and the observed performance, it was realized that in this application the rotation is the most problematic transformation. Since the introduction of the Three-Color SSGM to this application, it has been possible to subtract the edge information by thresholding. This opens a new perspective to this application. Further tests should be performed to find a sufficient objective function like a set distance. Here, it has to be focused especially on the monotonic behavior of the measurement when the images are rotated against each other.

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