Comparing Hexagonal Image Resampling Techniques with Respect to Feature Extraction

B. Gardiner
Ulster University

Bryan Scotney
Ulster University

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Bryan Gardiner[1], Sonya Coleman[1], Bryan Scotney[2]

[1]School of Computing and Intelligent Systems, University of Ulster, Magee, BT48 7JL
[2]School of Computing and Information Engineering, University of Ulster, Coleraine, BT52 1SA,
{b.gardiner; sa.coleman; bw.scotney}@ulster.ac.uk

Abstract

The hexagonal structure is considered to be preferable to the standard rectangular structure typically used for images in terms of the improved accuracy and efficiency that can be achieved for a number of image processing tasks. However, due to the lack of commercially available hexagonal image sensors, hexagonally structured images are generated by resampling from standard rectangular images and hence many resampling techniques exist for this purpose. Here we consider four such resampling techniques and apply recently developed scalable operators to them for the purpose of feature extraction. Each hexagonally structure image is evaluated with respect to feature extraction performance and we provide conclusions on the most accurate resampling technique currently available.

1. Introduction

Image content often represents curved structures that may not be well represented on a standard rectangular pixel based image, and the characteristics of which may not be well captured by feature extraction operators based on principal horizontal and vertical directions. The properties of operators developed on a rectangular grid are often influenced by the underlying Cartesian structure, i.e., operators may be dominated by the preferred directions along the *x*- and *y*-axes, leading to the inheritance of anisotropic properties. Such anisotropy is reflected in the spectral properties of the operators, and improvements can be achieved by developing operators that consider "circularity" [3, 5, 9].

To overcome these problems, a hexagonal pixel based image can be introduced, from which both spatial and spectral advantages may be derived: namely, equidistance of all pixel neighbours and improved spatial isotropy of spectral response. Pixel spatial equidistance facilitates the implementation of circular symmetric kernels that are associated with an increase in accuracy when detecting edges, both straight and curved [2], and the improved accuracy of circular and near circular image processing operators has been demonstrated in [5, 9]. Additionally, better spatial sampling efficiency is achieved by the hexagonal structure compared with a rectangular grid of similar pixel separation, leading to improved computational performance. In a hexagonal grid with unit separation of pixel centres, approximately 13% fewer pixels are required to represent the same image resolution as required on a rectangular grid with unit horizontal and vertical separation of pixel centres [14].

Although there are obvious benefits with hexagonal structured images, one of the main reasons for the lack of use of the hexagonal lattice is the absence of availability of hardware: both sensors that enable the capture of hexagonal images and devices that enable their display. To date, within the area of hexagonal image processing conversion of, or resampling of, rectangular tiled images to hexagonal tiled images is typically necessary, unless the use of a hexagonal CMOS sensor is used to capture a true hexagonal image [12]. These sensors are not commercially available at present, although there has been interest in creating hexagonal sensors for research purposes, for example [10, 11]. The process of resampling from a rectangular image to a hexagonal image is an important pre-processing step prior to the application of hexagonal image processing operators. It is essential to ensure that an accurate resampling technique is applied which closely mimics the hexagonal pixel structure and its advantages whilst also ensuring the ability of accurate processing. Therefore, we present a comparative study in which hexagonal pixel based images are generated using four of the main resampling techniques and these images are further used for feature extraction. Figure of Merit analysis is conducted using the generated hexagonal edge maps to determine the rectangular to hexagonal image resampling technique that provides the most accurate subsequent processing.

2. Hexagonal image simulation

We discuss a number of resampling techniques used for conversion from existing rectangular pixel based images to hexagonal pixel-based images. The main resampling techniques used to simulate a hexagonal pixel-based image are those discussed in [4, 7, 8, 13, 15, 17]. The approaches presented in [4, 13] are computationally intensive, therefore we compare only the four simplest resampling techniques [7, 8, 15, 17].

2.1 Half Pixel Shift

Rosenfeld [7] resampled images by shifting every second row of square pixels by a half pixel, resulting in a brick wall effect. As the pixel shape is square, both the vertical and horizontal sampling distances are equal; however, the equidistant property of the hexagon is not achieved as the distance to diagonal neighbours is greater than one, see Figure 1.

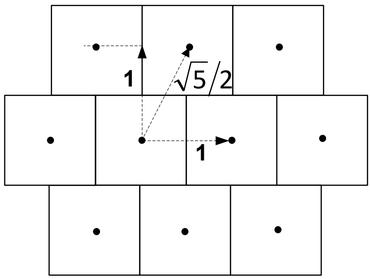


Figure 1. Half pixel shift resampling technique

2.2 Imitative Hexagonal Structure

He [7] created an imitative hexagonal structure in which each hexagonal pixel consists of four square pixels with its intensity level taken as the average of the four square pixel values (Figure 2). The clustering of pixels to create the imitative hexagonal pixels are offset every second row to generate a staggered effect between the pixel centre points. This resampled structure encounters a loss in image resolution and also does not comply with the equidistance property needed for true hexagon representation.

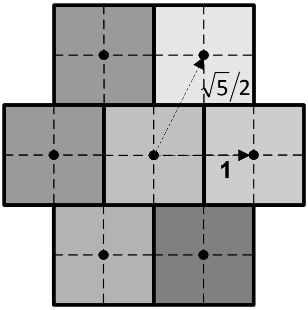
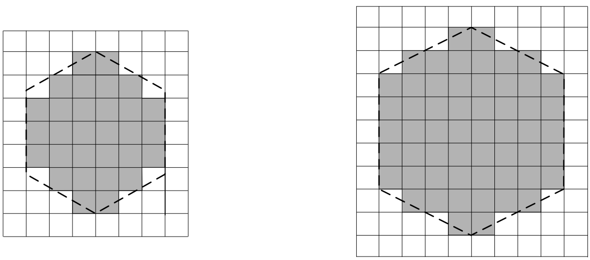


Figure 2. Imitative hexagonal structure using cluster of four square pixels

2.3 Pseudo Hexagonal Pixel

Wuthrich [17] proposed a method of creating a pseudo hexagonal pixel, known as a hyper-pixel, from a cluster of square pixels. Although this does not create a perfect representation of a hexagon, it creates a hexagon-like shape that complies with the main hexagonal properties. Selection of the number of pixels to be clustered for each hexagonal pixel is based on two issues: the arrangement must allow a tessellation with no overlap and no gaps between neighbouring hexagonal pixels; and the cluster must closely resemble a hexagon i.e. six sides of approximately equal length. Two possible choices of hexagonal pixel representations are shown in Figure 3. Both cases represent a hexagonal pixel adequately with no overlap or gaps when tiling; however, the cluster illustrated in Figure 3(b) is most often used as it is slightly superior in its ability to represent a hexagon in terms of having sides of near equal length [8].



(a) 30 pixel cluster (b) 56 pixel cluster

Figure 3. Two possible sub-pixel clusters

Grouping these hexagonal hyper-pixels will produce a simulated hexagonal image that tiles the image plane with no overlap or gaps and satisfies the properties of a hexagonal pixel-based image, see Figure 4.

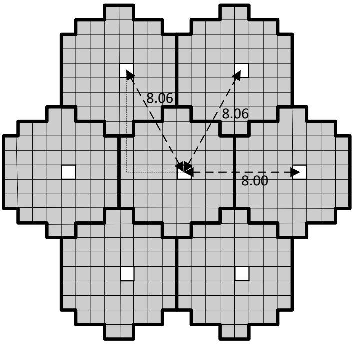


Figure 4. Cluster of seven hyper-pixels

The property of equidistance between neighbouring pixels is almost retained as the distance from the centre pixel to either of its neighbours on the horizontal axis is eight square pixels, whilst the distance from the centre pixel to any of its neighbours above or below the centre pixel can be computed as $\sqrt{7^2 + 4^2} = 8.06$. As these distances are very close, the feature of equidistance is almost satisfied, hence introducing almost no image distortion when using this resampling technique. However, as each hyper-pixel is created by using a cluster of 56 original pixels, there is a high loss in image resolution when using this technique. Note that, for purposes of illustration, in Figure 4 the centre of each hexagonal hyper-pixel is represented by a white square pixel.

Wu et al. [16] addressed the issue of loss of image resolution by firstly partitioning each original pixel into a 7×7 block of sub-pixels having the same intensity as the original pixel. Each hyper-pixel is then created by clustering 56 sub-pixels as in Fig.4, and the intensity of the hyper-pixel is calculated as the average intensity of the 56 sub-pixels used to create it. This is the approach that we also use in our study.

3. Performance Evaluation

We present analysis with respect to feature extraction performance for the four resampling techniques using synthetic images with Gaussian noise added at a number of signal-to-ratios.

3.1 Edge Extraction Algorithm

For edge detection, we use the operators developed in [6] for direct use on hexagonal pixel based images. In [6] we developed an efficient design procedure for scalable hexagonal derivative operators using an element based method that can be applied directly to hexagonal images. The shaded regions in Figure 5 illustrate the element structure that determines the size and shape of each operator. Here, we use three different sized operators denoted H_1, H_2, and H_3; these are the hexagonal equivalent to the standard square 3×3, 5×5 and 7×7 operators respectively.

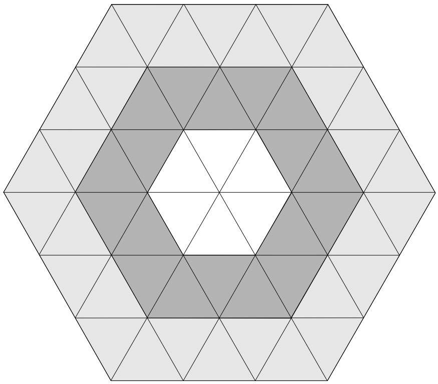


Figure 5: Hexagonal operator structures for operator sizes H_1, H_2, and H_3

3.2 Results

We generate images that contain either a horizontal, vertical or 60° oriented ramp edge. The edge detection operators are applied to each image and the edge detection accuracy is determined using the Figure of Merit evaluation technique [1] for each of the hexagonal operators (H_1, H_2, and H_3). The Figure of Merit value is averaged over five synthetic images for each image type at each signal-to-ratio. For further comparison, we also include the Figure of Merit results for the corresponding square operators in each case.

Figures 6, 7 and 8 provide the Figure of Merit versus signal-to-noise ratio graphs for each of the ramp edge types. Figure 6 presents the results when a vertical ramp edge is used. In Figure 6, we see that the rectangular image structure provides better edge detection performance than the hexagonal image structure in areas of high noise, however in Figure 6(a), where the smallest operator is applied, the hexagonal structure outperform the rectangular structure at $SNR \geq 50$. The results also show that the half pixel shift resampling technique is the most accurate technique to use when the image contains a vertical edge, whereas the worse performance is obtained using the 30 sub-pixel pseudo pixel.

Figure 7 presents the results when a horizontal ramp edge image is used. Generally, in Figure 7, we see that the 56 sub-pixel pseudo pixel resampled image provides the best Figure of Merit results regardless of the size of the operator being applied for images with high noise levels. It is important to note that in Figure 7(a), the use of the rectangular pixel based images and the 3×3 square operator provides the poorest results.

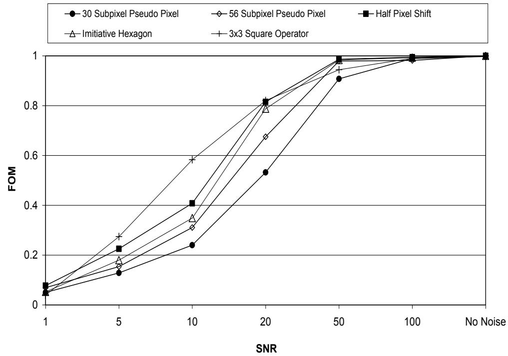
In Figures 7(b) and 7(c), when the $SNR \geq 10$ it becomes difficult to discriminate between the graphs and therefore we provide the actual Figure of Merit values in Table I and Table II respectively; the highest values are in bold font and the lowest values are in italics. Here, the best Figure of Merit performance is typically obtained using the imitative hexagonal approach when the H_2 operator is applied and using the 30 sub-pixel pseudo pixel approach when the H_3 operator is applied. Again, we note that the use of the rectangular pixel based images with square operators, 5×5 and 7×7, yields the poorest results.

Table I. Figure of Merit results using the H_2 operator on a horizontal ramp edge

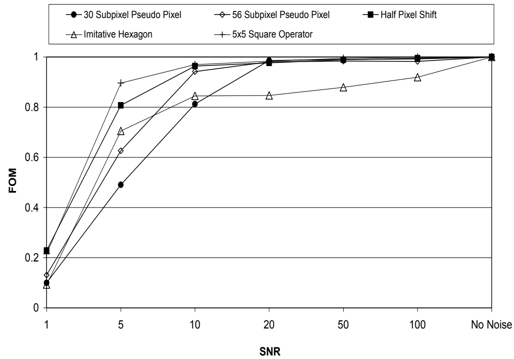
	SNR=10	SNR=20	SNR=50	SNR=100	No noise
30SPP	0.95478	0.98759	0.99837	**0.99993**	**1**
56SPP	**0.97050**	0.98521	0.99756	0.99991	**1**
HPS	0.93690	0.98483	0.99528	0.99921	**1**
IH	0.95752	**0.98817**	**0.99849**	0.99968	**1**
SQ5	*0.92734*	*0.97608*	*0.99190*	*0.99810*	**1**

Table II. Figure of Merit results using the H_3 operator on a horizontal ramp edge

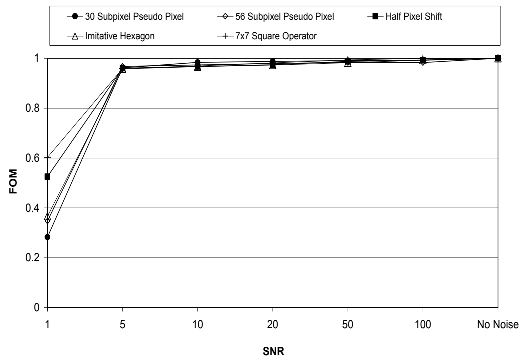
	SNR=10	SNR=20	SNR=50	SNR=100	No noise
30SPP	**0.97311**	**0.98579**	**0.99756**	**0.99993**	**1**
56SPP	0.96717	0.98053	0.99553	0.99927	**1**
HPS	0.97032	0.98373	0.99363	0.99881	**1**
IH	0.96990	0.98160	0.99598	0.99968	**1**
SQ7	*0.95970*	*0.97206*	*0.98764*	*0.99635*	**1**



(a) H_1 operator

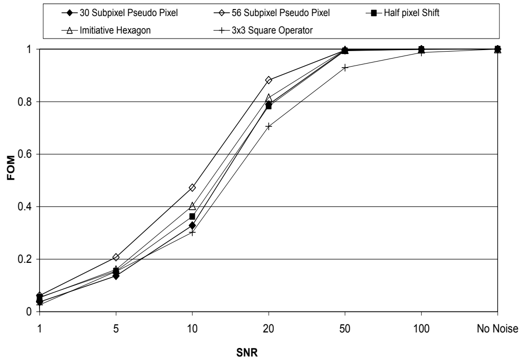


(b) H_2 operator

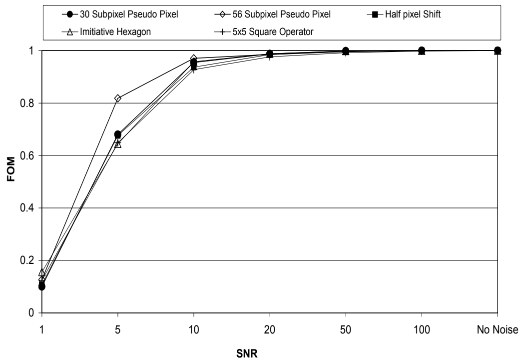


(c) H_3 operator

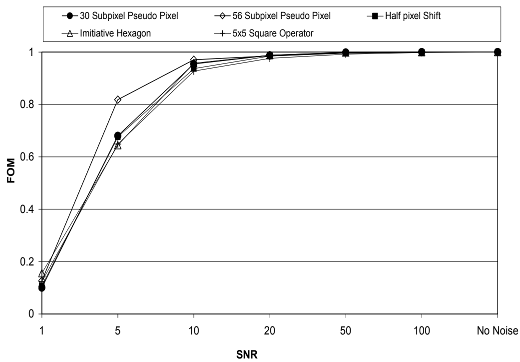
Figure 6. FoM vs SNR for a vertical edge



(a) H_1 operator



(b) H_2 operator



(c) H_3 operator

Figure 7. FoM vs SNR for a horizontal edge

Figure 8 presents the results when an oriented ramp edge image is used. In Figure 8(a), we see that the 56 sub-pixel pseudo pixel resampling technique provides the best performance results and the rectangular pixel-based images provide the lowest Figure of Merit results.

Table III. Figure of Merit results using the H_2 operator on an oriented ramp edge

	SNR=10	SNR=20	SNR=50	SNR=100	No noise
30SPP	**0.97623**	**0.98519**	**0.99539**	**0.99921**	**1**
56SPP	0.97535	0.98422	0.99462	0.99920	1
HPS	0.95139	0.96628	*0.97404*	*0.97471*	*0.98566*
IH	*0.89914*	*0.94069*	0.97539	0.98779	1
SQ5	0.97107	0.97836	0.98619	0.99055	1

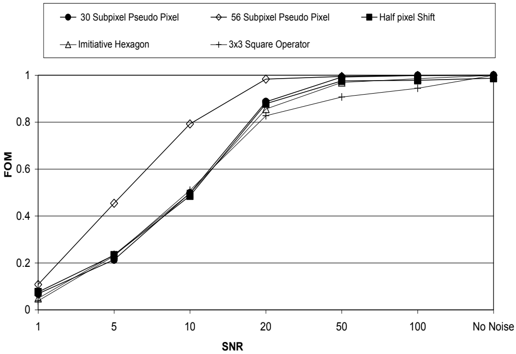
Table IV. Figure of Merit results using the H_3 operator on an oriented ramp edge

	SNR=10	SNR=20	SNR=50	SNR=100	No noise
30SPP	0.96775	0.97605	0.99116	**0.99834**	**1**
56SPP	**0.97075**	**0.97975**	**0.99141**	0.99780	**1**
HPS	0.95863	0.96680	0.97371	0.97530	*0.97046*
IH	*0.89880*	*0.93466*	*0.97135*	*0.98499*	**1**
SQ7	0.96731	0.97376	0.98197	0.98802	**1**

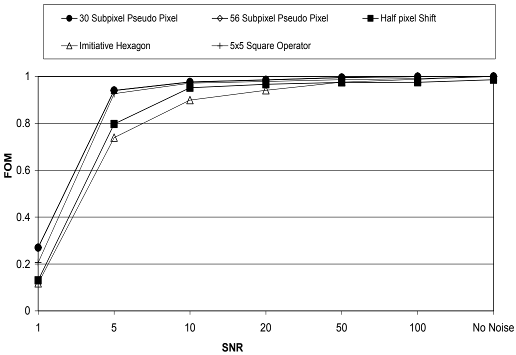
Tables III and IV illustrate that when an oriented edge is present in an image, the best resampling technique to use is either the 30 or 56 sub-pixel pseudo pixel approach. Additionally, in this case the rectangular pixel-based approach is not the poorest performer, but instead the imitative hexagon resampling technique.

4. Discussion

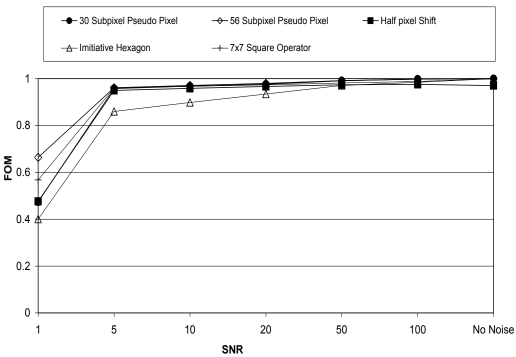
We present a comparative evaluation for four techniques that can be used to resample rectangular images onto hexagonal images structures. We also compare the performance results with the original equivalent rectangular based images. The results demonstrate that when a vertical ramp edge is present in an image, it is most accurately detected using a rectangular image structure and accompanying edge detection operators. This is primarily because of the staggered pixel effect that a hexagonal image structure introduces for a vertical edge. However, in the other two edge types, horizontal and 60° oriented, a hexagonal structured image provides the best feature extraction performance, and this is most often achieved using the 56 sub-pixel pseudo pixel approach, particularly in areas of high noise.



(a) H_1 operator



(b) H_2 operator



(c) H_3 operator

Figure 8. FoM vs SNR for a 60° oriented edge

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