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# Unsharp masking using quadratic filter for the enhancement of fingerprints in noisy background

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ABSTRACT

The paper summarizes the design and implementation of a quadratic edge detection filter based on Volterra series. The filter is employed in an unsharp masking scheme for enhancing fingerprints in a dark and noisy background. The proposed filter can account for much of the polynomial nonlinearities inherent in the input image and can replace the conventional edge detectors like Laplacian, LoG, etc. The application of the new filter is in forensic investigation where enhancement and identification of latent fingerprints are key issues. The enhancement of images by the proposed method is superior to that with unsharp masking scheme employing conventional filters in terms of the visual quality, the noise performance and the computational complexity, making it an ideal candidate for latent fingerprint enhancement.



## 1. Introduction

As crime rate increases steadily, fingerprint enhancement and consequent identification always remain key areas of research. Fingerprint is the impression left on a surface by the friction caused by the ridges on a finger or any part of hand and is a unique biometric identifier. The print is composed of dark ridges and light valleys [1,2]. Identification of fingerprints [3–5] is a key process in access control and in forensic sciences. In the former case, the fingerprints are less noisy and do not require much preprocessing. But the prints taken from crime scenes are blurred and noisy and so require enhancement of ridges to ease identification. The ridges in fingerprints carry significant amount of biometric information and they can be enhanced by improving the edge features of the image. Edges in images are formed by discontinuities in spatial, geometrical or photometric properties of objects [6]. Although edges are formed by high frequency components, simple high pass filtering does not suffice in detecting and improving edges as it blurs the image. Segmentation of images is done based on texture [7–9] and mathematical morphology [10,11]. Generally, edges are detected by the computation of the derivative of the image. This computation is very noise sensitive as noise appears as false edges in an image. So the chief performance criterion of an edge detector becomes the invulnerability to noise. The gradient based edge detectors [6,12] in the linear domain are

1. Laplace filter
2. Sobel filter
3. Laplacian of Gaussian (LoG)
4. Canny filter

Although Sobel filter has the advantage in speed, it suffers from lack of edge resolution. The Laplace filter and Canny filter have reasonably good edge resolution but are highly susceptible to noise. LoG filter had good resolution of edges as well as moderate noise invulnerability. But even the LoG does not suffice to enhance edges in images mixed with noise. Under such conditions, polynomial filters [13] perform better in detecting edges with high enough resolution. Images are formed by nonlinear processes and human vision is inherently nonlinear. So employing polynomial methods for image processing and analysis become a natural alternative. Much of the nonlinearities can be modeled by the quadratic term alone and hence the efforts in the design and implementation of quadratic filters. The present work proposes a quadratic filter based on Volterra series for enhancing noisy fingerprints. Although the idea of modeling nonlinearities by power series was proposed a century back by Vito Volterra, the practical applications were hampered by the large computational complexity. Recently, with increase in computational resources,

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interest is renewed in developing Volterra systems for signal and image processing with consequent enhancement of features that is otherwise not achievable with linear filters.

## 2. Literature survey

Fingerprint preprocessing falls into two categories, the spatial domain filtering techniques and the transform domain techniques, the latter type being more popular. The second category mostly uses Gabor filters [14,15] for fingerprint classification and enhancement. Directional Fourier filtering has been proposed [16] for automatic fingerprint identification system. In the spatial filtering domain, directional median filter [17] is used for fingerprint enhancement. Use of quadratic filters based on Volterra series, which current work is relied on, for fingerprint preprocessing has not been reported.

The theory of Volterra functionals was developed by Vito Volterra to model nonlinear systems as parallel combinations of linear and polynomial systems of increasing order, in the year 1887. Weiner applied Volterra series to Brownian motion [18] to develop analytic functionals. The work in polynomial systems was relegated for a long time because of the lack of resources to handle the increased computational complexity. Towards the end of 1980s work in implementation of polynomial systems was revived with the help of increased computational resources. Inherent nonlinearities in images can be modeled with polynomial systems and many classes of quadratic filters were developed for edge preserving noise smoothing, edge extraction, image interpolation, etc. Quadratic filter was employed for edge detection [19] and processing document images. A similar strategy has been used in this work to enhance noisy ridges.

## 3. Discrete Volterra series

Although the theory of linear systems is very advanced and useful, most of the real life and practical systems are nonlinear. Mild polynomial nonlinearities can be modeled by Volterra power series. An $N$th order Volterra filter [20,21] with input vector $x[n]$ and output vector $y[n]$ is realized by

$$y[n]=h_0+\sum_{r=1}^{\infty}\sum_{n_1=1}^{N}\sum_{n_2=1}^{N}\cdots\sum_{n_r=1}^{N}h_r[n_1,n_2,\ldots,n_r].\\ x[n-n_1]x[n-n_2]\cdots x[n-n_r] \tag{1}$$

$h_0$ is the output offset when no input is present and $r$ indicates the order of nonlinearity. The impulse response term $h_r[n_1,n_2,\ldots,n_r]$ is the $r$th order Volterra kernel, identification of which is one of the key issues in polynomial signal processing. The condition $r=1$ results in an LTI system and $h_1$ defaults to the impulse response. A quadratic filter results when $r=2$, which can cover much of the nonlinearity. One key advantage in using Eq. (1) is that the quadratic filter can be added in parallel with the linear filter. Although higher order terms can be added similarly, computational complexity becomes formidable. For a quadratic system,

$$y[n]=h_0+\sum_{n_1=1}^{N}h_1[n_1]x[n-n_1]\\ +\sum_{n_1=1}^{N}\sum_{n_2=1}^{N}h_2[n_1,n_2]x[n-n_1]x[n-n_2] \tag{2}$$

or equivalently by the matrix equation:

$$Y[n]=h_0+X^T[n]H_1+X^T[n]H_2X[n] \tag{3}$$

where

$$X[n]=[x(n)\ \ x(n-1)\ \ \cdots\ \ x(n-N+1)]^T \tag{4}$$

$$H_1=[h_1(0)\ \ h1(1)\ \ \cdots\ \ h_1(N-1)]^T \tag{5}$$

and

$$H_2=\begin{bmatrix} h_2(0,0) & h_2(0,1) & \cdots & h_2(0,N-1)\\ h_2(1,0) & h_2(1,1) & \cdots & h_2(1,N-1)\\ h_2(2,0) & h_2(2,1) & \cdots & h_2(2,N-1)\\ \vdots & \vdots & \ddots & \vdots\\ h_2(N-1,0) & h_2(N-1,1) & \cdots & h_2(N-1,N-1)\end{bmatrix} \tag{6}$$

### 3.1. 2-D quadratic filter

The two dimensional quadratic filter is governed by the equation

$$y[n_1,n_2]=\sum_{m_{11}=0}^{N_1-1}\sum_{m_{12}=0}^{N_2-1}\sum_{m_{21}=0}^{N_1-1}\sum_{m_{22}=0}^{N_2-1}h_1[m_{11},m_{12},m_{21},m_{22}]\\ \times x[n_1-m_{11},n_2-m_{12}]x[n_1-m_{21},n_2-m_{22}] \tag{7}$$

Eq. (7) can be represented in the matrix form as

$$y[n_1,n_2]=\mathbf{X}^T[n_1,n_2]\mathbf{H}_2\mathbf{X}[n_1,n_2] \tag{8}$$

The quadratic kernel $\mathbf{H}_2$ has $N_1N_2\times N_1N_2$ elements and each element consists of $N_2^2$ sub-matrices $\mathbf{H}(i,j)$ with $N_1\times N_2$ elements given as

$$\mathbf{H}_2=\begin{bmatrix} \mathbf{H}(0,0) & \mathbf{H}(0,1) & \cdots & \mathbf{H}(0,N_2-1)\\ \mathbf{H}(1,0) & \mathbf{H}(1,1) & \cdots & \mathbf{H}(1,N_2-1)\\ \vdots & \vdots & \ddots & \vdots\\ \mathbf{H}(N_2-1,0) & \mathbf{H}(N_2-1,1) & \cdots & \mathbf{H}(N_2-1,N_2-1)\end{bmatrix} \tag{9}$$

where each sub-matrix $\mathbf{H}(i,j)$ is given by

$$\mathbf{H}(i,j)=\begin{bmatrix} h(0,i,0,j) & \cdots & h(0,i,N_1-1,j)\\ h(1,i,0,j) & \cdots & h(1,i,N_1-1,j)\\ \vdots & \vdots & \vdots\\ h(N_1-1,i,0,j) & \cdots & h(N_1-1,i,N_1-1,j)\end{bmatrix} \tag{10}$$

The principal issues in Volterra systems are the identification of the kernel $H_2$ [22–24] and its computationally efficient implementation. Unlike in linear filtering, there are no general design methods for finding $H_2$. Design of two dimensional kernels for specific applications can be done using methods like optimization, bi-impulse response method [25], etc. The current work uses optimization of mean square error using Powell method. The second step is in realizing the kernel with minimum computational complexity [26,27]. Eq. (8) can be viewed as a filtering operation on the Kronecker product of $\mathbf{X}[n_1,n_2]$ with itself by the filter kernel $H_2$. A feasible implementation can be done with appropriate decomposition of $H_2$ like LU or SVD decomposition.

## 4. Methodology

Enhancement of noisy fingerprints is made possible with unsharp masking scheme in which a scaled version of the edges separated from the fingerprints is added with the noisy prints. The scheme as given in Section 5 is proposed for enhancing fingerprint in noisy background. It relies on a quadratic edge detection filter. The flow of work is as depicted in Fig. 1. The first phase of work is in designing the edge detection kernel $H_2$. The design is based on the minimization of mean square error between a synthetic true edge and its noisy version. The second phase is the computationally efficient implementation of $H_2$ based on singular value decomposition. These phases are discussed in Section 6. In the last phase, testing of the filter is done with standard images corrupted by impulsive and Gaussian noise of different noise