Chapter 9

Summary and Inferences

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9.1 Overview

Quadratic filters for edge detection, denoising and prediction are presented in the last part. Their performance indicators are compared with existing systems to infer the merits of quadratic systems. Sec. 9.2 gives a bird’s eye view of the whole research work highlighting the numerical figures of merit of quadratic systems. Sec. 9.3 presents the limitation in developing quadratic filters. The future scope and possible expansions are discussed in Sec. 9.4.

9.2 Summary of Work Done

The research work is primarily conceived with the notion that mild polynomial nonlinearities can be modeled using Volterra series. The filters based on this power series can outperform conventional linear and nonlinear systems, especially when there are polynomial components present in the signals processed. Three avenues, where effects of nonlinearity are strong and consequently the usefulness of quadratic systems are high, are selected as prediction, edge detection and noise removal. The crux of the work is the design and implementation of quadratic filters for these applications as outlined in the next sections.

9.2.1 Strategy of Design and Implementation

Quadratic filters cannot easily be designed by conventional methods. They are designed by utilizing the responses due to strategically placed bi-impulses or by optimization methods. Optimization of a cost function is selected as the design tool in this work. Once the design strategy is finalized, it is necessary to have a proper implementation methodology. Since the operations on the input data, in the case of quadratic filters, are basically Kronecker products a direct implementation is
impractical. Matrix decomposition methods, especially the singular value decomposition is preferred in this work.

Once the design and implementation methodologies are selected, potential areas where the nonlinear effects due to polynomial products are predominant are identified as

- Edge detection
- Noise removal and
- Prediction of speech signals.

### 9.2.2 Edge Detection

Edges in images are high frequency components caused by peripheries of objects, the detection of which is a key image processing operation. Quadratic filters are used for detecting edges with improved performance than other nonlinear edge detection filters. The applications for which quadratic edge detection systems developed are:

- Unsharp masking scheme for enhancing latent fingerprints.
- Detection of retinal microaneurysms due to diabetic retinopathy

**Unsharp masking for enhancing latent fingerprints**

Fingerprint, being a unique biometric identifier, its enhancement and recognition are rich areas of image processing. It has applications in both access control and forensic sciences. The focus of work is on enhancing latent prints from crime scenes to ease forensic identification. The broken ridges and valleys in the print are enhanced by improving the contrast between dark ridges and light valleys. In the contrast enhancement scheme of unsharp masking, an image is added with the
scaled version of edges separated from it. If the images are noisy, as is often the cases with fingerprints from crime scenes, the performance of conventional edge detectors like Laplacian, LoG, Canny, Sobel etc. deteriorates as noise appears as false edges. Quadratic edge detection filters with greater noise invulnerability are proposed and implemented in the unsharp masking. It is observed to have better signal to noise ratio than other filters as shown in Fig. 9.1. Specifically, the SNR improvement in the case of quadratic filter is \( \approx 4 \, \text{dB} \) above the nearest competitor, LoG filter. The computational complexities of various filters, except that of Canny filter which is very high, are shown in Fig. 9.2.

The quadratic filter using SVD method has the smallest complexity. The comparison of mean structural similarity index, a performance parameter for the preservation of structure of ridges, in presence of impulsive noise and Gaussian noise are in Fig. 9.3 and Fig. 9.4 respectively. Quadratic filter is observed to preserve the structure of ridges better than other filters in presence of both impulsive and Gaussian noise. LoG also performs almost at par with quadratic filter.
9.2. SUMMARY OF WORK DONE

Detection of Retinal Microaneurysms

Microaneurysms developed in the retina due to deposits of glucose and lipids caused by diabetes can silently worsen and result in permanent loss of vision. Surgery at an early stage is the cure. Automatic surgery is facilitated if the periphery of microaneurysm is enhanced from a fundus image. Three types of quadratic filters are designed and implemented for this end.

- Two dimensional Teager filter based on least square method.
- Two dimensional Teager filter based on minimization of mean square error.
- Two dimensional quadratic filter based on optimization.

The performance parameters in terms of the improvement in signal to noise ratio and the time of computation are compared with conventional edge detection filters as shown in Fig. 9.5. It is seen that the two Teager filters perform fairly identical, but better than conventional filters, although the complexity is more. The quadratic filter by optimization outperforms other filters with time of computation equal
Noise is any unwanted disturbance that gets added with the desired signal from outside the system or from within. They can also be due to the quantization of discrete signals during processing. Noise in communication systems is always Gaussian in statistics as a consequence of the central limit theorem, and well established methods like correlation detection, matched filtering etc. have been developed for separating the desired signal from the noise signal. But noise present in images are predominantly impulsive in nature, separation of which is difficult. Conventionally, nonlinear filters like mean and median filters are used for denoising images. Two dimensional quadratic filter designed based on the maximization of signal to noise ratio is proposed and implemented for removing impulsive noise from raw MRI data. The popular medical imaging scheme of MRI maps nuclear resonances, when subjected to strong magnetic fields, into intensity variations. The tumor tissue and body tissue have different resonant frequencies and this difference is used to contrast the tumour. The resolution of imaging is enhanced by changing the magnetic field rapidly.
These sharp changes introduce a great deal of impulsive noise into raw MRI data. The quadratic filter offered the highest signal to noise ratio of $\approx 10$dB above that of minimum filter, as seen from Fig. 9.7.

In the case of MRI, the edges mean the periphery of a region of interest such as a tumour. Edges in images are usually corrupted by additive noise and most edge detectors are sensitive to noise. So the preservation of edges on filtering is very critical. Quadratic filters are proposed in this work as better edge detectors in terms of noise invulnerability and edge preservation. Fig. 9.8 shows the edge crispness function for various filters. A low value of crispness indicates better edge preservation. Quadratic filter preserves the edges so well that the sensitivity is too small to be visible in Fig. 9.8.

### 9.2.4 Prediction of Speech Signals

The research consists of remodeling the differential pulse code modulation system for coding speech signals, by replacing the linear predictor in it by a quadratic predictor. The aim is to account for the polynomial components in speech signal. The modified system yields smaller mean square error between transmitted signal and received signal, on
passing through an additive white Gaussian noise channel, than that with linear predictor and quadratic lattice type predictor as shown in Fig. 9.9. It shows that the mean square error is roughly one third that of linear predictor, giving rise to better audio reception. The predictor based on optimization surpasses the quadratic lattice predictor in performance and in the ease of implementation.

9.3 Limitations of the Study

The last chapters elucidated the applications and advantages of employing quadratic Volterra filters for edge detection, noise removal and statistical prediction. Use of quadratic Volterra filters resulted in improved performance parameters such as signal to noise ratio, edge crispness, mean square error etc. than conventional filters. However, there are noteworthy limitations that are to be circumvented by the designers. The major limitations in working with polynomial systems for discrete signal processing are summarized below.
9.4. SCOPE FOR FURTHER WORK

9.3.1 Working without Frequency Domain

When working with LTI systems, one has the surety that only the input frequencies or a subset thereof can appear at the output. This is not the case with quadratic systems. There is no exact equivalent of frequency domain for quadratic systems. The familiar concepts with LTI systems such as the convenient input-output relationship, the spectral relationship and the much familiar computational tools like FFT are no longer applicable when working with quadratic or polynomial systems. Time domain filtering techniques need to be improved in their stead.

9.3.2 Higher Order Systems in Volterra Series

This research work is confined to quadratic systems with the assumption that majority of the effects due to polynomial nonlinearities are covered by the quadratic term in Volterra series expansion. This fails to exploit the effects due to cubic and higher terms, if there are any.

9.3.3 Difficulty in Hardware Realizations

Much of the DSP hardware in the market, based on Harvard architecture, are designed for LTI systems. They are not inherently designed for Kronecker products. This poses serious limitations when one tries to implement quadratic systems on DSP hardware.

9.4 Scope for Further Work

Polynomial systems, based on Volterra power series, is a relatively untrodden area of signal processing which offers a lot of challenges to researchers. In addition to the existing work, extensive research will be done with applications in image processing, computer vision,
communication etc. The limitations posed in Sec. 9.3 will be overcome by expansions of the present research work. It will be further extended in the following avenues.

### 9.4.1 Efficient Structures in Time Domain

Since the operations in the frequency domain are not easy with polynomial systems, it is imperative to look for efficient structures in the time domain. Matrix decomposition of the polynomial kernels coupled with distributed arithmetic will result in compact structures that can perform fast filtering.

### 9.4.2 Addition of Cubic Systems

Addition of cubic systems in parallel with quadratic systems can be done. This will be useful in edge detection as more high frequency components can be encompassed by the cubic term. The major challenge will be in harnessing the computational complexity arising from third order products.

### 9.4.3 Implementation on FPGA

The quadratic filters designed and tested for specific applications can be implemented on FPGA and can be used for real time applications. The parallel-cascade structure based on singular value decomposition is at par with conventional filters in terms of speed of execution. Further improvement in speed can be achieved by realizing each FIR filter in every channel based on distributed arithmetic.

The research work is summarized with emphasis on the key performance parameters of quadratic systems. They are contrasted with those of linear and conventional nonlinear systems to establish the
supremacy of quadratic systems for the applications of edge detection, noise removal and prediction. Also, the challenges in working with quadratic systems are presented. Possibilities of future expansions and further work are explored. Based on the inferences, impact of the work on various stakeholders is presented in the next chapter.