CHAPTER 1 - GENERAL INTRODUCTION

1.1 Introduction

The concept of biologically inspired (bio-inspired) processing has been around for several decades. It was the work of neurobiologist Paul A. Weiss [1] in the early 1940's, which sparked off this new approach to engineering. In the late 1980's professor Carver Mead [2] published his book “Analog (Expand) VLSI and Neural Systems,” in which he introduced his revolutionary “Neuromorphic” systems. According to Mead, the neurobiological system is well suited to accept ill conditioned data for input which is of great advantage for numerous tasks. Present-day sensors and signal processing systems are challenged by complex, dynamic environments and often require real-time processing capabilities. These capabilities include fast recognition, adaptation and control mechanisms which involve such tasks as object and pattern matching, image enhancement, edge detection, interpolation, morphological operations like skeletonization, target tracking, fusion of data from multiple sensors, speech recognition, sound localization and autonomous control.

Although, commercially available machinery visual sensors are beginning to approach the photoreceptor densities found in primate retinas, they are still outperformed by biological visual systems in terms of dynamic range and strategies of information processing employed at the sensor level. This has sparked recent interest in studying biological retinas in order to learn more about their information processing strategies with the hope of using this knowledge to design better mechanical visual sensors.

Biological visual system can be modeled as a cascade of sub filters covering the major processing layers found in mammal visual systems—from photoreceptors over ganglion cells in the retina up to simple cells in the primary visual cortex [3]. An understanding of the basic working of these cells helps in the study of visual models like Boundary Contour System (BCS) and Human Visual System (HVS) [4-10].

There exist three possible regular tessellation schemes namely the tessellations with squares, hexagons and triangles. Hexagonal Image Processing (HIP) with an effort to enhance the quality of the image is performed in this
thesis. The primary motivation behind using hexagonal pixel grid is that the retina of the eye closely resembles a hexagonal grid space.

Two dimensional signals are normally processed as rectangular sampled arrays. They are periodically sampled in each of two orthogonal independent variables. Another form of periodic sampling, namely hexagonal sampling offers substantial savings in machine storage and arithmetic computations for many signal processing operations. Hexagonal grid image processing exhibits several advantages such as smaller quantization error [13], consistent connectivity definition [47, 66], equidistance of neighboring pixel [66], greater angular resolution [13], higher symmetry [71], fewer sampling points [17], less storage and less computation time [3, 10, 20]. The possibility of using a hexagonal structure to represent digital images and graphics has been studied by many researchers [11-20]. Using hexagonal grid wider spectra can be sampled without aliasing with the same number of pixels or less pixel than using square grid. A hexagonal grid of pixels can be represented on the existing rectangular screens for modeling and processing purpose, which is more suitable for computer vision modeling.

To perform hexagonal image processing operations there is an approach in which hexagonal image processing can fit within the current scenario. Part of the image processing in a large system is done using hexagonal images in order to utilize its benefits, while the remaining part of processing is done using square images. This is possible by adopting solutions for conversion between square and hexagonal images. In spite of the many advantages of hexagonal structure, the use of hexagonal based image processing is limited in intelligent vision area. The prime reason being that, there is lack of hexagonal-based devices available to capture and display digital images on hexagonal grids. Simulation of hexagonal sampled images on common square display equipments has become a serious problem that affects the advanced research on hexagonal architecture in the field of computer vision and graphics.

Over the past years, there have been various attempts to simulate a hexagonal grid on a regular rectangular grid device. The simulation schemes include those using rectangular pixels, pseudo hexagonal pixels, mimic
hexagonal pixels, virtual hexagonal pixels and spiral architecture [21 - 28]. Some of these simulation schemes are not used to represent the hexagonal structure without suppressing the advantages that a real hexagonal structure possesses. The use of these techniques provides us the practical tool for image processing on hexagonal grids and makes it possible to carry out theoretical study of using hexagonal structure in existing computer vision and graphics systems.

The use of hexagonal grid is also fettered by its pixel arrangement. In the hexagonal structure, the pixels are no longer arranged in rows and columns. In order to take the advantages of the special structure of hexagonal grid and store hexagonal images data, several addressing schemes and coordinate systems have been proposed [29 - 32].

This research work started with implementation of hexagonal pseudo lattices such as half pixel shift [21, 33] and alternate suppression of rows and columns [20] and then entered on a real hexagonal lattice through the Hex-Gabor process which is elaborated in section 1.1.2. The half pixel shift method is used for the applications such as edge detection, image interpolation and enhancement. However, the results in Hex-Gabor interpolation disputes the fact that such methods require radial distance corrections and they defeat edge enhancement as some parts of the edges get averaged out.

As the edges are enhanced in one direction image smoothening occurs in orthogonal direction. Previous methods use small regions of image to enhance edges with appropriate directions selected for Gabor filter [34]. In this work, the operation on the entire image is performed in three directions which enhances intra-pixel information automatically, especially when sigma = 2/\pi. Subsequently, Hex-Gabor is applied to regular rectangular lattice and similar results were obtained as in the case of pseudo hexagonal lattice. Hex-Gabor kernel/filter in regular lattices is found suitable for enhancement and interpolation. Edge enhancement also creates conditions for a better edge detection. Applying canny edge detection after low pass filtering by Hex-Gabor has the ability to show gray scale region boundaries as edges and it is possible to bring out dominant contours in the image.
The original work in this thesis also included the Field Programmable Gate Array (FPGA) implementation of Cellular Logic array Processing (CLAP) algorithm based edge detection, thinning and reconstruction over a hexagonal lattice. The motivation behind the use of Gabor filters for hexagonal lattice is discussed in the following sections. Later, introduction is given about the applications used in this work such as Image enhancement, Interpolation, Edge detection and Skeletonization.

1.1.1 Significance of Gaussian Filters and Gabor filters

Gaussian filters have been shown to play an important role in edge detection in the human visual system and to be extremely useful as detectors for edge and line detection [35, 36]. It is very similar to the Difference of Gaussians (DOG) filter which is a well known approximation to the shape of spatial receptive fields in the visual system of cats and humans [5, 8, 9, 10, 24].

In 1946, Dennis Gabor [37] the inventor of the hologram proposed the expansion of a wave in terms of Gaussian wave packets. An example of such a wave packet is a sine wave multiplied by a Gaussian function. If a signal is modulated (multiplied) by a Gaussian window of a certain width and central time then a Fourier expansion of the modulated signal gives a measure of the local spectrum. Clearly such a spectrum is not unique since the width of the Gaussian is arbitrary; but this local spectra is extremely useful. If a collection of local spectra is computed for a suite of window positions the result is a time-frequency decomposition called a Gabor transform [38].

Gabor filters have desirable properties for picture analysis and feature extraction. Those filters are also used to describe the behavior of simple cells in area V1 of the human visual cortex which has turned out to be very successful. Hubel and Wiesel [6] found simple cells in cat’s visual cortex are sensitive to frequency and orientation of an image perceived. Gabor filter responses are widely and successfully used as general purpose features in many computer vision tasks, such as texture segmentation, face detection, face recognition, and iris recognition [39 - 43].
The motivation for use of Gabor filters comes from several factors:

- These are band-pass filters and this property has an important role in texture analysis as distinct textures most often differ significantly in their dominant spatial frequencies [37, 40].
- It was shown by M.Porat and Zeevi [43] that Gabor filters have the ability to capture the features even in presence of additive noise.
- Gabor filters are used to model simple cells. Simple cells of human visual cortex have receptive fields (RFs) which are restricted to small regions of space and are highly structured. They have three important characteristics: band pass, orientation selectivity and direction selectivity. They respond differently to the stimuli with different spatial frequencies, orientation and direction. These cells can be said to be localized spatial filters that respond only to certain spatial frequency band, orientation and directions. The coding of Gabor filter is based on the imitation of HVS and it should incorporate the property of HVS as localized spatial filter.
- It has been observed that most of the cells in the visual system can be combined in pairs, one cell of each pair has even symmetry and the other has odd symmetry. This observation can be modeled by a cosine function and sine function. Receptive field’s (RF) of both pair of cells can be combined in a complex notation (RF is a pattern of photoreceptors that determines the behavior of a cell in visual cortex) as
  \[ \exp(ikx) = \cos(kx) + i \sin(kx) \quad (1.1) \]

1.1.2 Gabor Filter for Hexagonal Lattice - Hex-Gabor (Proposed method)

One of the important features of the Gabor filter is that they can be easily tuned to different center frequencies, dilations and orientations [39 - 42]. As there is a little work in recognizing minute details in an image by either interpolation or enhancement on hexagonal grid, it is essential to build a suitable system for this. Hence, in this work, the Gabor filter multichannel system for hexagonal lattice is designed using the Hex-Gabor kernel proposed. Hexagonal sampling scheme involves three axis symmetry. Three orientations Hex-Gabor multichannel system can be designed in two ways (i) By performing
filtering in three distinct directions ($0^0$, $60^0$ and $120^0$) using Gabor filter on hexagonal lattice and adding the responses (ii) Filtering by the resultant kernel (Hex-Gabor kernel) which can be obtained by adding the responses at $0^0$, $60^0$, and $120^0$.

Some of its main features are:

- The filtering process of Hex-Gabor may be carried out in spatial or Fourier Domain.
- Hex-Gabor is considering the intra-pixel distances and directions of adjacent pixels in any regular lattice.
- Hex-Gabor in regular lattices is suitable for enhancement and interpolation.
- Hex-Gabor is permitting continuous differentiation and allows continuous representations in both space and Fourier spaces.
- It also permits adaptive scaling within a compact space which has been proved in this research work. Scaling also can improve resolution and is also a part of this work. Parametric Gaussian filter change of shape is considered in this thesis and the optimal parameter sigma is evaluated in chapter 3. The kernel is also used in rectangular domain and it was found to be effective in edge detection and enhancement.
- Hex-Gabor is doing a nonlinear filtering operation [44] using an isotropic kernel.

In this research work, image enhancement and interpolation are performed using Hex-Gabor kernel. The performance of the Hex-Gabor filter is compared with the Hex-spline which is proposed by D.Van De Ville et.al [45] and elaborated in chapter 3.

1.1.3 Image Enhancement, Edge Detection and Interpolation using Hex-Gabor

Image enhancement is the processing of images to increase their usefulness. In one important class of problems modifying its contrast and/or dynamic range enhances an image. When images are enhanced for human viewers as in television the objective may be to improve perceptual aspects: image quality, intelligibility and visual appearance. An image can often be enhanced when one or more of the following objectives are accomplished: modification of the contrast or dynamic range, edge enhancement, reduction of
blurring, reduction of noises like additive, multiplicative, salt and pepper noise [35, 46, 47]. The edges and quality of the images can be enhanced by Hex-Gabor. For analysis the reflected images and scattered images like X-ray images are considered.

Gray level image discontinuities in image intensity profiles are called edges [9, 47]. Edges contain major image information and need only a small amount of memory storage space compared to the original image. Hence, edge detection simplifies images and thus facilitates image analysis and interpretation. Some of the problems of edge detection like edge localization, the ability of an edge detector to locate in noisy data, necessity for smoothing are addressed in [35].

An important issue in image processing is the link between the discrete and continuous domain. The choice of an interpolating function to be used for re-sampling depends upon the task being performed [45, 48, 49, 52, 53, 54]. While using Hex-Gabor kernels for image enhancement it generates continuous image surface enabling interpolation. In addition to the fact that Gaussian kernels are suitable for this purpose, a compact support is also ensured in this method. Training of images is done to obtain specific orientation or circular features in an image for the purpose of super resolution [55, 56]. However, no such training is required in Hex-Gabor case as edge enhancement simultaneously takes care of the smooth parts of the image.

The problems addressed in this thesis are summarized as follows:
1. Image enhancement and interpolation using Hex-Gabor and its performance analysis compared with Hex-splines.
2. FPGA based solution of edge detection on hexagonal grid.
3. Use of Hex-Gabor as a preprocessing step which can bring out the dominant contours while performing the edge detection operation.
4. Hardware implementation of Skeletonization and reconstruction on hexagonal grid.

1.2 Major Contributions
Major contributions of the research work as reported in the thesis, can be summarized as below:

1. In regular lattice isotropic kernels are important, but for unequal pixel distances directional and orthogonal direction filtering are important. Hence, three orientations Gabor filter with windowing is designed and the resultant kernel is obtained by adding the responses at $0^0$, $60^0$, and $120^0$ in order to obtain Hex-Gabor kernel which can perform interpolation following enhancement. Conventional Gabor filtering does not do this because it only considers pixels along a line, whether it is horizontal, vertical or along axes in hex-domain. The three orientation axes information gets added in this case which may also consider the direction of the edges; this will modify existing pixel values. This may be used to gather mutual information simultaneously between three neighboring pixels and in three directions if intra-pixel information is derived.

2. Initially, the author used half pixel method for image enhancement and interpolation. The results with Hex-Gabor interpolation dispute the fact that the half pixel method requires radial distance corrections, and they defeat edge enhancement as part of the edges get averaged out. Previous methods use small regions of image to enhance edges with appropriate directions selected for Gabor filter [34]. In this method, as the edges are enhanced in one direction, image smoothening occurs in orthogonal direction. The operation on the entire image is performed in three directions which enhances intra-pixel information automatically, specifically when $\sigma = \frac{2}{\pi}$.

3. The parameter $\sigma = \frac{2}{\pi}$ yields maximum PSNR value. The Hex-Gabor kernel at this value has also some interesting properties which are elaborated in chapter 3. It was observed that, the image quality at other sigma values deteriorated substantially. Windowing was also investigated which shows that a hanning window requirement of eight times the size of kernel gives the best results. It was also noticed that this helps to reduce the magnitude of the kernel at the second pixel
location to almost zero as in the case of B-Spline. The isotropy is lost when sigma exceeds 2/\pi and smooth filtering qualities are lost for values above this value.

4. Gabor filter models may also be developed for X-ray images. It was observed that different values of sigma gave enhancement of different depth information. However, the consulting doctors were much interested to use this as a tool for viewing after some perfection.

5. Generally, addressing and storage of data are important issues while performing the image processing operations on hexagonal lattice. Various addressing schemes such as two-axes oblique coordinate addressing scheme, three coordinate symmetrical coordinate frame, single indexing scheme and spiral addressing scheme were proposed by many researchers [10, 29, 30, 31]. In this work, a new addressing scheme based on hexagonal structure suitable for hardware implementation is proposed.

6. An architecture for the CLAP algorithm based edge detection on hexagonal sampled image is proposed. Using the proposed method, edge detection was performed successfully which is evident from the verilog simulation results and FPGA implementation results (Chapter 4). The performance of the proposed architecture was compared with the work by Muthukumar Venkatesan et.al [57] and Stephan Hussmann et.al [58].

7. Skeletonization is an important representation for the shape analysis which is useful for many pattern recognition applications. Also, once the image has been edge detected it is often necessary to thin the edges. Hence, an attempt is made to design architecture for skeletonization of hexagonal sampled images based on Hilditch’s algorithm. Using the proposed modifying algorithm it is possible to reduce number of processing elements compared with the work by N. Lopich and Dudek [59]. An attempt is made to reconstruct the skeletons with the proposed architecture. In reconstruction process, hexagonal processing generates a more representative image.
1.3 Organization of the Thesis

Chapter wise organization of the rest of the thesis is as follows:

- Chapter 2 reviews the study of biological visual system and modeling of Boundary Contour System which is the ground work for the subsequent chapters. The features and mathematical background of hexagonal image processing, acquisition methods and addressing schemes are also reviewed in Chapters 2.

- In Chapter 3, the current approaches for interpolation and enhancement are reviewed. Hex-Gabor based interpolation and enhancement is proposed and the results are compared with the Hex-spline.

- In Chapter 4 and 5, hardware implementation of edge detection, thinning and reconstruction applications on hexagonal grid are addressed.

- Chapter 6 summarizes the results of this research work reported in the thesis.