# Chapter 3

## Scheme of Work and Methodology

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3.1 Overview

Polynomial filters, especially the quadratic systems, discussed in chapter 2 find extensive applications in speech and image processing, two areas where effects of nonlinearity are inherent and predominant. The following aspects of quadratic systems are considered below.

- Mathematical formulation of quadratic systems and the various actual and approximate representations of its kernel matrix $H_2$.
- Isotropy of quadratic kernel $H_2$ that can result in the saving of computational complexity stemming from Kronecker products.
- Design methodology to find the quadratic kernel matrix $H_2$.
- Implementation strategies for $H_2$.

Once the mathematical formulation, design and implementation strategy of quadratic filters are understood, it is imperative to consider specific applications where the features of such filters are put to better use. These fields are identified as

- Quadratic edge detection in biometric and medical images
- Removal of impulsive noise using quadratic filter
- Quadratic predictor for speech signals.

The first work is motivated by the improved edge crispness and noise invulnerability of two dimensional quadratic systems which makes them ideal edge detection filters. Teager and general quadratic edge detection filters are designed and tested for the following applications.

- Detection of retinal microaneurysms due to diabetic retinopathy.
- Enhancement of latent fingerprints in noisy background.
Removal of impulsive noise is an important problem in image processing. One major area where images are corrupted by impulsive noise is that of magnetic resonance imaging. It is proposed that a quadratic Volterra filter can remove impulsive noise much better than a conventional image filter like median or Gaussian filter. So impulsive noise removal is the second area of application of quadratic filters.

The third application area for which quadratic filters are designed and tested is that of nonlinear prediction. The motivation for research is the need for accounting the polynomial nonlinearities in speech signals, due to multiple reflections in the vocal tract. This model is incorporated in the design of a speech predictor. Such a quadratic predictor is included in a differential pulse code modulation system for improved mean square error between transmitted and received speech signals sent over an additive white Gaussian noise (AWGN) channel. The broad categorization of work is shown in Fig. 3.1. The impact of work in each category is as outlined in the subsequent sections.

3.1.1 Why the Three Areas?

The above three areas are chosen with the surmise that effects of polynomial nonlinearities are predominant in them and a well designed quadratic filter can outperform conventional filters. The specific requirements and constraints in each area are discussed as follows.

Prediction

Prediction involves in estimating the future value of a random process, often realized using linear FIR filters. In the present research, quadratic Volterra filters are used as speech signal predictors, instead of FIR filters, with remarkable improvement in performance. The work is justified by the fact that speech generation is a nonlinear process
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Fig. 3.1. Scheme of research
and the inherent polynomial components are modeled better using a quadratic predictor. This quadratic predictor is employed in a differential pulse code modulation system with reduced mean square error between the transmitted and received signals.

**Edge Detection**

In image processing and machine vision, isolation of edges is a key process and many filters such as Canny, Sobel, Laplacian, Laplacian of Gaussian (LoG) have been used conventionally for this end. These filters separate edges by computing spatial gradients, but they perform poorly in presence of additive noise. It is proposed that quadratic filters can detect the edges with greater resolution than conventional edge detectors even in presence of strong additive noise. Besides, edges in images are discontinuities in space which are approximated better with nonlinear functions and hence the motivation for employing quadratic systems for edge detection in presence of noise.

**Noise Removal**

Any unwanted signal that gets added with the desired signal is termed noise, the removal of which is a fundamental filtering problem. In communication systems where a large number of noise sources get added, the resulting noise is Gaussian in statistics and well established filtering methods like matched filtering are employed for noise removal. But in image processing the noise encountered is impulsive in behaviour, such as salt and pepper noise, the removal of which is done using nonlinear filters like order statistic filters. Gaussian filter also removes impulsive noise though it slightly blurs the image. Apart from these, quadratic filters are proposed for greater improvement in signal to noise ratio and better preservation of edges. The work is motivated
3.2 Filters for Edge Detection

Edges are discontinuities in brightness in images due to peripheries of objects, changes in illumination, texture etc. and manifest as sharp changes in pixel values. These changes in values can be gradual as in Fig. 3.2 or abrupt as in Fig. 3.3. Detection of edges is an important image processing operation that is useful in periphery detection and machine vision\cite{Pratt2001, Weeks2005}. The applications of edge detection include tumour localization in medical images for automated surgery, geographic localization in satellite images, periphery detection of objects for robotic vision etc. Conventionally, spatial gradient based detectors are used to locate the edges in images. The popular filters under this category are Laplacian, Laplacian of Gaussian(LoG), Canny etc. The major drawback with these methods is that they are very sensitive to additive noise. Noise introduces false edges in an image and the above mentioned filters perform poorly in presence of noise. But quadratic edge detection filters are less sensitive to noise and
3.3. FILTERS FOR NOISE REMOVAL

hence the motivation for the design and implementation of quadratic filter kernels for the following image processing applications. They are

- quadratic edge detection filter for detecting microaneurysms in retinal images due to diabetic retinopathy
- quadratic edge detection filter for the enhancement of noisy fingerprints

The design and implementation of each of these are explained in the chapters from 5 to 6 in part II.

3.3 Filters for Noise Removal

Noise is any unwanted signal that gets added with desired signals and its effect is to obscure the latter. The presence of noise is unavoidable and all one can do is minimizing it. The demarcation, as to what is signal and what is noise, is relative to the user. For example, for a pulmonologist who listens to the sound from a patient’s chest the rhythmic breathing sound is the signal and the heart beat in the background is the noise. The reverse is the case for a cardiologist. The sources of noise can be external to the system or from within the system that processes the signal. External noise sources affect the signal mostly during transmission through channels. The channels can be dedicated communication media such as wireless and wireline electromagnetic channels, optical fibres etc. or storage channels like magnetic hard disk etc. On transmission through communication channels, a large number of noise sources of varying statistics get added, and by the central limit theorem, the total noise follows Gaussian statistics. Besides external noise, there are inherent noise sources within systems. Such are Johnson noise due to thermally generated carriers in amplifiers, shot noise in conductors etc. One chief figure of merit, when working
in presence of noise, is the signal to noise ratio (SNR) which degrades as the signal progresses through the system because of the presence of internal noise sources. Isolation of desired signals from noise is a fundamental engineering problem to which linear system theory offers well established solutions and methods especially when the noise has Gaussian statistics. But linear systems fail when it comes to removing impulsive noise. Such a noise that is predominant in wireless communication signals, medical images etc., is removed using quadratic filters. Fig. 3.4 shows the original lena image and Fig. 3.5 shows the effect of added impulsive noise of power 100 on it.

Unlike images generated by digital cameras, images generated by medical imaging systems such as MRI machine are largely corrupted by impulsive noise as the acquisition of image happens under strong and rapidly varying magnetic fields. In the present work, a two dimensional filter kernel is developed and implemented for removing impulsive noise from magnetic resonance image (MRI) signals. The principal advantages in using quadratic filter are its edge and structure preservation features and noise invulnerability. The details of work done on this class of filter are explained in part III.
3.4 Filters for Nonlinear Prediction

Entropy, information and randomness are manifestations of the same entity, measurement of which is a fundamental problem in information theory, for which solutions were offered by Chaitin and Claude Shannon. According to Shannon,

"we have full knowledge about the past but cannot control it; we can control future but have no knowledge of it."

Lack of knowledge about the future motivated the research in prediction. One is always interested to know what will happen in future or at least what is the most probable thing that will happen in future. Theories of estimation and prediction stem from this interest and Nobert Wiener, a lightning brained mathematician, undertook this problem and predicted the trajectory of a bomb during the second world war. The later developments in the two areas are attributed to him.

Linear prediction is an important statistical signal processing operation that involves in predicting the future value of a random variable based on the past samples. This finds applications in speech coding, image sequence prediction, trajectory prediction, market prediction etc. The performance of predictors will be further improved if polynomial predictors that can model the nonlinearities in speech and image signals are employed in the differential coding systems. Quadratic predictors are designed and implemented for the following applications.

- Lattice type quadratic predictor for Gaussian signals
- Optimization based quadratic predictor for the differential coding and decoding of speech signals

These quadratic filters are contrasted against the linear predictor based on Levinson-Durbin recursion for testing the performance parameters.
The research work and the results obtained in differential PCM systems employing quadratic predictors are detailed in part IV.

3.5 Scope of Work

The research work in the areas of nonlinear prediction, edge detection and noise removal are targeted for various applications. The scope of work in various areas are outlined in the subsequent sections.

3.5.1 Strategy for Design and Implementation

The methods proposed for the design of quadratic systems lack generality. But two major methods are considered and the pros and cons of both are analyzed before deciding on one. Once the design for a specific application is accomplished, a computationally efficient method realization should be selected. Several methods are compared before matrix decomposition is selected.

3.5.2 Quadratic Edge Detection Filter

Two dimensional Quadratic filters are proposed for detecting edges in images with improved edge resolution and noise invulnerability. Such features are desirable for applications like

- enhancement of noisy fingerprints
- detection of retinal microaneurysms

The first application is useful in enhancing crime scene fingerprints that are unclear or buried in noise. It is a pre-processing stage before the prints are subjected to identification. Quadratic edge detection
filter that preserves the structure of image even with additive noise is used in an unsharp masking scheme for fingerprint enhancement.

The periphery of retinal microaneurysms typically 100\(\mu m\) dimension due to type-I and type-II diabetes are enhanced using a variation of quadratic filters viz. Teager filters, which track energy localizations and consequently the edges in the input image. A general quadratic filter can also be employed for the enhancement of retinal microaneurysms. The precise detection of periphery aids automatic surgery of microaneurysms in the initial stage of diabetic retinopathy. It forms the second application area of quadratic edge detection filter.

### 3.5.3 Modified DPCM System with Quadratic Predictor

The polynomial components in speech signals, due to multiple reflection in the vocal tract during speech generation, are not accounted for in a linear predictor and so it yields a large prediction error. These components are modeled using Volterra power series. A speech predictor based on Volterra quadratic system is proposed to yield smaller mean square error between actual speech signal and its predicted value. The quadratic predictor is used to replace the linear predictor in a differential pulse code modulation system, with improved performance.

### 3.5.4 Removal of Impulsive Noise from MRI Signals

Unlike in communication systems, the noise present in images are impulsive in nature, making filtering difficult. One key area where strong impulsive noise is present, and its removal is a critical operation, is
the generation of magnetic resonance imaging (MRI) signal. In MRI, nuclear resonances due to rapidly changing magnetic fields are transformed into images of body part under study. The strong variations in magnetic fields add impulsive noise with the resulting image which need to be removed. Conventionally, order statistic filters such as mean or median filters are employed for this task with unavoidable blurring of edges. A quadratic filter is used for the removal of impulsive noise from MRI images with greater signal to noise ratio and edge crispness than linear filters and conventional nonlinear filters.

3.6 Summary

This chapter details the scheme of research work adopted in the design and implementation of quadratic filters and their realizations for three applications. At the onset, quadratic filter is selected as a potential choice for nonlinear signal and image processing. Edge detection, noise removal and prediction are identified as areas where quadratic filtering could exploit more than that exploited by linear or other nonlinear filters in terms of performance parameters. The division of work under each category is also presented. The forthcoming parts in the thesis detail the work on quadratic system for the three areas.