Automated analysis and comparison of striated toolmarks

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ABSTRACT

In this paper, we present the new system GE/2 for the identification of toolmarks and firearms. It is based on a signal processing strategy that enables an automated evaluation of pictures taken from striation patterns. To this end, we introduce a suitable signal model which can be used to describe the characteristics of groove textures. This signal model can be adapted to both forensically important groove types: straight grooves, which can be found on pristine bullets, and curved grooves, which are typical for toolmarks and deformed bullets.

To obtain high quality data, a powerful imaging approach is presented. The underlying strategy, which is based on fusion techniques, is applicable to both illumination problems and focussing issues. To obtain a high reliability in the automated comparison, characteristic features, which we call "signatures," are required. To this end, a newly developed strategy is proposed to straighten curved grooves by means of the signal model mentioned above. Based on the signatures obtained, an automated comparison on the basis of correlation techniques is applied. Here, a benchmarking test for comparison algorithms is introduced which makes it possible to compare the efficiency of different systems. Finally, the integrated system GE/2 is presented, consisting of the Image Acquisition Station and a computer to perform the processing of the data.

Keywords: forensic science, toolmarks, firearm bullets, striation patterns, groove straightening, imaging system, automated visual inspection, image processing

1. INTRODUCTION

The forensic task which motivated this work is the imaging and comparison of toolmarks and of striation marks on firearm bullets. Bullets and toolmarks found at crime play an essential role within forensic science. For a long time, the groove structures on the circumferential surface of bullets have been used to identify several bullets fired from the same gun or to recognize the appropriate gun for a given bullet. In case of toolmarks, which are often found in case of burglaries and thefts, groove-like textures also arise due to the motion of the tool relative to the object touched. The ultimate goals of the comparison of these marks are the discovery of connections between crimes, and the identification of the tools and firearms used in crime. To this end, huge archives of munitions and marks have to be maintained, which can contain some 1,000 marks of the same kind.

The current procedure for the identification work is essentially manual and visual. The forensic examiner memorizes microscopically observed marks, searches for similar marks in a very large archive, and compares them with his mental images. Due to this inconvenient and costly archive comparison, long waiting times for the forensic processing of a case result. Moreover, the success rate of identifying connections using this method is very low. Obviously, the assistance of an automated system would be very helpful. The requirements for a useful technical solution to this task are the following:

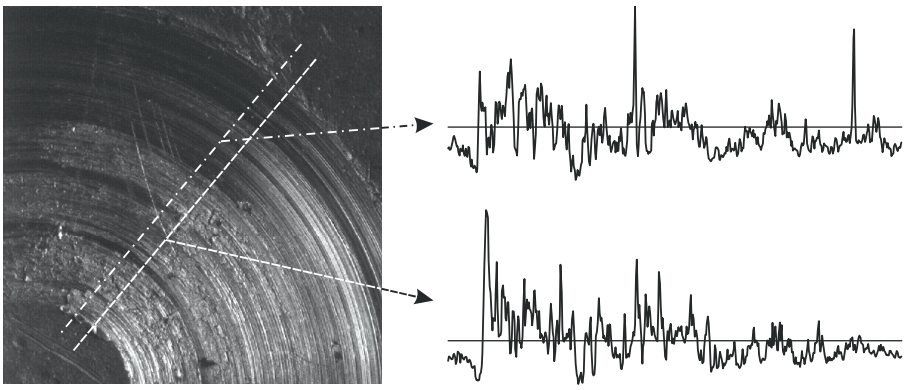


Figure 1. Extraction of intensity profiles from a striation mark: errors due to local disturbances.

- an automated imaging system that provides high-quality images and thorough data acquisition, which can be performed under easily reproducible conditions,
- the extraction of certain features necessary for a database search,
- the generation of a hit-list of possible striae correspondences, and finally,
- a visual comparison of the most likely entries of the hit-list, performed by a forensic examiner.

Considering the properties of the marks in the cases relevant to forensic science, every step has to be adapted to the specific properties of groove-like textures in order to obtain reliable identification results. Stepping up to this challenge, we present in this paper a new image processing system for the task of analysing and comparing striated marks. After the automated image acquisition and enhancement, a meaningful signature is extracted from the texture. Based on the signatures obtained, an objective and quantitative comparison of striation patterns can be achieved.[6,7]

The strategy employed is based on a novel signal model which is presented in Sect. 2. Taking the signal properties into account, powerful strategies for the image acquisition can be applied to obtain images of high quality; see Sect. 3. After that, the proposed signal model is used to robustly extract the signature of the toolmark, as shown in Sect. 4. Section 5 presents the results of the comparison of signatures, and in Sect. 6, the setup of the system GE/2 is described.

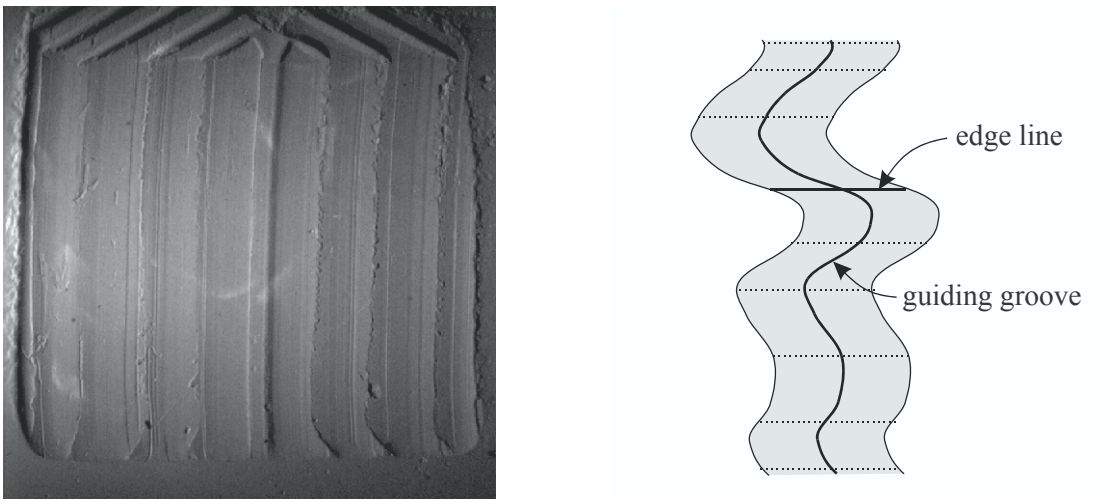
2. SIGNAL MODEL

Most approaches to automate the comparison of striation marks are based on extracting intensity profiles along lines perpendicular to the direction of the grooves, as shown in Fig. 1. Here, the extracted profile may vary due to local disturbances like scratches, durst particles or, in case that castings are examined, due to cavities or inclusions.

The two profiles depicted in Fig. 1 are placed not far from each other, but even in this case, the profiles show significant differences which may deteriorate an automated comparison and make it impossible to achieve reliable and reproducible results. To reduce the effect of such local disturbances, we propose a more reliable strategy that considers the whole length of the grooves. This strategy is model-based as it uses a kinematic model which describes the process of the groove generation. Consequently, the first step of this strategy is to develop suitable signal models. Here, it is important that the cases of straight and curved grooves be distinguished, as discussed in the following subsections.

2.1 Pristine Bullets

In the case of pristine bullets, such a kinematic model is easy to find. At the time of firing, the kinematics provides for the generation of strictly straight grooves on the circumferential surface



(a) (b)

Figure 2. Toolmark grooves: (a) casting of a toolmark; (b) corresponding signal model.

of the bullet. All individual characteristics of the barrel are mapped onto parallel grooves. Due to the rifling of the gun, the grooves show an angle of twist.[3] To extract the information of interest reliably, a projection along the grooves has to be performed.

However, curved grooves may also occur on firearm bullets. The described assumption of straight grooves may not always be reasonable, especially when bullets have been deformed at the impact. In that case, one is concerned with signal models which are much more difficult to handle, and which are of importance particularly for toolmarks.

2.2 Deformed Bullets and Toolmarks

In the case of toolmarks as well as deformed bullets, the simple signal model developed for pristine bullets showing straight grooves cannot be applied. Since the grooves are not rectilinear, the motion has more degrees of freedom which have to be taken into account.

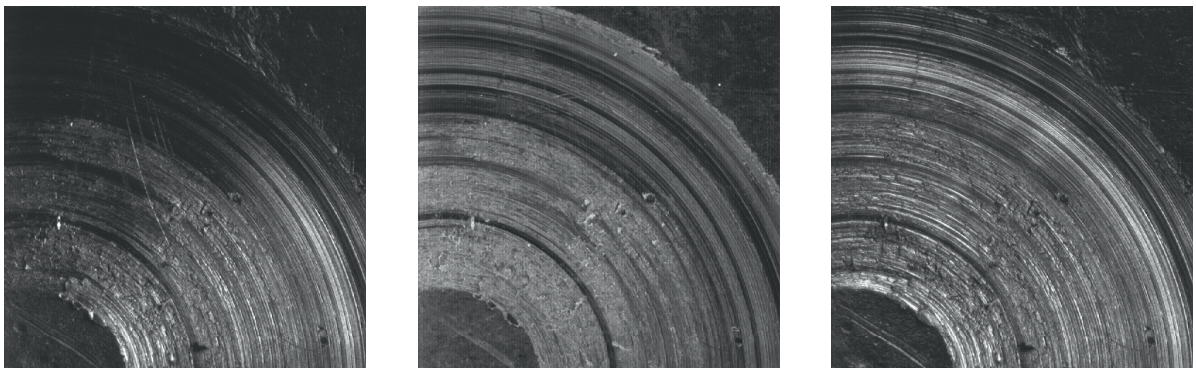
The generation process of groove-like toolmarks shows that the resulting textures emerge from the motion of a one-dimensional cutting edge. In general, the motion can be considered as a combination of a translation and a rotation. Tests with large databases have proven that most toolmarks show only a pure translation of the edge. Therefore, the approaches described in this paper will focus on such marks. However, the comprehensive methodology implemented in GE/2 allows to deal with all sorts of groove-shaped toolmarks.

To give an example, a casting of a sample toolmark is shown in Fig. 2(a). As in most cases, the assumption of a pure translation of the tool seems to be suitable. In order to apply the signal model, the corresponding parameters have to be estimated from an image of the mark. Figure 2(b) shows the model parameters: the edge as a so-called “edge line” and the path of the tool, which can be determined by means of a pronounced groove—the “guiding groove.”

But before applying the signal model to a captured image, some considerations should be made in order to guarantee that high-quality images are obtained. Here, the signal properties can also be exploited to develop powerful image acquisition strategies.

3. IMAGING

In forensic science, the requirements concerning the quality of the images to be evaluated are especially high. To provide for a reliable comparison of forensic marks, a reproducible imaging even of the finest individual marks is necessary. Therefore, great efforts must be made in the area of image capture. Ideally, the requirements to be fulfilled by the image acquisition system comprise



(a) (b) (c)

Figure 3. Image acquisition problems: (a) example of an image of a toolmark obtained with directional lighting; (b) image of the same toolmark obtained with diffuse lighting; (c) enhanced image obtained by fusion methods.

- a high-quality image acquisition providing for high contrast, high resolution, high image sharpness, and high signal to noise ratio (SNR) in the whole image,
- a thorough coverage of the surface containing the marks of interest,
- an easily reproducible recording situation, and finally,
- a mostly automated image acquisition.

Due to the limitations of optical systems, illumination problems as well as difficulties in imaging all interesting areas simultaneously and with the required resolution, it is often not possible to meet all these requirements with only one image of the object. Instead, these requirements can be fulfilled by acquiring several images under different recording conditions. Examples of images showing a deficient quality due to an inadequate image acquisition are shown in Figs. 3(a) and (b). The system GE/2 is capable of systematically varying all the illumination parameters as well as the object distance. In this paper, we will focus on illumination problems, because they play a crucial role in the imaging of groove structures.[5]

3.1 Image capture

To image surface textures showing marks with high contrast, a suitable illumination has to be chosen. It can be shown that the image intensities obtained from such surfaces highly depend on the direction of the light source, if directional lighting is used;[5] see Fig. 3(a). Since a diffuse illumination pattern can be thought of as a superposition of many single directional light sources from different directions, diffuse lighting will generally lead to a homogeneous appearance with high contrast attenuation, and thus to suboptimal results; see Fig. 3(b). However, although directional lighting is preferable to illuminate subtle surface structures, the position of the light source will have to be adjusted for each location of the surface, if an optimal local contrast is wanted.

The system GE/2 is equipped with appropriate illumination strategies leading to optimally illuminated series of images for all forensically relevant marks. The following examples show some possible cases:

- **Circumferential surface, straight grooves:** To record image series of circumferential surfaces showing a single band of straight, parallel grooves, like e.g. pristine bullets, it is necessary to vary the illumination direction such that the incident light is always perpendicular to the grooves.[5] That way, the surface contrast is maximized. Thus, the elevation angle—i.e. the angle to the perpendicular of the surface—is varied. If the interesting surface areas are not all in-focus simultaneously, the object distance is varied, too.

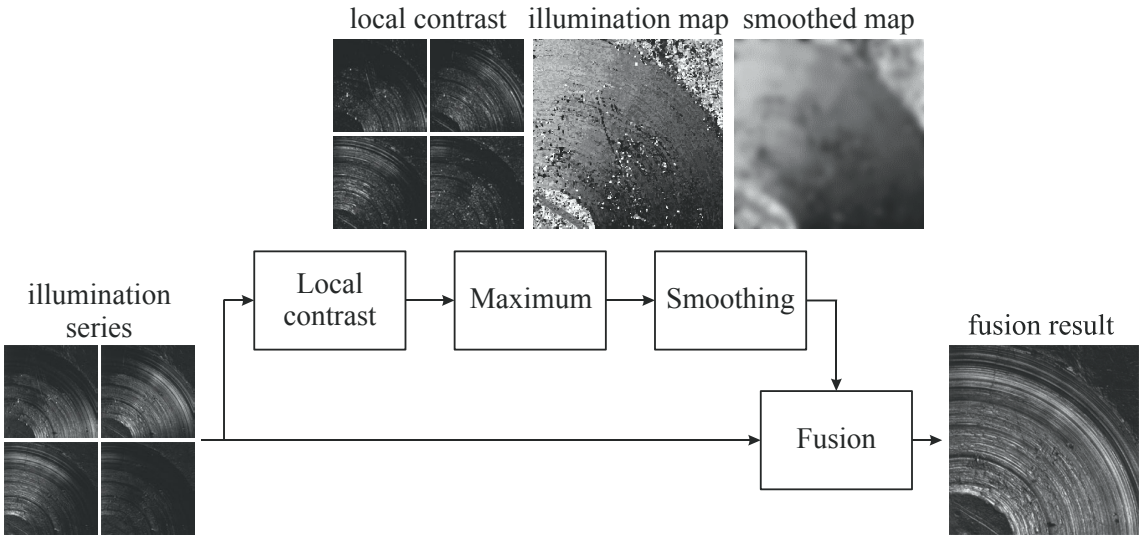


Figure 4. Structure of the algorithm for fusing 1-D illumination series.

- **Plane surface, curved grooves:** In case of curved grooves on plane surfaces, it is usually sufficient to record an image series in which the azimuth—i.e. the angle to the local groove direction—is varied. This case is typical for a wide range of forensically relevant marks generated by screwdrivers and other tools.
- **Curved surface, curved grooves:** In the most complicated case of curved surfaces containing curved grooves, such as deformed bullets, the elevation angle as well as the azimuth of the light source are varied to assure for each location a high quality in at least one image of the series. Additionally, also the object distance and the object pose may be varied as well to provide for a proper focusing and low distortions.

3.2 Fusion strategy

After an image series has been acquired, a suitable strategy has to be applied to combine the information of interest distributed over the series to an enhanced result showing overall a high quality; see Fig. 3(c). Such a result is not only advantageous to enable a computerized comparison, but it can also be used to support forensic examiners in matching of striae, because a larger area of the surface can be visualized with high contrast simultaneously than when using conventional tools like comparison macroscopes.

In this paper, only one-dimensional illumination series—i.e. series in which only one illumination parameter is varied—will be discussed. However, by applying this method in several stages, the system GE/2 is also able to fuse multidimensional series of images.[5] Figure 4 shows the structure of the fusion algorithm for the case of a varying azimuth.

The fusion algorithm is based on the selection of the best illuminated image segments of the series for each location based on a the maximization of a local criterion. Since in our case a high contrast is desired, the local gray level variance and the local entropy are suitable options to compute this criterion. Three properties of the proposed fusion method are responsible of its good performance:

1. The fusion result resembles locally the best illuminated image of the series.
2. The smoothness of the selected illumination direction guarantees that no artifacts are contained in the resulting image.
3. The resulting image achieves globally good results in the sense of maximizing the local contrast.

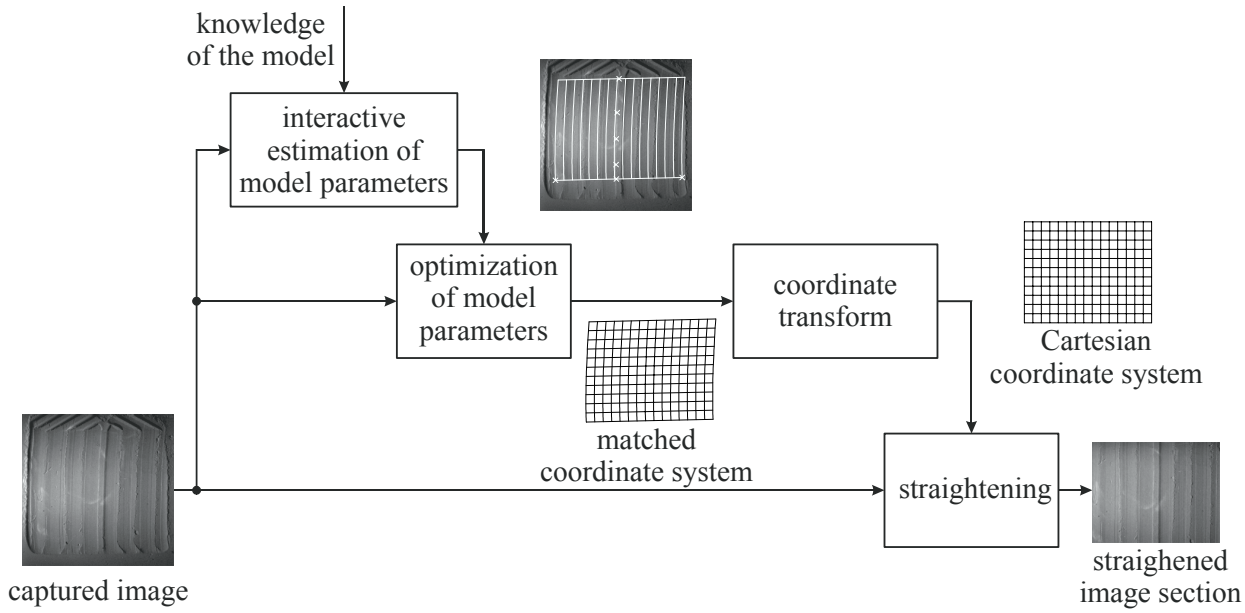


Figure 5. Model-based groove straightening algorithm.

A fusion of an image series in which the elevation angle of the illumination direction is varied can be performed in an analog manner. In addition, the system GE/2 uses the presented algorithms to fuse defocus series. Here, the varied parameter is the object distance, which is chosen such that each image region can be found at least once in-focus in the series.

4. GENERATION OF A SIGNATURE

To provide for an efficient computerized comparison of marks, it is not convenient to use the two-dimensional images themselves for this task. Instead, a data reduction should be performed first to extract a *signature*—that means a unidimensional "fingerprint" of the groove structure—from the image.

As stated in Sect. 2, most systems use a single profile of the groove structure to obtain a signature.[1,2,4] In contrast to these approaches, the system GE/2 considers the whole length of the grooves to suppress the influence of local disturbances according to Fig. 1 on the resulting signature. Since local disturbances affect only minor regions of the marks, a suitable filtering along the grooves can reduce their influence. Filtering the gray values along a groove yields one point of the signature. Repeating the groove tracing for all grooves of the texture, the desired signature is obtained.

4.1 Groove Straightening

If the local orientation of the grooves changes within the area of interest, a straightening has to be performed to consider the whole length of the grooves. To cope with this task, the system GE/2 employs the model-based strategy depicted in Fig. 5.

Firstly, the model parameters needed to describe the kinematics of the groove generation are estimated interactively by the forensic examiner. Here, the width and the length of the striation pattern are selected by using the computer mouse. Thus, the knowledge of the expert on the area of interest can efficiently be exploited.

To overcome the influences of the interactive estimation and to improve the reliability and reproducibility of the straightening, a computerized optimization of the guiding groove is performed based on correlation methods. As the result of the optimization, a matched coordinate system is obtained that can be used to perform a straightening of the grooves; see Fig. 5.

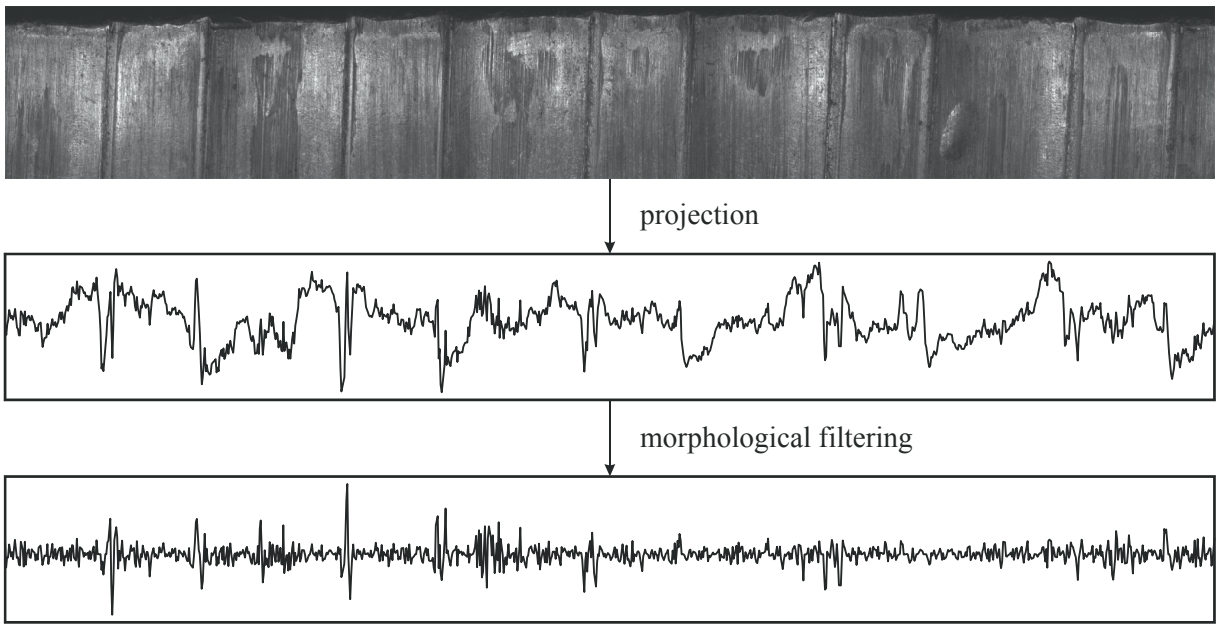


Figure 6. Impact of the feature extraction on a projection of a bullet image.

The final step of the strategy is the groove straightening, which is performed by means of a transform of the matched coordinate system into a Cartesian coordinate system. The resulting image represents the straightened image section.

4.2 Projection and Feature Extraction

Once an image showing straight grooves is available, a projection is computed by performing a filtering in the direction of the grooves. Subsequently, significant features must be extracted from the projection. Unfortunately, the projection itself seems not to be adequate for a direct comparison, because it consists of two different signal components:

- System features, such as the type and width of the mark, represent signal disturbances or noise that should be ignored.
- The individual features are essentially the location and distinctness of fine structures. They establish the signal components describing the characteristic features of the mark.

Thus, instead of using the projection for a direct comparison, a selective extraction of the relevant information has to be performed which results in the desired signature. For this purpose, a morphological filter is employed. Here, morphological methods allow to incorporate specific knowledge on certain signal properties by means of an appropriate choice of the so-called structuring element.

Figure 6 shows an example of the projection and the feature extraction performed by the system GE/2 for the case of a firearm bullet. It can easily be seen that bright areas without information of interest still appear in the projection as plateaus, whereas in the result of the morphological filtering these areas have already been suppressed. In contrast to this, grooves and peaks which can be considered as characteristic features are still visible.

5. COMPARISON OF MARKS

In the comparison stage, the similarity of two signals describing two different marks has to be examined. To perform a database search, the comparison has to be carried out between the given mark and each entry of the database. When a new exhibit is added to the database of the marks, a first preselection detects and classifies system features such as—e.g. in the case of firearm

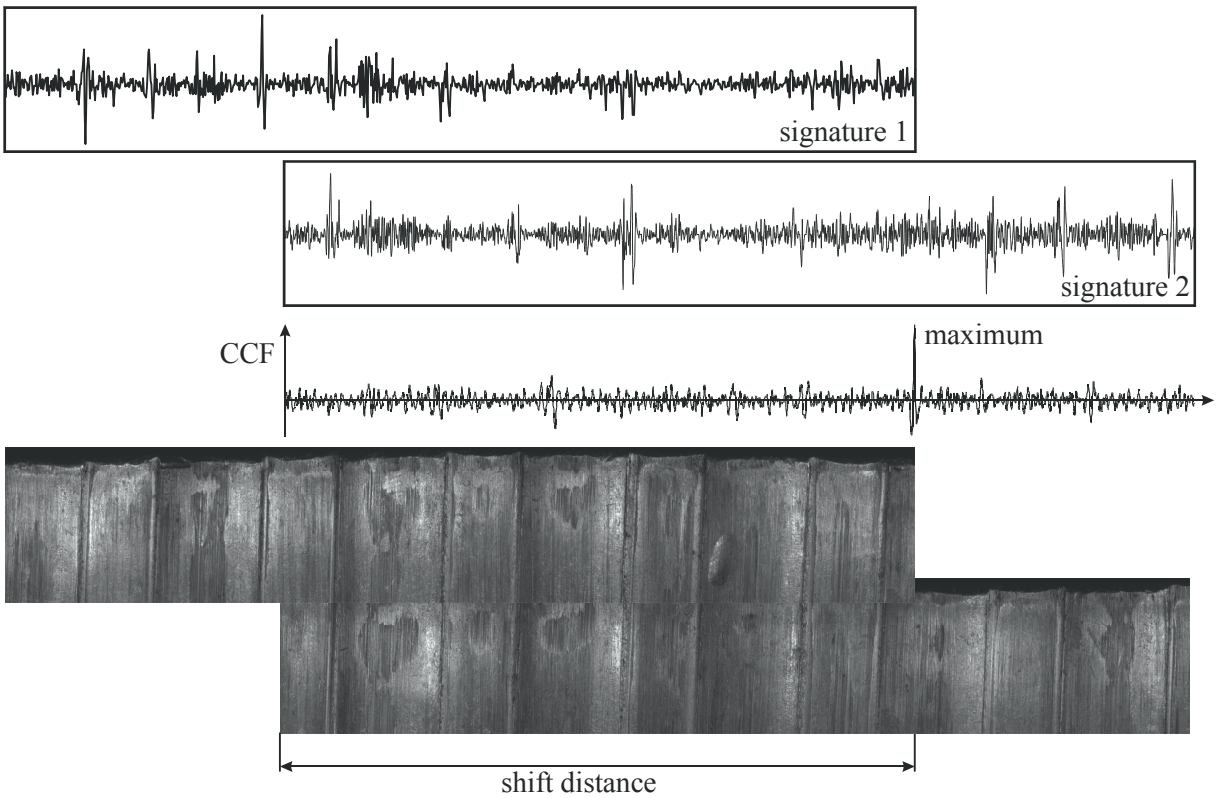


Figure 7. Automated comparison: (top) the two signals compared; (middle) CCF; (bottom) visual comparison.

bullets—the number and width of the lands. The preselection reduces the amount of marks coming into question and leads thus to a faster and more efficient comparison.

5.1 Comparison Principle

A suitable distance measure to evaluate the similarity of marks is based on the empirical cross-correlation function (CCF) of the two filtered signals. The actual comparison algorithm implemented in GE/2 ensures that a similarity is detected independently of a global offset and a global scaling factor. Such signal deviations may arise due to changes in the reflection properties of different specimens.

The automated comparison performed by GE/2 yields two important results:

- First, the examiner is interested in the best possible match between two marks to be able to speed the subsequent visual comparison. The location of the maximum of the CCF describes exactly the lateral shift leading to an optimal match of two striation patterns. The system GE/2 uses this knowledge to simplify the visual inspection by displaying the two examined marks side by side shifted by this distance.
- Finally, the cross-correlation coefficient itself obtained as the maximum of the CCF represents a quantitative measure of the similarity between the two marks. Based on this measure, a sorted list of all entries of the database—the *hit-list*—is generated, where the most promising marks are placed at the top of the list.

Figure 7 visualizes the proposed strategy with an example of the comparison of two different bullets. In the upper area, both signals resulting from the feature extraction of the images are shown. Below, the CCF of the two signals is depicted, the pronounced maximum of which indicates the optimal shift of both signals. At the bottom, the corresponding original images are represented, shifted by the same distance. The great similarity of both bullets—which indeed were fired from the same gun—is clearly visible.

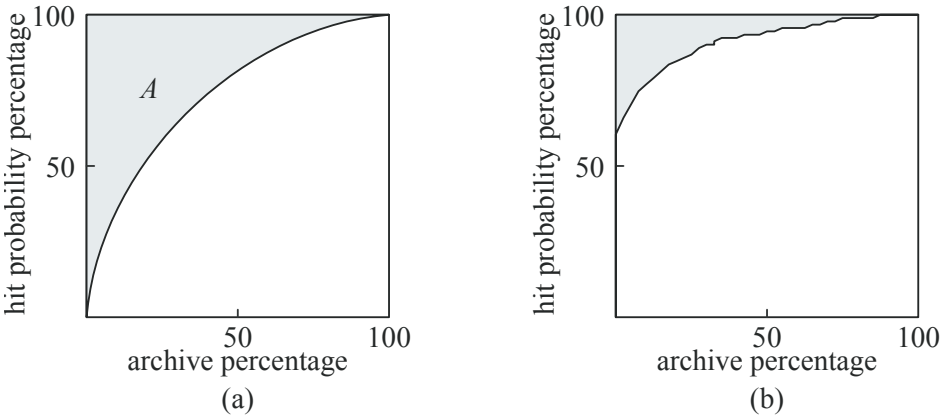


Figure 8. Concentration curve: (a) principle; (b) results of GE/2.

5.2 Assessment

To assess the whole comparison methodology presented and to evaluate different systems for the examination of marks, a quantitative measure describing the quality of the hit-lists produced by them is needed. To facilitate the work of a forensic examiner, the part of the database to be compared visually should be kept as small as possible. Thus, a high concentration of hits at the first positions of the hit-list is desired. Consequently, the assessment should be based on a measure of concentration.

A particularly clear way of representing concentration is through a coordinate system, in the form of a *concentration curve*;[6] see Fig. 8(a). It represents the relative cumulative frequency distribution for the finding of an existing hit in a hit-list or in an archive. Such a curve is obtained by plotting the cumulative hit rate over the percentage of the archive searched. The area A above the curve denotes the average portion of the archive to be examined until an existing match is found. Thus, to obtain a high concentration of matches at the first positions of the hit-list, this area should be as small as possible.

The system GE/2 has been assessed using the presented methodology. To this end, a specific database made available by the German forensic institute "LKA Berlin PTU" consisting of 54

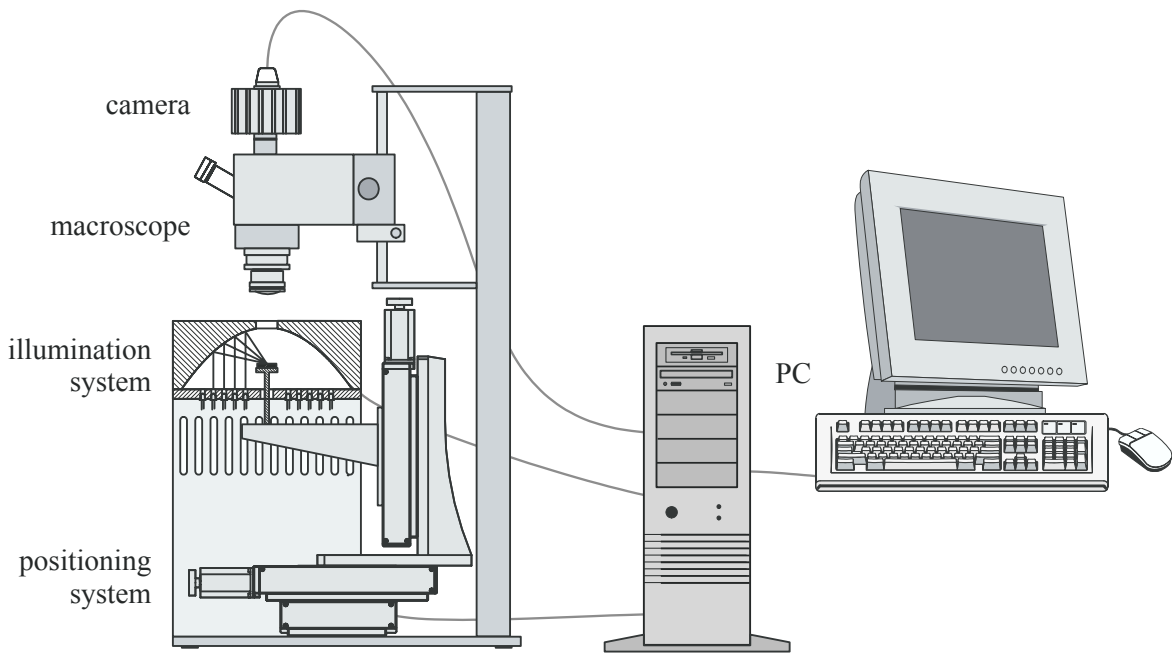
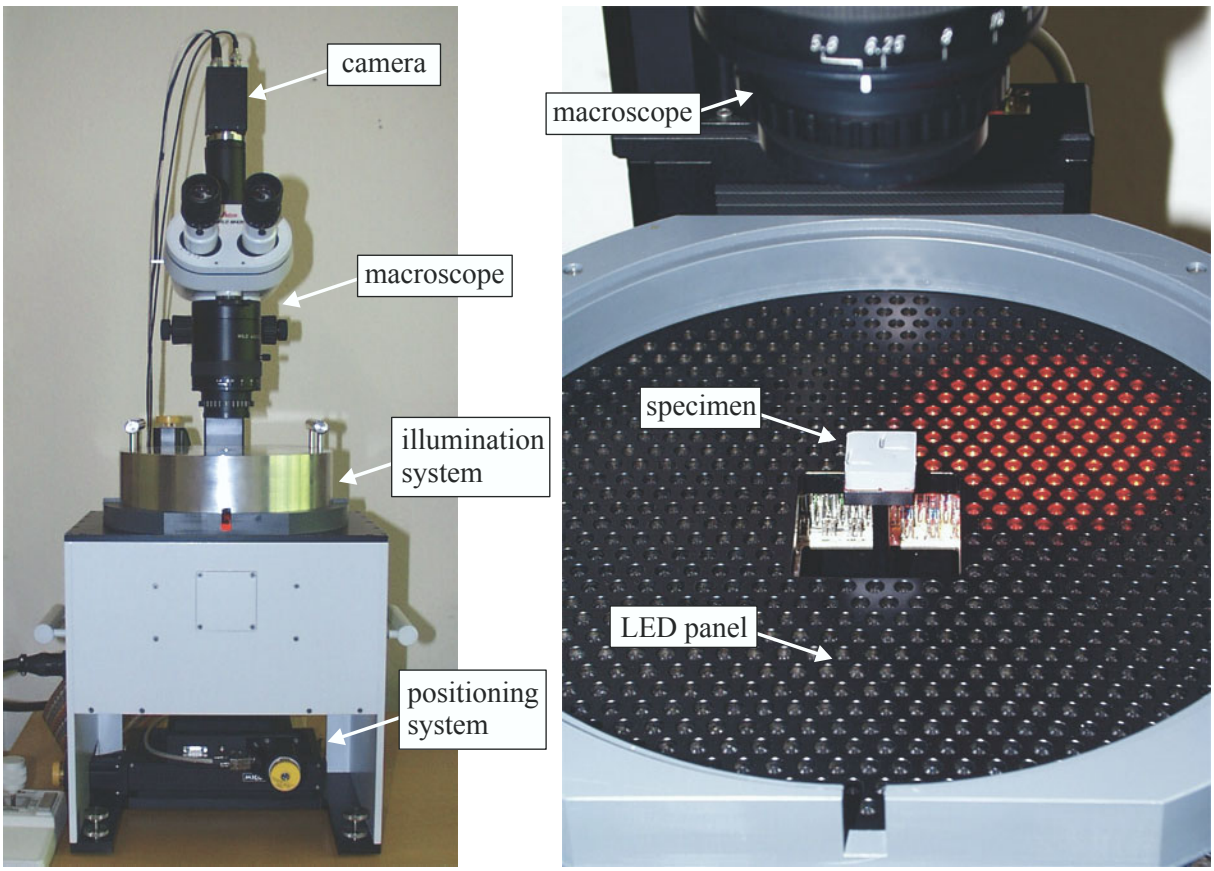


Figure 9. Setup of GE/2: (left) Image Acquisition Station; (right) PC.



(a) (b)

Figure 10. Image Acquisition Station (IAS) of GE/2: (a) general view; (b) illumination system (parabolic reflector removed).

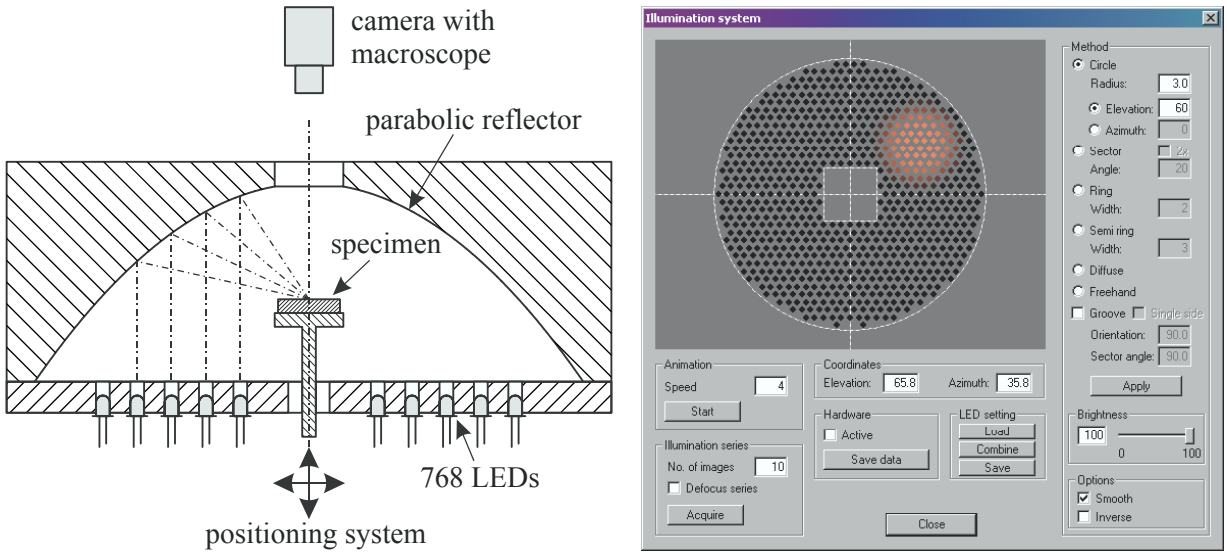
marks from 6 different tools was used. Obviously, the system GE/2 leads to a clear concentration of hits at the first positions of the hit-list; see Fig. 8(b). On the average, only 11.6% of the archive has to be searched to find an actually existing hit. In addition, in 59.5% of the cases, the first position of the hit-list contains a real correspondence. Only 2.2% of the archive have to be searched to find 50% of the hits. If 90% of the existing hits are to be found, only 34.8% of the archive have to be processed.

An additional and very important advantage of GE/2 consists in its low computational expense. A single comparison takes approximately 1 ms. Thus, a comparison with 1,000 marks of an archive coming into question will take only one second!

6. SETUP OF GE/2

The setup of GE/2 combines the image acquisition and signal processing in a single workplace. Thus, the examiner is enabled to evaluate the recorded data without having to move to another place.

The principle of the setup is shown in Fig. 9. The images are recorded by the Image Acquisition Station (IAS), which provides for suitable illumination and positioning of the specimen. The images are taken by means of a Leica macroscope with a conventional video camera. The digitized images are displayed and evaluated on a PC, where the signal processing, the comparison algorithms as well as the database administration take place. Moreover, this PC is used to control all parameters of the Image Acquisition Station.



(a) (b)

Figure 11. Illumination system: (a) principle; (b) control dialog of the GE/2 software.

6.1 Image Acquisition Station (IAS)

The highlights of the Image Acquisition Station of the system GE/2, see Fig. 10, comprise:

- The setup has a modular design, which makes it easy to transport. It requires a base area of 50x60 cm.
- The camera unit and the optical setup provide for high quality images of 512x512 pixels. If desired, the image resolution can be increased to other values. The images are acquired using a Leica macroscope with zoom optics.
- The illumination system provides for a suitable illumination of the marks; see Sect. 6.2.
- The positioning device provides for a three-dimensional positioning of the sample with an accuracy of better than 3 µm. By means of a fully computerized control, the positioning system can be used for a fast acquisition of defocus series.
- For the acquisition of firearm bullets, a supplementary rotary unit can be mounted.

6.2 Illumination System

For the benefit of a high flexibility, the illumination system of GE/2 takes advantage of an indirect illumination principle; see Fig. 11(a). The light is generated by a panel of 768 bright LEDs which are all individually controllable. The parallel beams of the LEDs meet at the focus point of a parabolic reflector, where the specimen is positioned.

All illumination parameters like brightness, angle of incidence etc. are controlled by the computer. To set up the illumination, a software control provides for the interactive as well as the automated adjustment of all illumination parameters; see Fig. 11(b). Besides the intuitive and user-friendly interface, the computer control guarantees an absolute reproducibility of arbitrary illumination constellations. Thanks to the choice of LEDs as a light source, a new illumination is set up instantaneously without any delay time. Together with the fully automated lighting control, illumination series can be recorded automatically in an extraordinarily short acquisition time.

7. CONCLUSIONS

In this paper, the powerful system GE/2 for the analysis and comparison of striation marks has been presented. To take advantage of the signal properties of the images acquired, a novel model-based description of their texture has been introduced that can be applied to a wide range of forensically relevant marks such as toolmarks as well as marks on firearm bullets.

To acquire high-quality images of surfaces containing marks, the Image Acquisition Station of GE/2 has been presented. The sophisticated data acquisition leads to concise images of the marks based on an image fusion strategy. Aided by the signal model, a strategy to trace and straighten the groove-shaped marks has been described. As a result of the whole methodology, a meaningful signature is extracted which faithfully describes the essential features of the marks.

To achieve the ultimate goal of matching striation patterns, a comparison algorithm has been presented which leads to an efficient and reliable detection of similar marks. Aided by the system GE/2, the forensic examiner is enabled to focus on the most promising entries of the marks database. To objectively assess the whole system, an assessment methodology has been proposed which has proven its suitability for the test of different imaging and comparison systems. The results achieved by the system GE/2 emphasize its convenience as well as its high quality.

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