AN AUTOMATED SYSTEM FOR THE MACROSCOPIC ACQUISITION OF IMAGES OF FIREARM BULLETS

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Abstract: Image fusion methods are presented that allow an acquisition of high-quality images of firearm bullets. The paper focusses on three problems that cause optical systems to fail acquiring images of sufficient quality: illumination, depth of focus, and visibility. In all cases, the accompanying limitations are compensated by obtaining series of images and combining them into an improved result by means of appropriate data fusion techniques.
Keywords: image acquisition, data fusion, firearm identification

1 INTRODUCTION

In recent years, image processing technology has found increasing interest by forensic scientists for extending their capabilities in the analysis of documents, photographs, tool marks, etc. [1]. One important task within this area is the automatic identification of firearms based on macroscopic images of bullets [2, 3]. Such images contain groove-shaped traces that can be considered a “fingerprint” of the firearm on the circumferential surface of a bullet. To achieve a reliable comparison of these traces, high-quality images of all relevant areas of the bullet have to be obtained, preferably automatically, under reproducible conditions. Unfortunately, this cannot be accomplished with only one image. A solution to this problem consists in obtaining image series in which the acquisition parameters (illumination angle, object distance, and object pose) are systematically varied. By formulating criteria for selecting the best segments, the images can be fused to an improved result, in which all areas are contained with sufficient quality.

2 IMAGE ACQUISITION PROBLEMS

Due to the metallic and spatially structured surface of firearm bullets, and the limitations of optical systems, the image acquisition stage bears several difficulties:

- The choice of diffuse illumination generally leads to an undesirable contrast attenuation. Thus, a distant, collimated point source should be preferred. The illumination direction is described by the elevation angle θ and the azimuth φ. Since image intensities highly depend on the illumination direction, optimal lighting would imply that different surface areas are illuminated from different directions, which is extremely difficult.
- The resolution of subtle surface details requires a limited depth of focus. As a result, in many cases, it is not possible to obtain images in which all areas are in-focus.
- The spatial extent of a bullet leads to distortions due to perspective, and visibility problems. Ideally, images of all surface areas should be acquired under similar geometric conditions.

Quality deficiencies of the image data due to these problems can hardly be compensated in later processing steps. However, image series can be acquired in which the acquisition parameters are varied, so that every surface portion is contained with sufficient quality in one image at least. By means of appropriate data fusion techniques, an image can be obtained in which all areas are contained with sufficient quality.

A series in which only the illumination direction (θ,φ) is varied will be denominated *illumination series*. For a virtual increasement of the depth of focus, a *defocus series* – i.e. a series in which the object distance is varied stepwise – can be acquired. To obtain an image of the whole circumferential surface of the bullet surface, a *concatenation* of images acquired by stepwise alteration of the object position by certain angle increments $\Delta\alpha$ has to be performed. In the next section, efficient techniques for fusing such image series are discussed.

3 IMAGE FUSION

3.1 Image series acquisition

The images $d(\overline{x},\overline{\omega})$ of a series are two-dimensional signals with respect to the location $\overline{x}=(x,y)^{\mathrm{T}}$ indexed with the parameter vector of the acquisition situation $\overline{\omega}=(\varphi,\theta,\zeta,\alpha,\ldots)^{\mathrm{T}}$, where φ and θ represent azimuth and elevation angle of the illumination direction, ζ the object distance, and α the rotational position of the bullet. Additional parameters could also be taken into account, if necessary.

Before an image series can be acquired, it has to be determined how the parameter space has to be sampled. The goal is to obtain all surface areas in good quality with as few images $\left\{d(\overline{x},\overline{\omega}_i), i=0,\ldots,n\right\}$ as possible. For defocus series, every portion of the surface $z(\overline{x})$ will be contained at least once in focus, if the following conditions hold:

$$\zeta_i=\zeta_0+i\Delta z,\quad i=0,\ldots,n,\quad \Delta z\le\delta z,\quad \zeta_0\le z(\overline{x})\le\zeta_n, \tag{1}$$

where δz denotes the depth of focus. For firearm bullets, it is not necessary to sample the illumination space two-dimensionally, because the signal of interest $t(\overline{x})$ consists of straight, approximately parallel grooves. Such grooves only show a high contrast if they are illuminated perpendicularly, demanding only variation of the elevation angle θ [4].

3.2 Fusion of image series

In this work, a systematic data fusion approach is used which is based on the minimization of a so-called “energy function” [5]

$$E=E_{\mathrm{D}}(D,r)+\lambda E_{\mathrm{C}}(r),\quad \lambda>0. \tag{2}$$

$E_{\mathrm{D}}(D,r)$ models the relationship between the given image data (i.e. the image series)

$$D=\left\{d(\overline{x},\overline{\omega}_i), i=0,\ldots,n\right\}, \tag{3}$$

and the fusion result $r(\overline{x})$. $E_{\mathrm{C}}(r)$ models desired characteristics of the fusion result $r(\overline{x})$ or those known a priori. The regularization parameter λ serves to weight both components.

The energy terms $E_{\mathrm{D}}(D,r)$ and $E_{\mathrm{C}}(r)$ are to be defined in such a way that the result is more desirable, the lower the energy is. Consequently, E has to be minimized to obtain $r(\overline{x})$.

By defining Gibb’s densities, a connection of this approach with the Bayesian fusion theory and the Markov Random Fields theory can be achieved [5]. Thus, methods for solving inverse problems of statistical mechanics can be also utilized.

3.3 Fusion of illumination series

For a better understanding, a fusion algorithm for illumination series will be presented first. Following, the fusion task will be generalized in such a way that it will fit within the framework discussed in the last section. It will be shown that the method represents a very efficient approximation for the solution of the fusion problem by energy minimization.

Although only one-dimensional series – i.e. series, in which only one parameter is varied – will be treated here, an extension to the two-dimensional case is also possible. Fig. 1 shows the structure of the fusion algorithm for the case of a varying elevation angle θ.

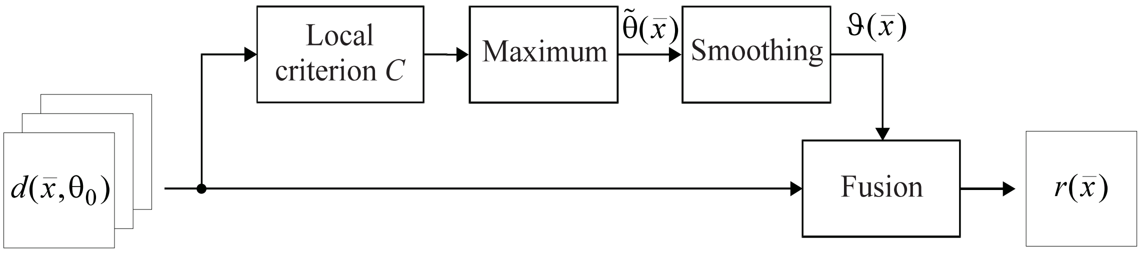


Figure 1. Structure of the algorithm for fusing illumination series.

The principle of the fusion algorithm consists in the selection of the best illuminated image segments of the series for each location based on a local criterion C. The local grey-level variance and the local entropy are suitable criteria C, if a high-contrast fusion result $r(\bar{x})$ is desired. The selected illumination direction, which is stored for each location $\bar{x}$ in the so-called *illumination map*

$$\tilde{\theta}(\bar{x}) = \arg\max_{\theta_i} C\{d(\bar{x},\theta_i)\}, \tag{4}$$

has to be a spatial function varying slowly compared to the signal of interest. This is necessary to avoid artifacts in the fusion result. To assure that this condition is satisfied, a smoothing of the illumination map with a binomial low-pass filter is performed [6]:

$$\vartheta(\bar{x}) = \mathrm{LP}\{\tilde{\theta}(\bar{x})\}. \tag{5}$$

The resulting function $\vartheta(\bar{x})$ denotes the best-suited local illumination direction.

The actual fusion is performed by weighted superposition of two adjacent images $d(\bar{x},\theta_i)$ with a linear interpolator γ taking the best local illumination direction $\vartheta(\bar{x})$ into account:

$$r(\bar{x}) = \sum_i d(\bar{x},\theta_i)\gamma(\vartheta(\bar{x})-\theta_i) = \frac{\vartheta(\bar{x})-\theta_l}{\theta_{l+1}-\theta_l} d(\bar{x},\theta_l) + \frac{\theta_{l+1}-\vartheta(\bar{x})}{\theta_{l+1}-\theta_l} d(\bar{x},\theta_{l+1}). \tag{6}$$

The interpolation takes care of a smooth transition between θ-neighbouring images. The narrow extent of γ provides for an averaging of only similarly illuminated images to avoid an undesirable contrast loss due to destructive interferences of light and shadow in different images of the series.

Three properties of the proposed fusion method are responsible of its good performance: 1.) for each location $\bar{x}$, the fusion result $r(\bar{x})$ resembles that image $d(\bar{x},\theta_i)$ of the series which shows the best illumination; 2.) the smoothness of the illumination map $\vartheta(\bar{x})$ guarantees that no artifacts are contained in the resulting image $r(\bar{x})$; 3.) the resulting image achieves globally good results in the sense of the local measure C. By formulating energy terms that penalize the non-fulfillment of any of these conditions, an energy function of the form of eq. (2) can be obtained:

$$\begin{aligned} E &= \sum_i \sum_{\bar{x}} \left(r(\bar{x}) - d(\bar{x},\theta_i)\right)^2 \gamma(\theta_i - \vartheta(\bar{x})) + \lambda_1 \sum_{\bar{x}} \left(\mathrm{HP}\{\vartheta(\bar{x})\}\right)^2 + \lambda_2 \sum_{\bar{x}} (-1)\cdot C\{r(\bar{x})\} \\ &= E_{\mathrm{D}}(D,r,\vartheta) + \lambda_1 E_{\mathrm{S}}(\vartheta) + \lambda_2 E_{\mathrm{C}}(r). \end{aligned} \tag{7}$$

This equation represents a compact, implicit formulation of the fusion problem, in which all known and desirable characteristics of the magnitudes involved in the fusion process as well as their mutual relations are given. The first addend $E_{\mathrm{D}}(D,r,\vartheta)$ in eq. (7) provides for data proximity to $r(\bar{x})$. To fulfill the smoothness constraint for the optimal illumination angle $\vartheta(\bar{x})$, the second addend $E_{\mathrm{S}}(\theta)$ penalizes high energy components of $\vartheta(\bar{x})$ by measuring the energy of the high-pass filtered signal $\mathrm{HP}\{\vartheta(\bar{x})\}$. The third addend $E_\mathrm{C}(r)$ checks if the local criterion $C\{\}$ leads to high values in the fusion result $r(\bar{x})$ globally.

For the assumptions made here, the minimization of E with respect to r and ϑ would lead to the optimal fusion result at the expense of a very high computation time. The fusion strategy proposed instead, however, represents an *efficient approximation* of the energy minimization approach based on a separate optimization of the addends of eq. (7) and with no need to consider the weighting factors λ_i.

3.4 Fusion of defocus series

The fusion of defocus series can be performed similarly to illumination series, if the optimal elevation angle $\vartheta(\bar{x})$ is replaced by the optimal object distance $\xi(\bar{x})$, and the angles θ_i by the actual object distances ζ_i:

$$E = E_\mathrm{D}(D,r,\xi) + \lambda_1 E_\mathrm{S}(\xi) + \lambda_2 E_\mathrm{C}(r). \tag{8}$$

The qualitative meaning of the energy terms as well as the local criterion C remain the same as with illumination series. In particular, a certain smoothness of the optimal object distance $\xi(\bar{x})$ has also to be postulated here, because for the empirical estimation of focus by means of the criterion C, spatial averaging in a neighbourhood is required. Thus, within this neighbourhood, a nearly constant object profile has to be assumed.

An additional advantage of fusing defocus series is that, since the distance to the selected surface areas is nearly constant in case of a small depth of focus δz, the image acquisition process has telecentric properties.

3.5 Concatenation

To obtain an image of the whole circumferential surface of a bullet, an image series

$$D = \{d(\bar{x},\alpha_i), i = 0,\ldots,n\}, \quad \alpha_i = \alpha_0 + i\Delta\alpha \tag{9}$$

is acquired in which the object is rotated by a certain angle increment $\Delta\alpha$ after each single image, so that the same border area is always contained in two consecutive images; see Fig. 2. Due to the knowledge of $\Delta\alpha$, the translations τ between consecutive images are also approximately known. However, for a precise reconstruction of the surface, τ has to be determined more exactly by means of cross-correlation of the overlapping stripes [7].

To guarantee similar illumination and geometric conditions in the overlapping areas, $\Delta\alpha$ has to be chosen small enough. In the overlapping areas, a weighted averaging between consecutive images is performed to suppress small grey-level fluctuations.

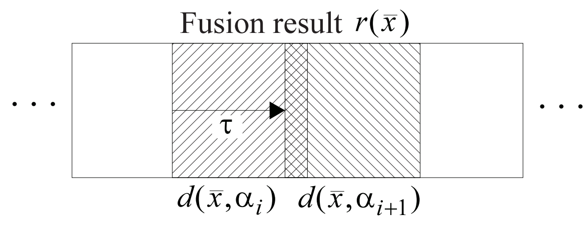


Figure 2. Concatenation principle.

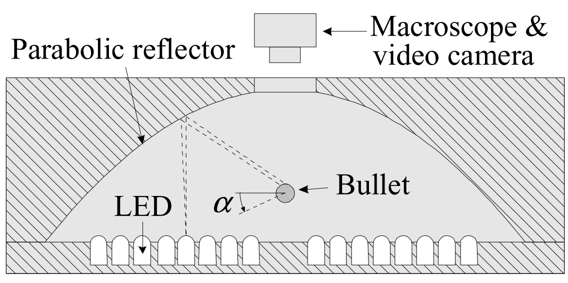


Figure 3. Illumination system.

4 EXPERIMENTAL RESULTS

To obtain image series, an automated system was set up which consists of a flexible illumination module, a commercial macroscope, and a 3-D positioning device. The illumination system is composed of a platform in which 256 LEDs are placed, and a parabolic reflector in the focus of which the bullet is fixed; see Fig. 3 [8]. The location of an LED on the platform determines the direction (θ,φ) from which the bullet is illuminated. By variation of these parameters, any area on the bullet surface can be acquired with maximum contrast. An opening in the reflector allows image acquisition with a macroscope and a CCD camera. All images throughout this paper were digitized with 512×512 pixels, and 8 bit grey levels.

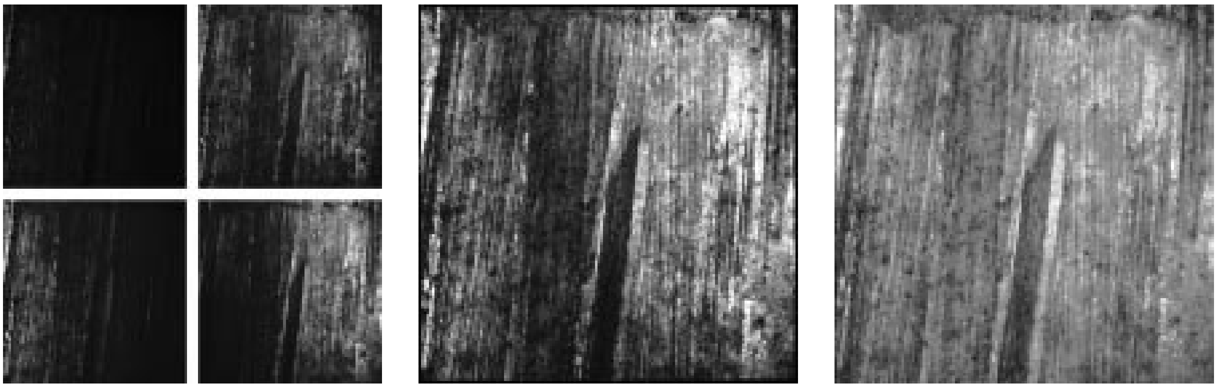


Figure 4. Bullet: a) illumination series (images 10, 15, 20, and 25); b) fusion result (criterion C: variance in a 3×3-mask; smoothing of $\tilde{\theta}(\bar{x})$ with a binomial filter of size 49×49); c) diffuse lighting.

In Fig. 4a, four images of an illumination series consisting of 40 images ($\Delta\theta\approx4.6°$) can be seen. By comparison of the fusion result Fig. 4b with the same diffusely illuminated bullet area (Fig. 4c), it can be stated that in the fusion result the grooves are contained with much higher contrast.

Figure 5. Defocus series of a bullet: a) image 5; b) image 14; c) fusion result (criterion C: variance in a 5×5-mask; smoothing of $\tilde{\zeta}(\bar{x})$ with a binomial filter of size 21×21).

Figs. 5a and 5b show images 5 and 14 of a defocus series consisting of 20 images ($\Delta z = 78.5\mu\text{m}$). Obviously, in the fusion result Fig. 5c all surface areas are in-focus, in contrast to the single images of the series. By means of fusion, a virtual increase of the depth of focus could be achieved.

In Fig. 6, the concatenation result of an image series of a bullet is shown. In the corresponding series, the elevation angle θ of the illumination ($\Delta\theta\approx9.5°$), the object distance ζ ($\Delta z = 131.5\mu\text{m}$), and the rotational position α of the object ($\Delta\alpha = 1.8°$) were varied. For each selected object distance, an illumination series was fused by calculating the grey-level variance in a 5×5-neighbourhood. The signals $\tilde{\theta}(\bar{x})$ were smoothed with a binomial filter of size

49×49. The other parameters were chosen as in Fig. 5. Compared with the bullet shown in Fig. 5c, in this image the contrast is more uniform due to illumination variation.

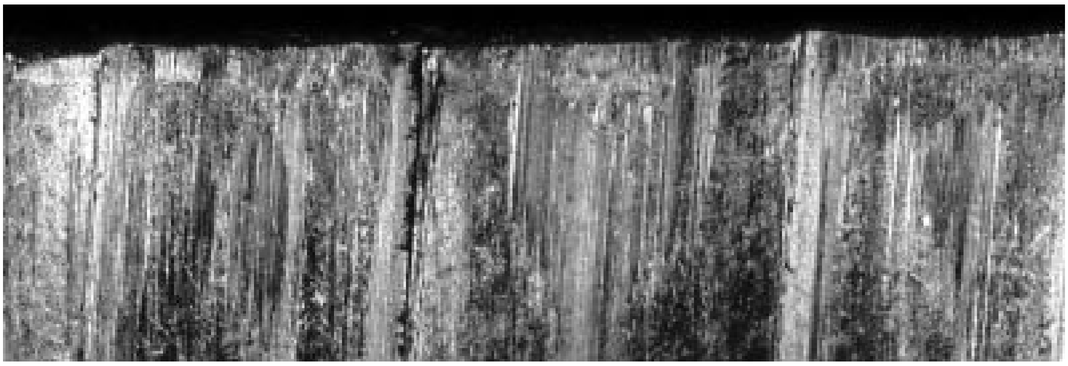
. . .  . . .

Figure 6. Bullet: concatenation result. Only approximately 30% of the whole circumferential surface is shown.

5 SUMMARY

In this paper, methods for obtaining high-quality images of bullets have been presented. To compensate the limitations of optical systems, image series were obtained by varying the acquisition parameters systematically. By means of data fusion, images were combined to an improved result which could not have been acquired physically with only one image. The fusion task has been formulated by means of an energy function. By minimization of this function, the optimal fusion result with respect to the assumptions met was obtained. In our case, the structure of the energy function allowed to perform the computationally expensive optimization by means of an efficient approximation.

The performance of the proposed algorithms has been demonstrated with images of firearm bullets. However, the methods presented are also suitable for acquisition of high-quality images of any other object for automated visual inspection purposes. As a rule, surface features could be obtained much more robustly and with higher contrast by means of the fusion methods presented. Hence, the increased effort in image acquisition appears to be absolutely reasonable in many computer vision tasks, where high-quality images are needed.

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