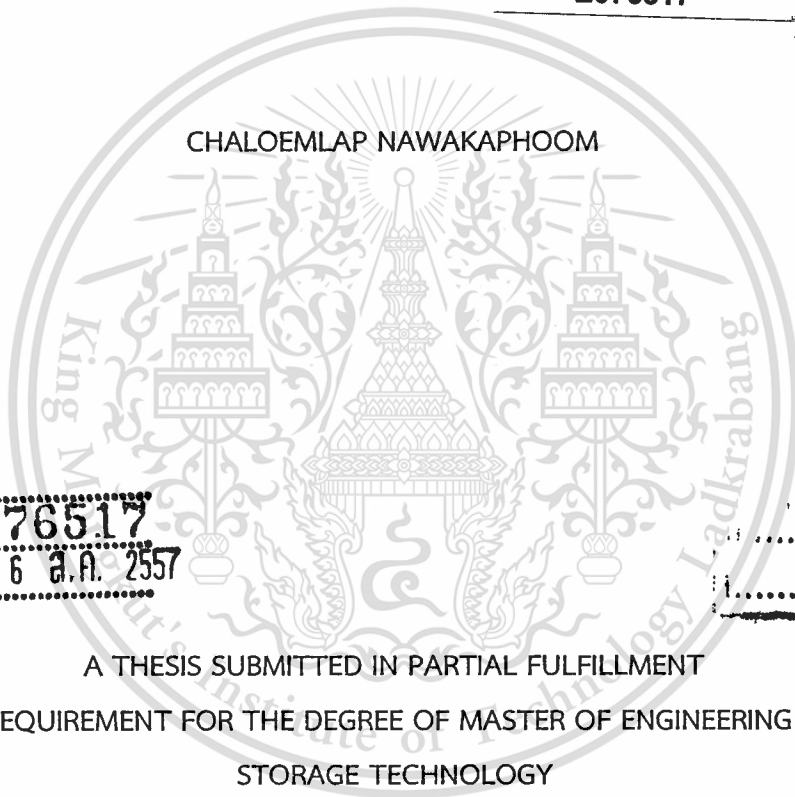


สำนักหอสมุดกลาง พระจอมเกล้าลาดกระบัง

APPLICATIONS OF IMAGE FUSION USING WAVELET TRANSFORM
IN SLIDER ORIENTATION MEASUREMENT



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หัวข้อวิทยานิพนธ์	การประยุกต์ใช้การรวมภาพโดยวิธีการแปลงเวฟเลทเพื่อวัดการวางตัวของสไลเดอร์
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บทคัดย่อ

ระบบการวัดค่าการวางตัวของสไลเดอร์ในปัจจุบันใช้เลเซอร์เป็นตัววัดค่ามุมและรับแสงสะท้อนของเลเซอร์โดยใช้จอ CCD รูปภาพที่จับได้ถูกนำไปใช้คำนวณค่าการวางตัวของสไลเดอร์ ปัญหาอย่างหนึ่งของระบบการวัดแบบเลเซอร์ คือ ความไม่ชัดเจนของรูปจุดแสงสะท้อนของเลเซอร์ซึ่งสะท้อนจากสไลเดอร์บน HGA มายังจอ CCD ทำให้มีข้อมูลไม่เพียงพอในการคำนวณค่ามุมการวางตัวของสไลเดอร์ โดยปกติแล้วรูปจุดแสงสะท้อนของเลเซอร์ที่รับได้บนจอ CCD ควรเป็นวงกลมที่ชัดเจนหรือใกล้เคียงวงกลมมากที่สุด แต่ในบางกรณีรูปที่รับได้มีลักษณะบิดเบี้ยวไปจากรูปวงกลมมากจนไม่สามารถนำไปใช้คำนวณวัดค่ามุมได้ สาเหตุอาจเกิดเนื่องจากการยิงเลเซอร์ไปโดนร่อง Air Bearing บนสไลเดอร์, สิ่งเจือปนในวัสดุเคลือบผิวหน้าสไลเดอร์ เป็นต้น นอกจากนี้ ยังพบว่าพื้นที่บางส่วนของหน้าสไลเดอร์ไม่เหมาะสมสำหรับการวัดเนื่องจาก เกิดการกระเจิงของแสง ปัญหาดังกล่าวยังเกิดขึ้นที่การวัดความสูงของสไลเดอร์อีกด้วย

ในวิทยานิพนธ์นี้การรวมภาพถูกพิจารณานำมาประยุกต์ใช้แก้ปัญหาจุดแสงสะท้อนของเลเซอร์ที่บิดเบี้ยวได้อย่างเหมาะสม ด้วยแนวคิดที่ว่า ข้อมูลของรูปภาพหลาย ๆ รูปจากพื้นผิวของสไลเดอร์เดียวกันจะถูกรวมเข้าด้วยกันโดยวิธีการรวมที่เหมาะสม รูปภาพที่ได้หลังการรวมจึงมีข้อมูลที่สมบูรณ์ขึ้นและให้ภาพที่มีคุณภาพชัดเจนขึ้น หลังจากนั้นจึงนำรูปผลลัพธ์ที่ได้ไปคำนวณค่ามุมการวางตัวของสไลเดอร์โดยการคำนวณที่มีความสัมพันธ์กับตัวงานมาตรฐานซึ่งเป็นตัวแทนของผลิตภัณฑ์นั้น ผลการทดลองพบว่า การรวมภาพสามารถนำมาใช้แก้ปัญหารูปที่วัดไม่ได้ให้สามารถวัดได้ ได้อย่างสมเหตุสมผล

โปรแกรม MATLAB ถูกนำมาใช้ดำเนินการทดลอง และการคำนวณเพื่อตรวจสอบผลการทดลอง

Thesis Title: Applications of Image Fusion using Wavelet Transform
in Slider Orientation Measurement

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ABSTRACT

The current pitch static attitude and roll static attitude measuring systems are of laser-based. A charge-coupled device (CCD) sensor installed in this system detects a reflected laser spot on the screen. The captured image of laser spot is then used to calculate the slider orientation. One of the concerned issues of laser spot captured image, is that this image sometimes has inadequate information for the measuring process. In general, the captured image should appear in a perfect circle for accurate measurements. However, for some reasons such as grooves on the slider, the obtained images have a shape of distorted circle. This results in measurement inaccuracy. Image fusion is the matching of solutions to solve the unclearness of captured images for measurements. The information of a set of images from the same surface will be combined by the appropriate fusion rule to obtain the better-fused image with pre-image processing. Then the resulting fused image will be calculated to obtain the value of slider orientation correlated to the position of the standard hard gauges. MATLAB has been used to prove the proposed concept.

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CHAPTER 1

INTRODUCTION AND LITERATURE REVIEW

1.1 Backgrounds and Problem Statement

A slider is an important component in hard disk drive (HDD). It is located at the tip of a head gimbal assembly (HGA) and responsible for reading/writing information from/to the media [1]. The orientation of the slider has crucial effect on the flying height that has to be kept as small as possible. Two important parameters of the slider orientation are pitch static attitude (PSA) and roll static attitude (RSA) [2]. These two parameters are being controlled in the hard disk drive process at head gimbal assembly (HGA) as well as at head stack assembly (HSA) level.

A non-contact angular measurement system of hard disk drive's sliders or a laser-based measurement system is currently used for quality assurance. The machine is composed of a laser source which generates laser beam and emits directly to the slider surface. The beam of laser is then reflected to the CCD camera. As a result, the position of the laser spot can be detected. The position of detected laser spot is then calculated to angle value by the some calculation of built in software [3].

The surfaces of sliders are of various coating materials, together with the effects of air bearing or other undesired contamination; they might in some cases result in light scattering as the laser beam reflected from them. Furthermore, the captured images sometimes do not appear in a perfect circle as they should for a perfect calculation. These factors are all make the measurements inaccurate. A replacement of a measuring system with higher performance could be one of a possible way to solve the aforementioned issues. As for example, a position sensitive detector (PSD) system has been replaced CCD as discussed in [3]. In [4], a new CMOS vision chip has been developed especially for laser spot position detection [4]. However, the cost of such solutions is very high. For this reason, this paper proposed another method in attempt to circumvent this difficulties using image processing.

An image has its own information and once the information is processes as digital data, it can be analyzed or managed as desired. This also applied to the captured laser

spot images. In general, the captured images from the same slider surface or HSA surface are likely to give the same measurement results. It is also assumed that more images contain more information compared to just only one image. It should be noted that the desired information is still obtained from the same source. Since each captured image might not hold all the essential information for measurement, therefore image fusion is the proposed solution which attempts to solve the unclearness of captured images for better measurement accuracy. Hence, the proposed technique will use a set of images instead of only one image for measurements. This set of images will be fused by using wavelet transform techniques. Image fusion by wavelet transform is widely used and has satisfied results in many fields such as medical, satellites, and material evidences [5-7]. Therefore this research will propose a method that makes use of this technique to solve the concern issue.

The paper is divided into two main parts; the first part is concerning image fusion using wavelet transform technique. Appropriate fusion rule or synthesis coefficient will be applied on to the set of images, and the fused image with more complete information will be obtained. To do so a pre- image processing is necessary. After the fused image is matched to the measurement system, the value will be calculated from the fused image to the angle value in the second part. Images of standard parts are also needed as a reference such that the value calculated from the synthesized images could be compared for more accurate measurement.

MATLAB is the chosen tool to develop and prove the proposed concept in this research. A basic data element in MATLAB is an array that does not require dimensioning. This is especially helpful to solve problems with matrix and vector formulations. An image is a set of matrices that define the pixels value of the image, such a grey scale value in black and white images, and Red, Green and Blue or Hue, Saturation and Intensity values in color images. This is totally matched to image processing analysis [11].

1.2 Objective

To study the feasibility of image fusion by using wavelet transformation technique to come over the concern issue of current laser based non-contact angular measurement system. Research will be in two parts, which is study in wavelet transformation technique to process the capture images to be adequate informative objects for measuring system. The other part is study in angle value transferring from the obtained image.

1.3 Scope of work

1.3.1 To get sufficient information images, which processed by the fusion technique using wavelet transform, suitable for angle measurement.

1.3.2 To transfer information from the obtained image to angle value or slider orientation. The verification of result will be done by comparison of angle value reading of current system and proposed system.

1.4 Expected Benefits

1.4.1 Being able to solve the issue of current slider orientation measuring system by proposed system of image fusion using wavelet transform technique.

1.4.2 Alternative lower cost choice to solve issue of current slider orientation measuring system instead of higher performance hardware replacement.

CHAPTER 2

THEORY

2.1 Laser based measurement system for slider orientation measurement

Manufacturing process nowadays has to guarantee PSA and RSA value before drive assembly. The stations to measure those orientation angle values are HGA process and HSA process. HSA also do measure at slider surface but in form of HGA stacking. This research aims to solve merely the issue on HSA station. A HSA laser-based measurement system consists of two laser sources for up and down surfaces. There are five cameras installed on the platform with 3-axes step motor system. The HSA will be fixed on the jig for measurement. The measurement is performed by capturing a picture of the laser beam reflection from the slider and sent to display on the computer screen. The software then calculates the measured PSA, RSA and Z from the obtained picture.

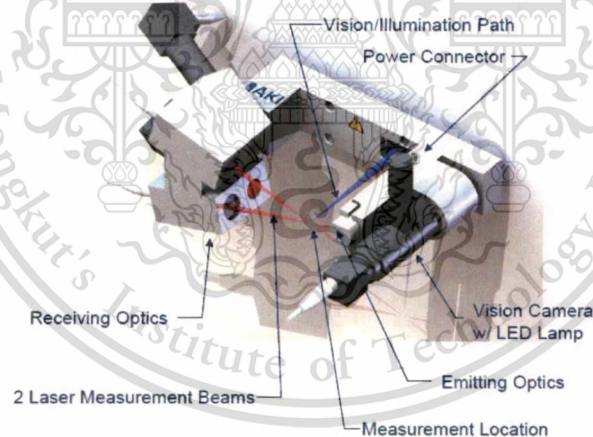


Figure 2.1 Laser-based measurement system for HSA orientation measurement

The cause of non-circular obtained image is from the slider itself or the deviation between slider lots which is not able to avoid them to go to the measurement process.

Image processing system is an alternative way, instead of replacement by higher performance devices, proposed in this research.

2.2 Wavelet Transform Introduction

Many of literatures proposed different image fusion techniques. The one widespread used method is wavelet based transformation which appropriate to perform fusion procedure because of 4 following reasons [5]

1. It is multiresolution approach well suited to manage the different image resolutions.
2. The discrete wavelet transform (DWT) allows the image decomposition in different kinds of coefficients preserving the image information.
3. Such coefficients coming from different images can be appropriately combined to obtain new coefficients, so that the information in the original images is collected appropriately.
4. Once the coefficients are merged, the final fused image is achieved through the inverse discrete wavelets transform (IDWT), where the information in the merged coefficients is also preserved.

The complex information such as image is able to be decomposed into forms at different positions and scales and subsequently reconstructed with high precision by using wavelets.

This research works on images of reflect of laser spot on CCD camera. The capture image is operated in grey scale mode or it can be called black-white photo. They consist of a splitting of the picture into a large number of small squares, called pixels. The camera associates a light intensity, 0 (completely white) to 256 (completely black) to each pixel. Then all information of all pixels together presents to be the picture. Thus, an image consists of a sequence of pairs of numbers, so called a numbering of the pixels together with light intensity presented in each pixel [6].

Therefore, discrete wavelet transform is able to apply for images decomposition then inverse transform to obtain new images after their coefficients are combined.

2.2.1 One-dimensional (1-D) discrete wavelet transform

Wavelet transform algorithm is an improved technique of Fourier transform. The major drawback of Fourier transform is its signal does not contain any local information. That is not suitable for non stationary signal analyzing so wavelet transform has been presented to overcome this issue. Wavelet may be seen as a complement to classical Fourier decomposition method. Suppose, a certain class of functions is given and we want to find 'simple functions' f_0, f_1, f_2, \dots , such that each

$$f(x) = \sum_{n=0}^{\infty} a_n f_n(x) \quad (2.1)$$

for some coefficients a_n .

A wavelet means a small wave approaching to represent the equation (2.1) for a large class of functions f [6]. The wavelet function is defined in reference [6][7] are

$$\psi_{j,k}(x) = 2^{\frac{j}{2}} \psi(2^j x - k) \quad (2.2)$$

And the scaling function is given by

$$\varphi_{j,k}(x) = 2^{\frac{j_0}{2}} \varphi(2^{j_0} x - k) \quad (2.3)$$

For all $j_0, k \in Z$ (where Z is the set of integers) and $\varphi_{j,k}(x) \in L_2(R)$ Here, k determines the position of $\varphi_{j,k}(x)$ along x axis, j_0 determines $\varphi_{j,k}(x)$'s width and $2^{j_0/2}$ controls its height or amplitude. Suppose $f(x) \in L_2(R)$ (where R is the set of real numbers and $L_2(R)$ denotes the set of measurable, square-integrable one-dimensional functions) relative to the wavelet function $\psi(x)$ and scaling function $\varphi(x)$.

If the function being expanded is a sequence of numbers (e.g., samples of a continuous function $f(x)$), the resulting coefficients are called the *discrete wavelet transform* (DWT) of $f(x)$.

The DWT transform pair is defined as following [7]

$$W_{\varphi}(j_0, k) = \frac{1}{\sqrt{M}} \sum_x f(x) \varphi_{j_0, k}(x), \quad (2.4)$$

$$W_{\psi}(j, k) = \frac{1}{\sqrt{M}} \sum_x f(x) \psi_{j, k}(x), \text{ for } j = j_0, \quad (2.5)$$

and

$$f(x) = \frac{1}{\sqrt{M}} \sum_k W_{\varphi}(j_0, k) \varphi_{j_0, k}(x) + \frac{1}{\sqrt{M}} \sum_{j=j_0}^{\infty} \sum_k W_{\psi}(j, k) \psi_{j, k}(x) \quad (2.6)$$

Where $f(x)$, $\varphi_{j_0, k}(x)$, and $\psi(x)$ are functions of the discrete variable $x = 0, 1, 2, \dots, M-1$. Normally, let $j_0 = 0$, and M (the length of the discrete samples of $f(x)$) is a power of 2 (i.e., $M = 2^j$) so that the summations are performed over $x = 0, 1, 2, \dots, M-1$, $j = 0, 1, 2, \dots, j-1$, and $k = 0, 1, 2, \dots, 2^j-1$.

The transform itself is composed of M coefficients, the minimum scale is 0, and the maximum scale is $j-1$. The coefficients defined in Equation (2.4) and (2.5) are usually called *approximation* and *detail coefficients*, respectively. The process of computing these coefficients is referred to as *DWT analysis*. On the other hand, *DWT synthesis* (or inverse DWT) is defined by Equation (2.6) to reconstruct $f(x)$ with these coefficients. Finally, it should be noted that Equation (2.4) through (2.6) are valid for orthonormal bases and tight frames alone [7][8].

The most basic wavelet transform is the Haar transform described by Alfred Haar in 1910. It serves as the prototypical wavelet transform. Some limitations of the Haar transform is resolved by the newer version of wavelet transform (in 1998 by Ingrid Daubechies) [9]. The basis of the Haar transform is a two-point average and difference operations which the basis functions are given as following equation (2.7) and (2.8) [10]

$$\varphi_{2k}[n] = \begin{cases} 1/\sqrt{2}, & n=2k, 2k+1 \\ 0, & \text{otherwise} \end{cases}, \quad (2.7)$$

and

$$\varphi_{2k+1}[n] = \begin{cases} 1/\sqrt{2}, & n=2k \\ -1/\sqrt{2}, & n=2k+1 \\ 0, & \text{otherwise} \end{cases} \quad (2.8)$$

This follows that

$$\varphi_{2k}[n] = \varphi_0[n-2k], \quad (2.9)$$

and

$$\varphi_{2k+1}[n] = \varphi_1[n-2k] \quad (2.10)$$

Assume that the eight-point signal $x(n)$ is decomposed into two four-point signals by Haar transform. The basic concept of Haar transform is the signal will be decomposed to be 2 sets of signals.

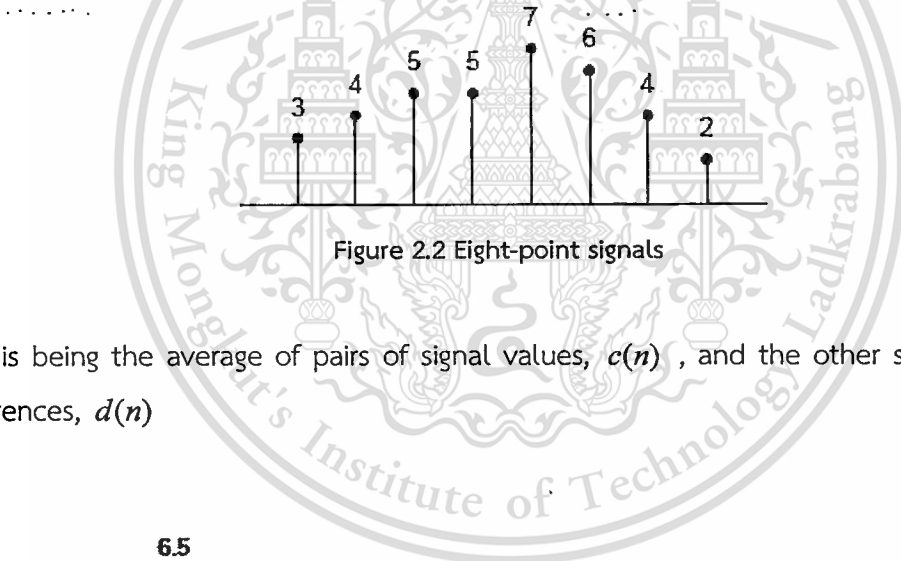


Figure 2.2 Eight-point signals

One is being the average of pairs of signal values, $c(n)$, and the other signal is their differences, $d(n)$

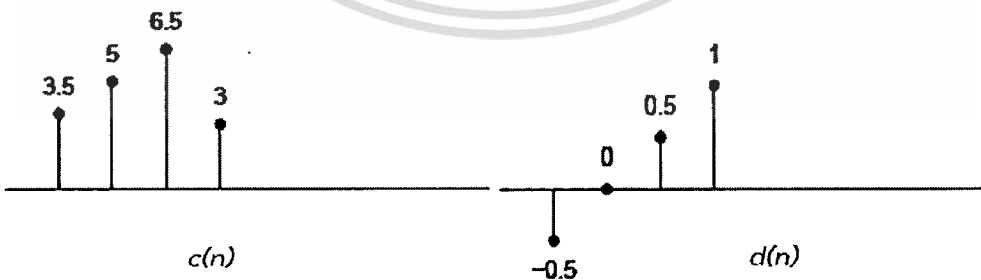


Figure 2.3 Left $c(n)$ is average of pairs of signal values,
Right $d(n)$ is average of different of signal values.

This decomposition can be written as [9]

$$c(n) = 0.5 x(2n) + 0.5 x(2n+1) \quad (2.11)$$

$$d(n) = 0.5 x(2n) - 0.5 x(2n+1) \quad (2.12)$$

The original signal $x(n)$ can be reconstituted or reversed from the two shorter signals by using

$$y(2n) = c(n) + d(n) \quad (2.13)$$

$$y(2n+1) = c(n) - d(n) \quad (2.14)$$

The Basic Haar decomposition is shown as the following block diagram

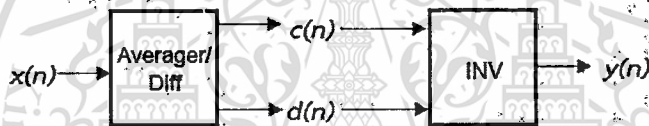


Figure 2.4 Block diagram shows basic concept of Haar transform

When the simple signal decomposition procedure is repeated a number of times, the Haar transform is expressed. In case of example eight-point signal, the decomposition can be repeated up to three times thus the Haar transform can be shown in block diagram as in Figure 2.5

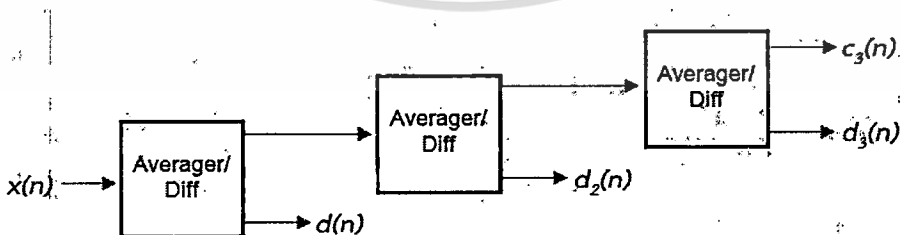


Figure 2.5 Block diagram shows example Haar transform of eight-point signal

The eight-point signal $x(n)$ is represented to be the set of four output signals produced by three-level operation of The Haar wavelet decomposition. The four signals have lengths 1, 1, 2, and 4 respectively.

$$\begin{aligned} c_3 &= [4.5] \\ d_3 &= [-0.25] \\ d_2 &= [-0.75, 1.75] \\ d &= [-0.5, 0, 0.5, 1] \end{aligned} \quad (2.15)$$

These four values are called the 'wavelet representation' of the signal $x(n)$.

In 1988 Daubechies constructed a family of easily implemented and easily invertible wavelet transforms that generalize the Haar transform. The only difference is that the decomposition is replaced by a new one; Haar transform uses average and difference. The new decomposition for the simplest Daubechies wavelet transforms is shown as [9]

$$\begin{aligned} c(n) &= h_0x(2n) + h_1x(2n + 1) + h_2x(2n + 2) + h_3x(2n + 3) \\ d(n) &= h_3x(2n) - h_2x(2n + 1) + h_1x(2n + 2) - h_0x(2n + 3) \end{aligned} \quad (2.16)$$

And the inverted transforms are expressed by

$$\begin{aligned} y(2n) &= h_0c(n) + h_2c(n-1) + h_3d(n) + h_1d(n-1) \\ y(2n+1) &= h_1c(n) + h_3c(n-1) - h_2d(n) - h_0d(n-1) \end{aligned} \quad (2.17)$$

Where the multiply are

$$h_0 = \frac{1+\sqrt{3}}{4\sqrt{2}}, \quad h_1 = \frac{3+\sqrt{3}}{4\sqrt{2}}, \quad h_2 = \frac{3-\sqrt{3}}{4\sqrt{2}}, \quad h_3 = \frac{1-\sqrt{3}}{4\sqrt{2}} \quad (2.18)$$

When the original signal is a linear signal, $x(n) = an + b$, the output $d(n)$ will be zero and the output signal $c(n)$ will be linear.

This Daubechies transform properties contrast to Haar expression that will not show any zero outputs of linear signal decomposition. Thus, a sparse representation for piecewise-linear signals is stated by the wavelet transform using the Daubechies decomposition [9].

The wavelet transform can also be considered as a filter bank, and then the wavelet transforming a signal is regarded as passing the signal through this filter bank. The outputs of the different filter stages are the wavelet and scaling function transform coefficients.

Filter bank is the building block of discrete-time wavelet transform. Two-channel filter bank for one dimensional signal is shown as block diagram below

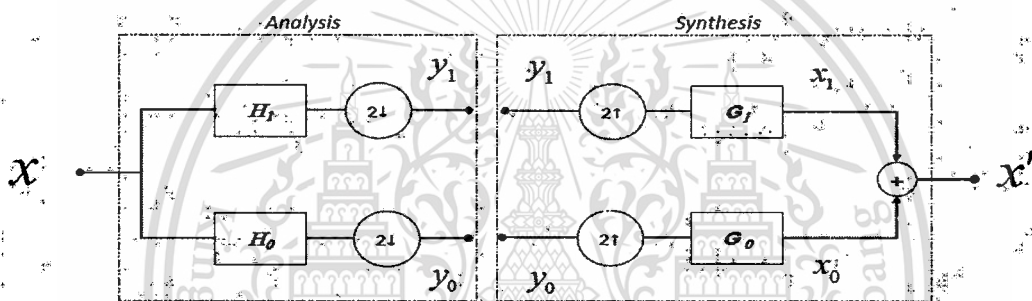


Figure 2.6 Two-channel filter bank for 1-D signal

For the perfect reconstruction $\hat{x} = x$, the filters must meet conditions

$$\begin{aligned} g_0[n] &= -h_0[-n] \\ g_1[n] &= h_1[-n] \end{aligned} \quad (2.19)$$

Thus, if one filter is lowpass, the other one will be highpass and filter bank also should be orthogonal to have orthogonal wavelets. The orthogonal condition for one dimensional two channel filter bank is

$$g_1[n] = (-1)^n g_0[-n+1] \quad (2.20)$$

Consider to the discrete-time Haar filters, the lowpass is the average of two neighboring samples, while the highpass is their difference. The corresponding orthogonal filter bank has filters $g_0[n]=[1/\sqrt{2},1/\sqrt{2}]$ and $g_1[n]=[1/\sqrt{2},-1/\sqrt{2}]$ which are the basis functions of the discrete-time Haar expansion. Related to Haar scaling function the filters can be stated as

$$h_0[n] = \begin{cases} 1/\sqrt{2}, & n=0,1 \\ 0, & \text{otherwise} \end{cases} \quad (2.21)$$

$$h_1[n] = \begin{cases} 1/\sqrt{2}, & n=0 \\ -1/\sqrt{2}, & n=-1 \\ 0, & \text{otherwise} \end{cases} \quad (2.22)$$

While (2.21) is lowpass filter and (2.22) is highpass filter

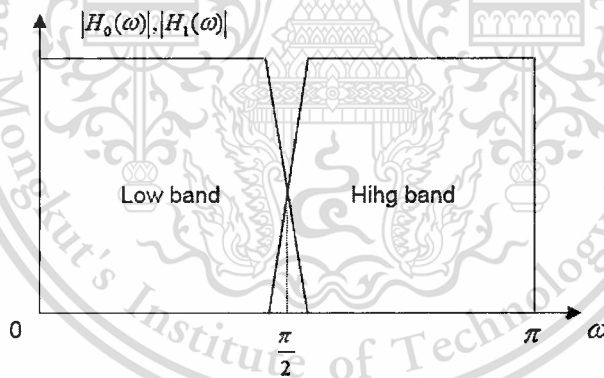


Figure 2.7 1-D signal with Two-channel filter banks

Then the lowpass output is

$$y_0[k] = h_0[n] * x[n] \Big|_{n=2k} = \sum_{l \in \mathbb{Z}} h_0[l] x[2k-l] = \frac{1}{\sqrt{2}} x[2k] + \frac{1}{\sqrt{2}} x[2k+1] \quad (2.23)$$

And the highpass output is

$$y_1[k] = h_1[n] * x[n] \Big|_{n=2k} = \sum_{l \in \mathbb{Z}} h_1[l] x[2k-l] = \frac{1}{\sqrt{2}} x[2k] - \frac{1}{\sqrt{2}} x[2k+1] \quad (2.24)$$

Since $y_0[k] = x[2k]$ and $y_1[k] = x[2k+1]$, the filter bank implements Haar expansion. It is important to note that the impulse responses of the analysis filters are time-reversed versions of the based functions $h_0[n] = \varphi_0[-n]$ and $h_1[n] = \varphi_1[-n]$ since convolution is an inner product involving time reversal [10]. Discrete wavelet can be constructed via iterated filter banks as block diagram in Figure 2.8 and Figure 2.9

An orthogonal wavelet transform will be expressed when $h_i[n]$ is an orthogonal filter and $g_i[n] = h_i[-n]$.

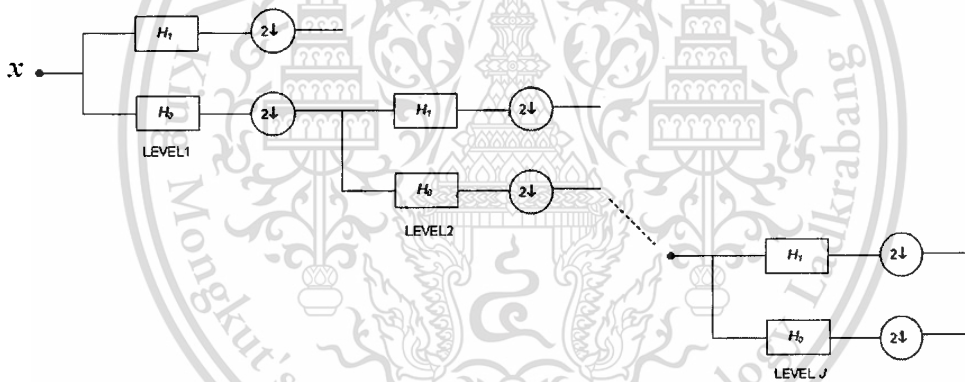


Figure 2.8 Analysis phase of discrete wavelet via iterative filter banks

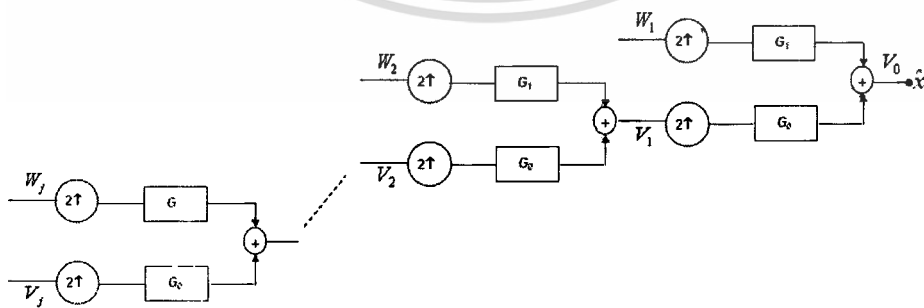


Figure 2.9 Synthesis phase of discrete wavelet via iterative filter banks

The two-channel filter banks in aforementioned sections have the property to split the signal into two lower-resolution output. One was a lowpass or coarse resolution version, and the other was a highpass version of the input. Then, the lowpass or coarse version is applied by decomposition repeatedly. This leads to a hierarchy of resolutions, also so called a multiresolution decomposition. V_0 is considered as the space of all square-summable sequences if $V_0 = l_2\{\mathbb{Z}\}$ then a multiresolution analysis consists of a sequence of embedded closed spaces $V_j \subset \dots \subset V_2 \subset V_1 \subset V_0$. It is obvious that

$$\bigcup_{j=0}^J V_j = V_0 = l_2\{\mathbb{Z}\} \quad (2.25)$$

The orthogonal complement of V_{j+1} in V_j will be denoted by W_{j+1} , and thus $V_j = V_{j+1} \oplus W_{j+1}$, with $V_{j+1} \perp W_{j+1}$, where \oplus denotes the direction sum. If V_0 is split and repeat splitting on V_1, V_2, \dots, V_{j-1} , then V_0 can be decomposed in the following manner by simply iterating the decomposition J times. V_j will be called *approximation spaces* and W_j will be call *detail spaces*[10].

$$V_0 = W_1 \oplus W_2 \oplus \dots \oplus W_j \oplus V_j \quad (2.26)$$

Then, the process of building up the signal is intuitively very clear — one starts with its lower resolution version belonging to V_j , and adds up the details until the final resolution is reached.

2.2.2 The two-dimensional (2-D) wavelet transform implementation for multi resolution decomposition images

An easy way to construct two-dimensional wavelets is to use tensor products of their one-dimensional counterparts. This results in one scaling function and three different “mother” wavelets [10]. First a 1-D filter bank will be applied to the rows of the image then the same transform will be applied to the columns of each channel of the result. Therefore, 3 highpass channels are obtained corresponding to vertical, horizontal, and diagonal, and one approximation image.

$$\begin{aligned} \varphi_{LL}(x,y) &= \varphi(x)\varphi(y), & \psi_{LH}(x,y) &= \varphi(x)\psi(y), \\ \psi_{HL}(x,y) &= \psi(x)\varphi(y), & \psi_{HH}(x,y) &= \psi(x)\psi(y), \end{aligned} \quad (2.27)$$

... The diagram of two dimensional analysis filter banks is shown in Figure 2.10

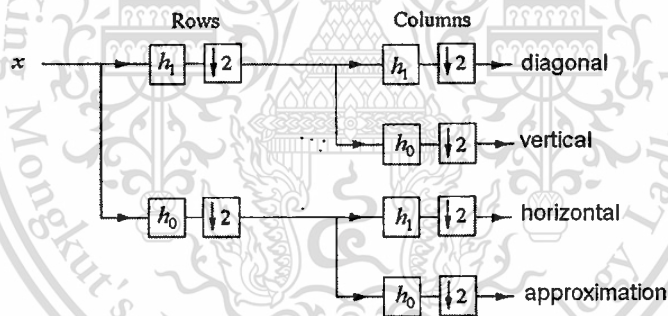


Figure 2.10 Two dimension analysis filter banks

When an image $I(x,y)$ is operated by a filtering and down-sampling horizontally using the 1-D lowpass filter L and highpass filter H to each row, the coefficient matrices $I_L(x,y)$ and $I_H(x,y)$ are produced. Vertically filtering and down-sampling, using the lowpass and highpass filters L and H are applied after to each column in $I_L(x,y)$ and $I_H(x,y)$. Then four subimages $I_{LL}(x,y)$, $I_{LH}(x,y)$, $I_{HL}(x,y)$, and $I_{HH}(x,y)$ will be created. $I_{LL}(x,y)$ is a smooth subimage corresponding to the low-frequency band of the multi-scale image decomposition. It represents the coarse approximation of $I(x,y)$

While $I_{LH}(x, y)$, $I_{HL}(x, y)$, and $I_{HH}(x, y)$ are detail subimages, which represent the horizontal, vertical and diagonal directions of the image $I(x, y)$ [5].

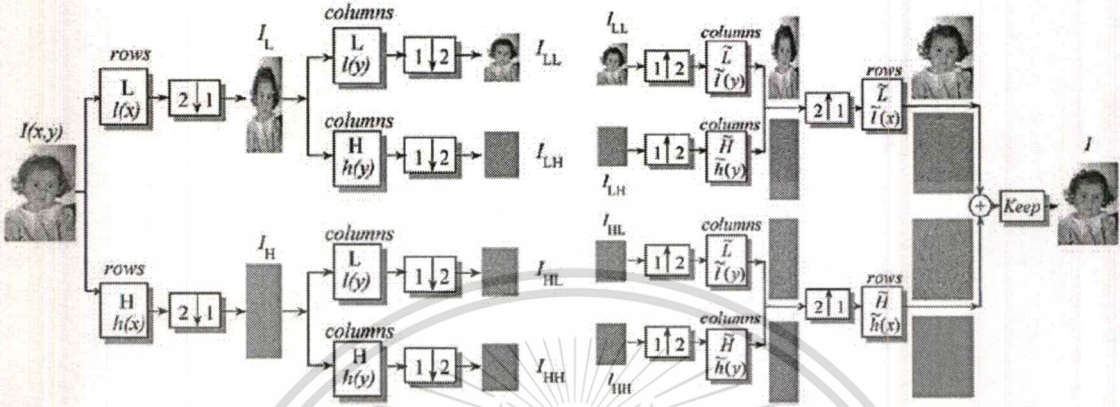


Figure 2.11 One stage of 2-D DWT multiresolution image decomposition, Right details image decomposition; Left details image reconstruction.

[G. Pajares, J. Manuel de la Cruz] [5]

Let $I(x, y)$ be the original image size $M \times N$, $l(i)$ the analysis lowpass coefficients of a specific wavelet basis, $i = 0, 1, 2, \dots, N_l - 1$, where N_l is the support length of the filter L , $h(j)$ the analysis highpass coefficients of a specific wavelet basis, $j = 0, 1, 2, \dots, N_h - 1$, where N_h is the support length of the filter H , Then

$$\begin{aligned} I_L(x, y) &= \frac{1}{N_l} \sum_{i=0}^{N_l-1} l(i) \square_I((2x+i) \bmod M, y), I_H(x, y) \\ &= \frac{1}{N_h} \sum_{j=0}^{N_h-1} h(j) \square_I((2x+j) \bmod M, y) \end{aligned} \quad (2.28)$$

for $x = 0, 1, 2, \dots, (M/2) - 1$ and $y = 0, 1, 2, \dots, N - 1$

$$\begin{aligned} I_{LL}(x, y) &= \frac{1}{N_l} \sum_{i=0}^{N_l-1} l(i) \square_L(x, (2y+i) \bmod N), \\ I_{LH}(x, y) &= \frac{1}{N_h} \sum_{j=0}^{N_h-1} h(j) \square_L(x, (2y+j) \bmod N) \end{aligned} \quad (2.29)$$

$$\begin{aligned}
 I_{HL}(x, y) &= \frac{1}{N_l} \sum_{i=0}^{N_l-1} l(i) \square_{H_l}(x, (2y+i) \bmod N), \\
 I_{HH}(x, y) &= \frac{1}{N_h} \sum_{j=0}^{N_h-1} h(j) \square_{H_h}(x, (2y+j) \bmod N)
 \end{aligned}
 \tag{2.30}$$

for $x = 0, 1, 2, \dots, (M/2)-1$ and $y = 0, 1, 2, \dots, N-1$

The 2-D inverted wavelet transform analysis is described as the followings [5]

Let $R \times C$ be the size of a subimage to restore, $\tilde{l}(i)$ the synthesis lowpass coefficients of a specific wavelet basis, $i = 0, 1, 2, \dots, N_l$, where N_l is the support length of filter \tilde{L} , $\tilde{h}(j)$ the synthesis highpass coefficients of a specific wavelet basis, $i = 0, 1, 2, \dots, N_h$, where N_h is the support length of the filter \tilde{H} .

$I_{LL}(x, y)$ is synthesized by upsampling by the factor of 2 along the y-axis and filter with lowpass filter \tilde{L} . Let $I_{sy}(x, 2y) = I_{LL}(x, y)$ and $I_{sy}(x, 2y+1) = 0$, for $x = 0, 1, 2, \dots, R-1$ and $y = 0, 1, 2, \dots, C-1$ then

$$I_{sy}^{-1}(x, y) = \frac{1}{N_l} \sum_{i=0}^{N_l-1} \tilde{l}(i) I_{sy}(x, (y+i) \bmod 2C)
 \tag{2.31}$$

After that upsample I_{sy}^{-1} by a factor of 2 along the x-axis and filter with lowpass filter \tilde{L} . Let $I_{sx}^{-1}(2x, y) = I_{sy}^{-1}(x, y)$ and $I_{sx}^{-1}(2x+1, y) = 0$, for $x = 0, 1, 2, \dots, R-1$ and $y = 0, 1, 2, \dots, C-1$

$$I_s(x, y) = \frac{1}{N_l} \sum_{i=0}^{N_l-1} \tilde{l}(i) I_{sx}^{-1}((x+i) \bmod 2R, y)
 \tag{2.32}$$

$I_{LH}(x, y)$ is also synthesized by upsampling by the factor of 2 along the y-axis but filter with the highpass filter \tilde{H} . Let $I_{Hy}(x, 2y) = I_{LH}(x, y)$ and $I_{Hy}(x, 2y+1) = 0$, for $x = 0, 1, 2, \dots, R-1$ and $y = 0, 1, 2, \dots, C-1$ then

$$I_{Hy}^{-1}(x, y) = \frac{1}{N_h} \sum_{j=0}^{N_h-1} \tilde{h}(j) I_{Hy}(x, (y+j) \bmod 2C)
 \tag{2.33}$$

After that upsample I_{hy}^{-1} by a factor of 2 along the x-axis and filter with lowpass filter \tilde{L} . Let $I_{hx}^{-1}(2x, y) = I_{hy}^{-1}(x, y)$ and $I_{hx}^{-1}(2x+1, y) = 0$, for $x = 0, 1, 2, \dots, R-1$ and $y = 0, 1, 2, \dots, C-1$ then

$$I_H(x, y) = \frac{1}{N_I} \sum_{i=0}^{N_I-1} \tilde{I}(i) I_{hx}^{-1}((x+1) \bmod 2R, y) \quad (2.34)$$

By the same procedure as $I_{LH}(x, y)$ the vertical and diagonal detail subimages $I_{HL}(x, y)$ and $I_{HH}(x, y)$ can be reconstructed with corresponding filtering operations. (\tilde{H} in both row and column for I_{HH} , \tilde{L} in column followed by \tilde{H} in row)

Two instructive examples of analysis and synthesis are stated as the following diagram.

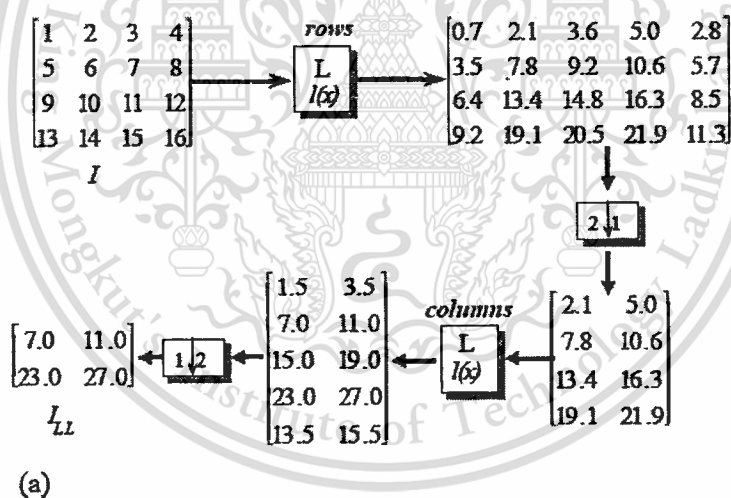


Figure 2.12 Instructive examples: (a) analysis, [G. Pajares, J. Manuel de la Cruz] [5]

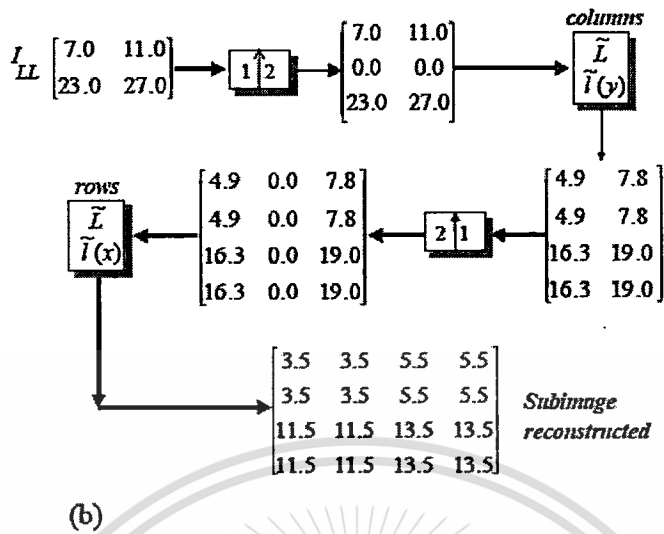


Figure 2.12 Instructive examples: (b) synthesis. (cont.) [G. Pajares, J. Manuel de la Cruz] [5]

2.3 Image fusion using wavelet transform

Image fusion is the technique to combine information from two or a set of images then the fused image should have more complete and useful information. Image fusion using wavelet transform is one wide spread fusion technique. The concept of image fusion using wavelet is governed by equation (2.35)

$$I(x, y) = W^{-1} \left\{ F \left[W \langle I_1(x, y) \rangle, W \langle I_2(x, y) \rangle \right] \right\} \tag{2.35}$$

The two dimensional (2D) wavelet transforms W of the two registered input images $I_1(x, y)$ and $I_2(x, y)$ are operated by filtering and down-sampling process as aforementioned procedures. Then Fused strategy F is used to combine their coefficient matrices. The result image $I(x, y)$ is obtained from the inverse wavelet transformation, W^{-1} . The result fused image $I(x, y)$ can then be used for further purpose.

Figure 2.13 illustrates over view procedure of wavelet based image fusion.

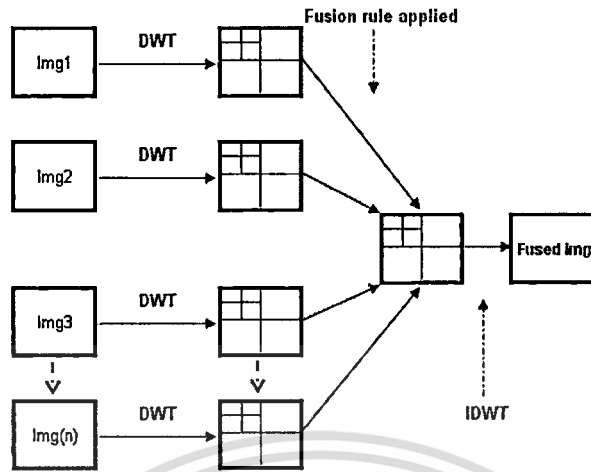


Figure 2.13 Wavelet based image fusion diagram

Fusion process should conserve all important analysis information in the image and should not introduce any artifacts or inconsistencies while suppressing the undesirable characteristics like noise and other irrelevant details [12].

2.3.1 Fusion of DWT coefficient matrices

A fusion rule or fusion strategy will be defined suitably to each case depend on the purpose of applications. Some procedures such as coefficient grouping and coefficient combining technique, principal component analysis (PCA) and morphological processing, and pixel based maximum selection algorithm are presented in Ref.[5][7][12] respectively. The algorithm in used in this research is the basic method provided in MATLAB which are 'max', 'min', 'mean', 'rand', 'img1', and 'img2'. Let A is the coefficient matrices from 'image A', B is the coefficient matrices from 'image B' and C is the combined matrices between matrices 'A' and 'B' then these basic algorithm describe as the following;

$$'max' : C_{i,j} = \begin{cases} A_{i,j} , & abs(A) \geq abs(B) \\ B_{i,j} , & abs(A) < abs(B) \end{cases} \quad (2.36)$$

$$\text{'min'} : C_{i,j} = \begin{cases} A_{i,j}, & \text{abs}(A) \leq \text{abs}(B) \\ B_{i,j}, & \text{abs}(A) > \text{abs}(B) \end{cases} \quad (2.37)$$

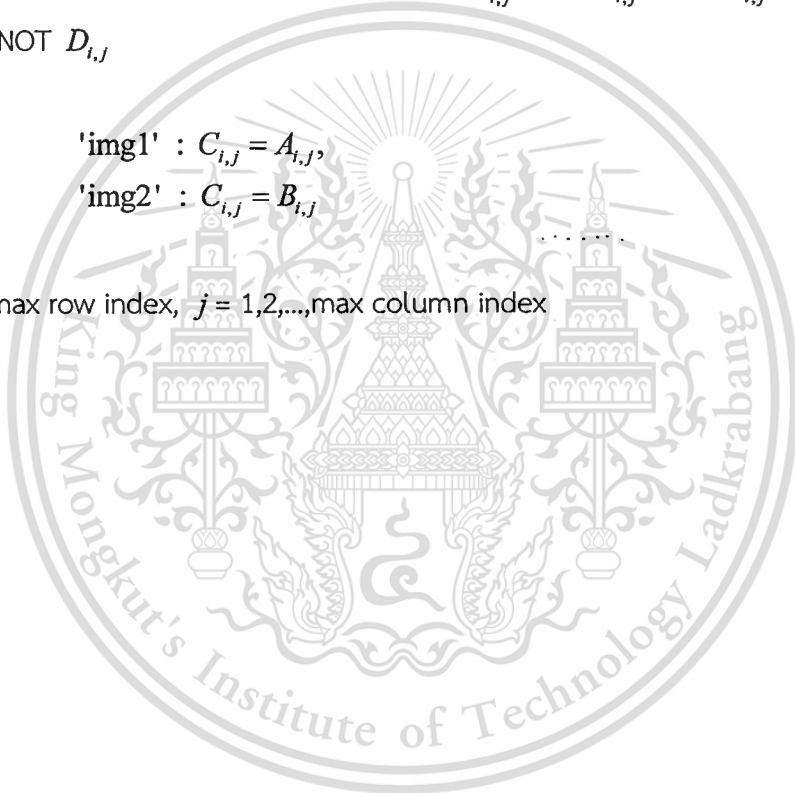
$$\text{'mean'} : C_{i,j} = \frac{(A_{i,j} + B_{i,j})}{2} \quad (2.38)$$

$$\text{'rand'} : C_{i,j} = A_{i,j}(D_{i,j}) + B_{i,j}(\sim D_{i,j}); \quad (2.39)$$

While $D_{i,j}$ is a Boolean random matrix which size $D_{i,j} = \text{size } A_{i,j} = \text{size } B_{i,j}$,
 $\sim D_{i,j}$ is NOT $D_{i,j}$

$$\begin{aligned} \text{'img1'} : C_{i,j} &= A_{i,j}, \\ \text{'img2'} : C_{i,j} &= B_{i,j} \end{aligned} \quad (2.40)$$

for $i = 1, 2, \dots, \text{max row index}$, $j = 1, 2, \dots, \text{max column index}$



CHAPTER 3

RESEARCH METHODOLOGY

This research purposes the alternative ways to come over the immeasurable issue of the currently in used laser based measurement system. The sliders have multicoated material on the top surface and also complicated grooves so that might lead to light scattering effect. Then the image on CCD sensor has insufficient information to calculate the angle value of the sliders.

Image processing is purposed in this research instead of high performance hardware replacement. Moving the set of camera both CCD sensors and laser units by small steps, slider is still mount at the same position, will get multi images with the same angle information as shown in Figure 3.1. The same slider and same CCD camera but different area to reflect the laser beam could be considered as single sensor system which captures the real world as a sequence of images [11]. The redundant information from a set of images will be used for further angle value calculation.

Image fusion using wavelet transform technique is performed to get the intersected information from captured images. The satisfied obtained image is further calculated its center position then transferred to angle value or PSA and RSA of the slider which illustrated in Figure 3.1. Image preprocessing is also applied in the process. The calculated angle values by MATLAB are compared to the reading values from the currently in used machine.

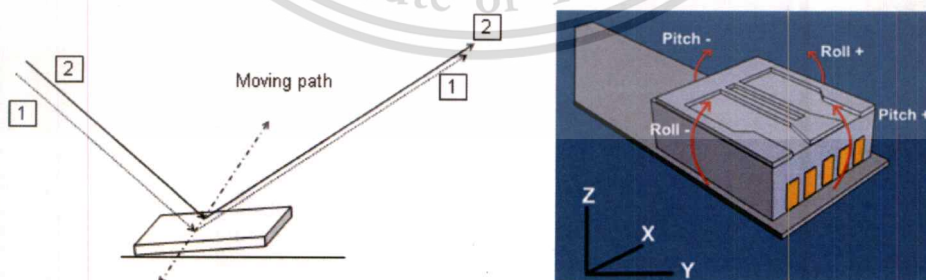


Figure 3.1 Left illustrated multi images capture procedure,
Right shows definition of angle value of a slider.

There are two main parts in this research. The first part is concerning image fusion using wavelet transform technique. Appropriate fusion rule or synthesis coefficient matrix will be applied on to the set of images, and the fused image with more complete information will be obtained. After the fused image is matched to the measurement system, the value will be calculated from the fused image to the angle value in the second part. Images of standard parts are also needed as a reference. The getting of multi input images from moving a set of camera and laser unit by small steps will not be detailed in this research. After multi images have been captured, the overall research procedures are as the following

1. Image preprocessing
2. Image decomposition by Discrete Wavelet Transform
3. Image fusion or coefficients matrices merging by desired rule
4. Image synthesizing by Inverted Discrete Wavelet Transform
5. Finding image centroids
6. Angle value Transferring

Items 5 and 6 are in the second part of the research, the others are in the first part.

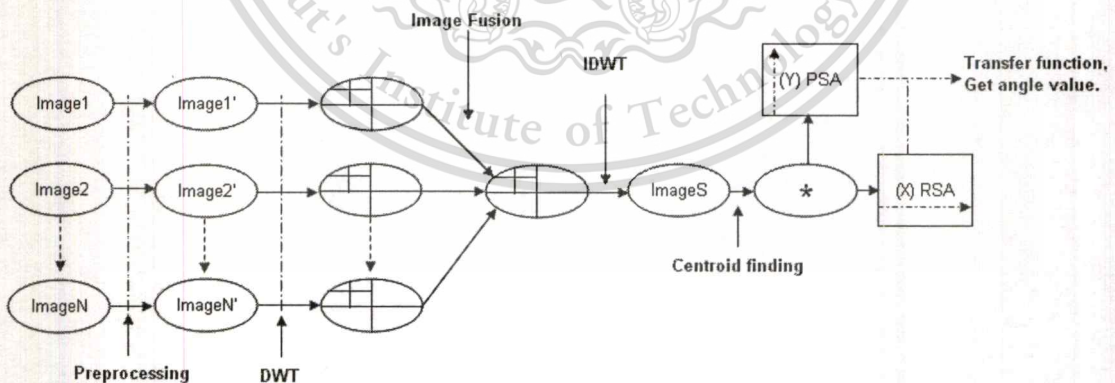


Figure 3.2 Diagram illustrates overall procedures of the research.

3.1 Part one : Image fusion using wavelet transform

The proposed methodology in this research will be applied when an obtained image has insufficient information to measure angle value. Then the first process step is to get at least another input image to combine and get more completed image suit for the measurement. More images can be captured by moving a set of camera and CCD screen as shown in Figure 2.1. Images are captured from the different area of the slider but the angle information is the same. In some cases the captured image from the CCD camera are not perfect. This can be seen as light scatter or distorted circle in Figure 3.3 (b)-(d).

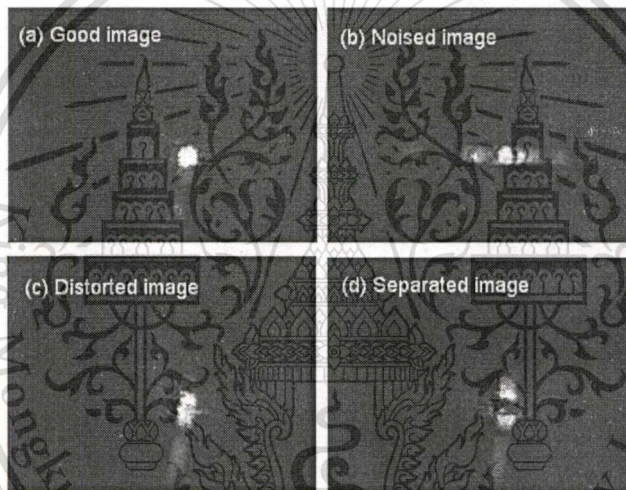


Figure 3.3 Input images from CCD camera.

(a) Good image, (b) Noised image, (c) Distorted image, (d) Separated image.

3.1.1 Image preprocessing

In order to prepare the images for the wavelet decomposition, image preprocessing is applied. The first process applied to the image is image registration which is to get the same reference points between the two images that will result in the good result of image fusion. However, actually the images are collected from the same CCD screen or computer screen of the current system so they are precise in the same position already.

The original image size is 1280x1024 pixels, it is most of the dark area that could be reasonable considered as unnecessary pixels and cause of high processing time as well. Thus they are cropped to 300x200 pixels in this experiment for faster wavelet transform process.

The Second step is changing class of image to image in double class. Image of class variables is also impact to the fusion process and display process. In MATLAB function image is read to data in class of integer which will contain 0 to 255 for 8 bits gray scale image (2^8). Input image in this research is converted to the class of double before fusion process for 2 main reasons, one is the double precision is higher than integer precision. Double class is real number and convert from integer by dividing value in each pixel by 255 (The maximum value of gray integer image). The other reason is the default display range of the grayscale image of class single or double is [0 1]. Then the double class is more suitable to process in the experiment. When 2 mentioned steps are completed then images are ready for image decomposition by wavelet transform.

The next steps are applied for the purpose of roundness finding. The third step is image binarization or convert image to binary image that is only bring the readiness to image Morphology. Removing the open area and fills holes in the binary image will be done, a hole is a set of background pixels that cannot be reached by filling in the background from the edge of the image. A dilation and erosion method is also applied in the step of image Morphology. Then the roundness can be calculated by the morphological grayscale reconstruction algorithm [15] in the built in script in MATLAB software. Briefly, the boundary will be calculated by the difference value between the pixels then the area also be estimates by the inner boundary pixels. The roundness value of each image will be kept for further fusion rule.

3.1.2 Image decomposition by Discrete Wavelet Transform

The two dimensional discrete wavelet transform horizontally filters and down-samples using the 1-D low pass filter L and high pass filter H to each row of the image I . The coefficient matrices have then been produced. After that, following by vertically down-sampling using low pass and high pass filters L and H to each column and the

sub-images have been produced [14]. 2 level wavelet decomposition has been used in this experiment so the approximate coefficient matrix is repeating the procedure again.

Then at the end of 2-level wavelet decomposition, 7 coefficient matrices have been produced. There are 1 approximate coefficient matrix, 3 detail coefficient matrices of level1 decomposition and 3 detail coefficient matrices of level2 decomposition. The process has been repeated on all input images before the coefficient matrices will be merged by the proposed fusion rule in the next step. One stage of 2D-DWT multi resolution image decomposition is shown in the Figure 3.4 and 7 coefficient matrices have been shown is the two-dimensional wavelet tree in the Figure 3.5

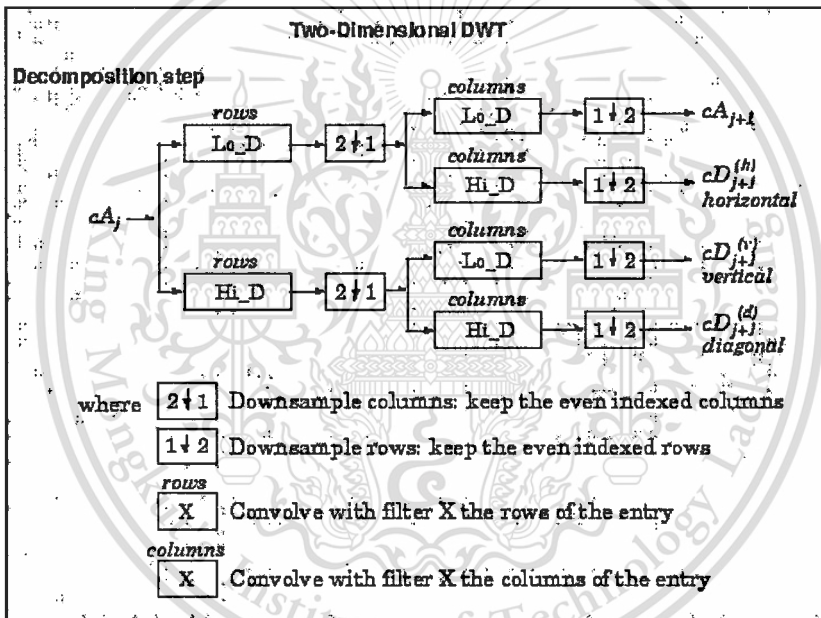


Figure 3.4 One stage of 2D DWT multi resolution image decomposition.

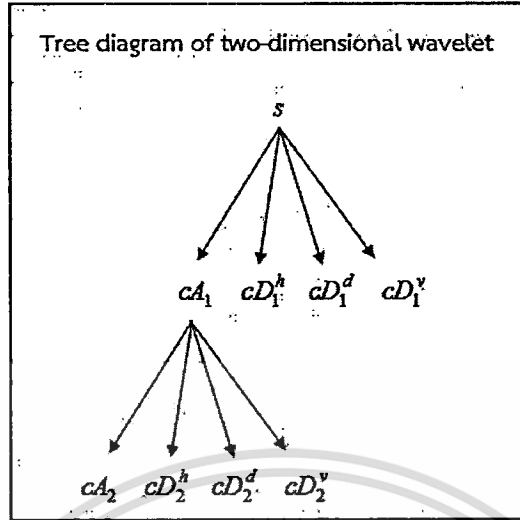


Figure 3.5 the two-dimensional wavelet tree

3.1.3 Image fusion or coefficients matrices merging by desired rule

The purpose of fusion is to make the final image as circular as possible before measuring its angle values. The circular or roundness comparison is desired for the fused strategy. Roundness of laser spot is defined by equation (3.1)

$$\text{Roundness} = \frac{4 \times \pi \times \text{area}}{(\text{perimeter})^2} \quad (3.1)$$

Roundness is equal to one only for a circle and it is less than one for any other shape. The multi value in case of separated input image will be averaged. Then the roundness of each image has been weighted to all coefficient matrices of each images follows equation (3.2) and (3.3)

$$I' = \sum_{i=1}^n w_i C_i \quad (3.2)$$

$$w_i = \frac{R_i}{\sum_{j=1}^n R_j} \quad (3.3)$$

Where I' is fused image, w_i is a weight calculated for coefficient matrix of each input image, C_i is a coefficient matrix of each input image, R_i is a roundness of each input image

The example of roundness is shown in Figure 3.6. In Figure 3.6 the roundness of (a) is 0.90 which is the closest to one, (b) is multi value so will be ignored and not choose to be the template, (c) is 0.85 which closer to one than (d) at 0.65 so the template of fusion will be prior to (a), (c) and (d) respectively. The weighted coefficient matrices of 2 images has been shown in Figure 3.7



Figure 3.6 Defined Roundness of images

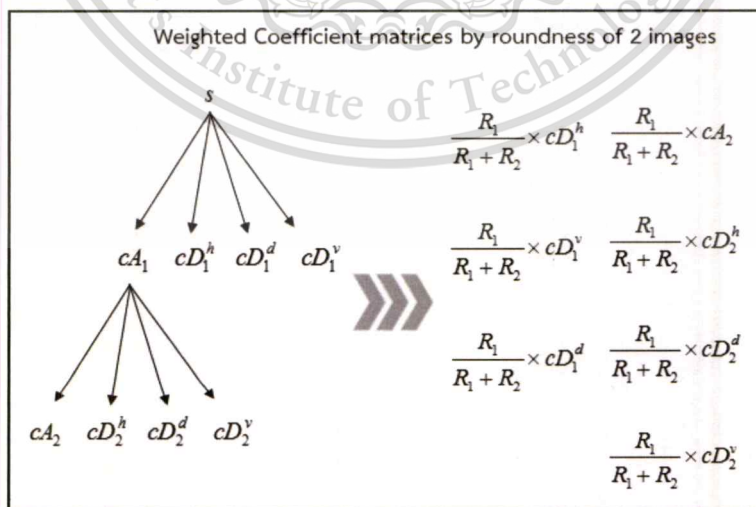


Figure 3.7 2-level decomposition coefficient matrices weighted by roundness of 2 images

3.1.4 Image synthesizing by Inverted Discrete Wavelet Transform

After coefficient matrices have been weighted by the roundness of each image, 7 weighted coefficient matrices have been produced. There are 1 approximated coefficient matrix, 1 level1 horizontal detail, 1 level1 vertical detail, 1 level1 diagonal detail matrix and level2 horizontal, vertical and diagonal detail matrices respectively. Then Inverted Discrete Wavelet Transform (IDWT) will be applied as shown in Figure 3.8. The process has been done as the steps detailed in Figure 3.9. The up sampling method is using zero padding which is the default calculation in MATLAB. Then the result image has been obtained. Post image process, binarization which use Otsu's method [13], noise elimination, erosion and dilation processed by the morphological grayscale reconstruction algorithm [15], are also performed appropriately to the fused image.

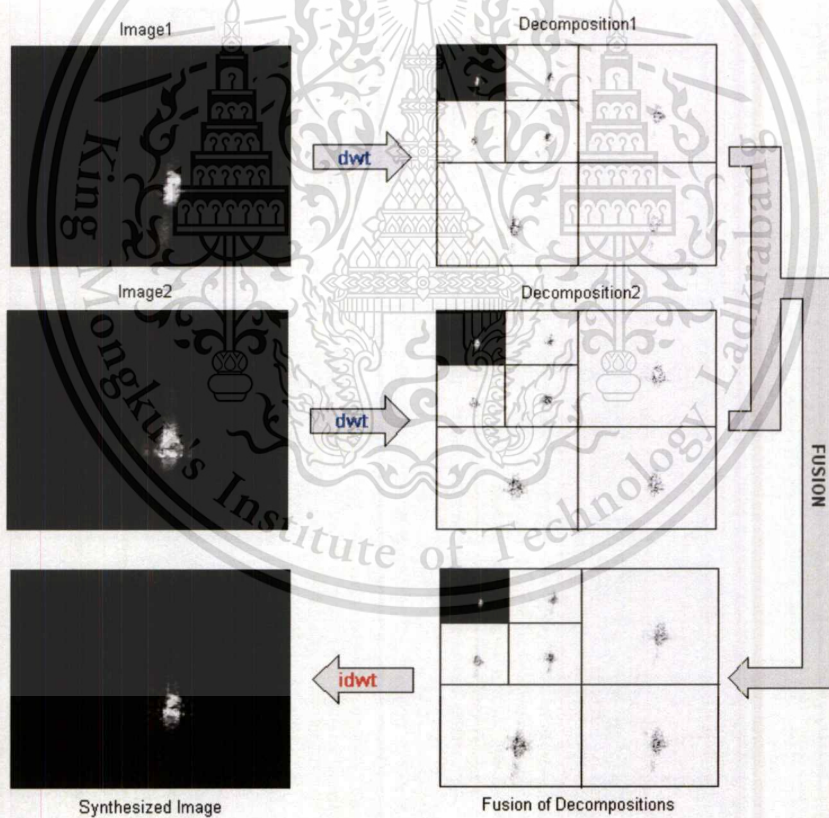


Figure 3.8 Image synthesis by invert discrete wavelet transform

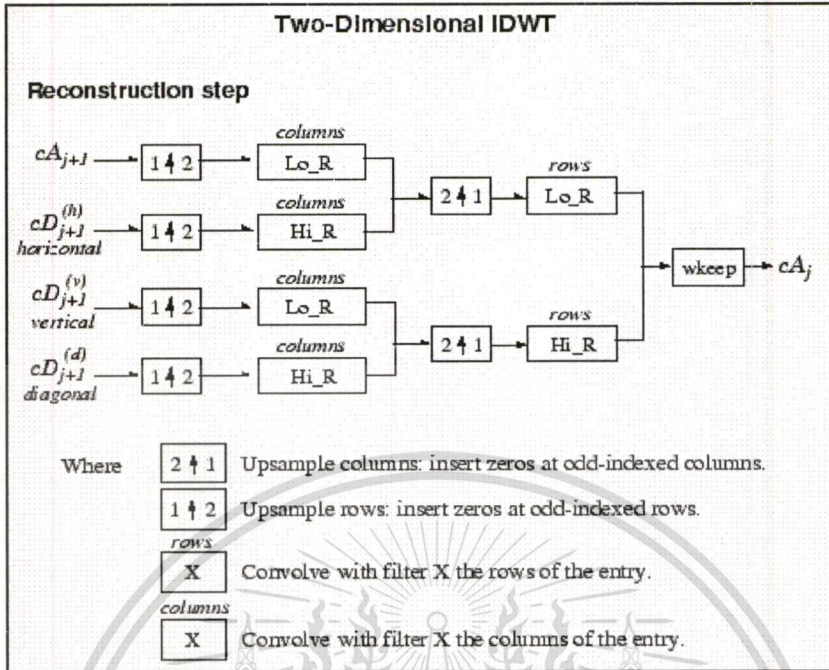


Figure 3.9 Image reconstruction steps

3.2 Part two: Angle value calculation

The first part of this research is Fusion phase and the second part is measurement phase. There are two steps in the second part which are Centroid finding and Angle value Transferring. In the proposed methodology, a centroid of an image is referred to its angle position.

The position of the centroid is reported in two elements. The first element of the centroid has horizontal coordinates (or x-axis) at the center of the image, and the second element has vertical coordinates (or y-axis) at the center of the image as well. The y-coordinate represents PSA values and the x-coordinate represents RSA values. Built in function in MATLAB used to find centroid is using pixel connectivity based on Morphological reconstruction [15]. The directions of PSA and RSA are represented by coordination, as shown in Figure 3.10.

The hard standard gauges, which were built by a very high precision machine, are used to collect the laser spot images reflected from the gauges. Their centroid are calculated and correlated to the reading value, which were received from the machine. Transfer function of the centroids of the images to the angle values is established by linear interpolation of image centroid and machine reading value.

The transfer function are separated in range of positive and negative values both PSA and RSA since it is easier to compensate the offset value into the system, which is the same as the current measuring system.

The method will begin by getting the image of standard parts then find their centroid value. This purpose is to collect the centroid value to interpolate the transfer function of centroid position to angle value. Once the transfer function is existent, the image of laser spot from good parts will be collected with machine's reading. Then the images from the good parts will be processed and calculated their angle value by using the transfer function of the gauges. After that the value will be compared between the PSA and RSA value from machine's reading and the value from the calculation.

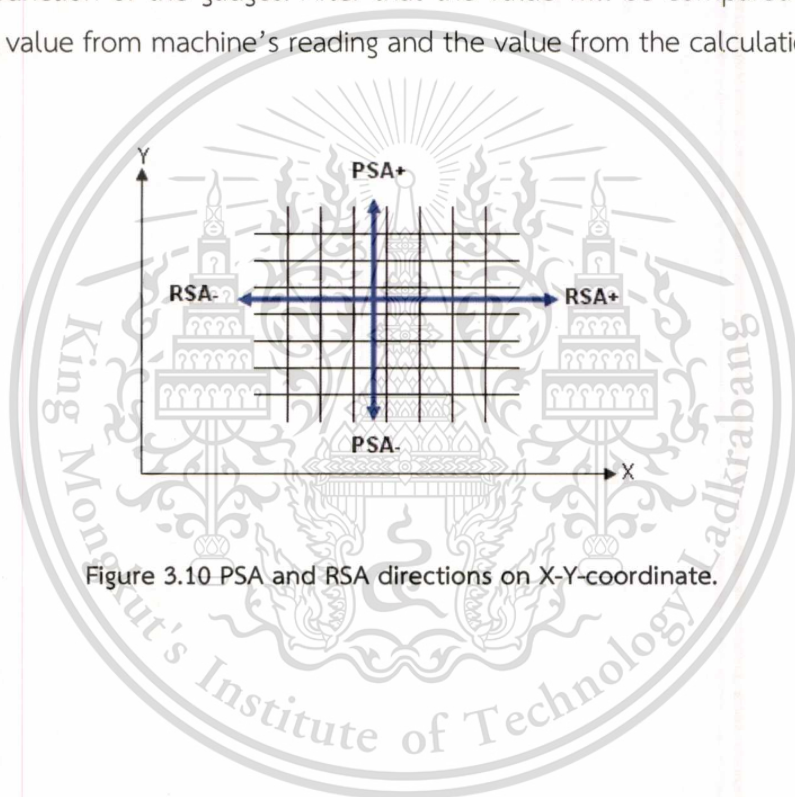


Figure 3.10 PSA and RSA directions on X-Y-coordinate.

CHAPTER 4

EXPERIMENTAL RESULT AND DISCUSSION

There are various products of sliders. They differ in properties of materials on the surface and the groove pattern of the air bearing. Therefore only one product and a corresponding standard hard gauge image of laser spot has been collected for this experiment. The experimental result will be discussed in two phase which are Fusion phase and Measurement phase.

4.1 Fusion phase

Image fusion will be divided into 4 steps which are Image preprocessing, Image decomposition by Discrete Wavelet Transform, Image fusion or coefficients matrices merging by desired rule and Image synthesizing by Inverted Discrete Wavelet Transform.

4.1.1 Image preprocessing

The result will be compared since image of double class, Binarization, Removing open area, Hole filling, Dilation and Erosion then Roundness number will be shown for the final step of image preparation as diagram in Figure 4.1

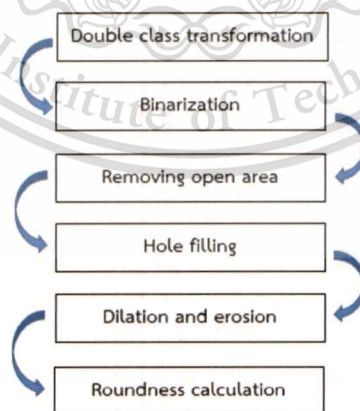


Figure 4.1 Image preprocessing step diagram

The results of image preprocessing are shown in Figure 4.2



Figure 4.2 Results of Image preprocessing

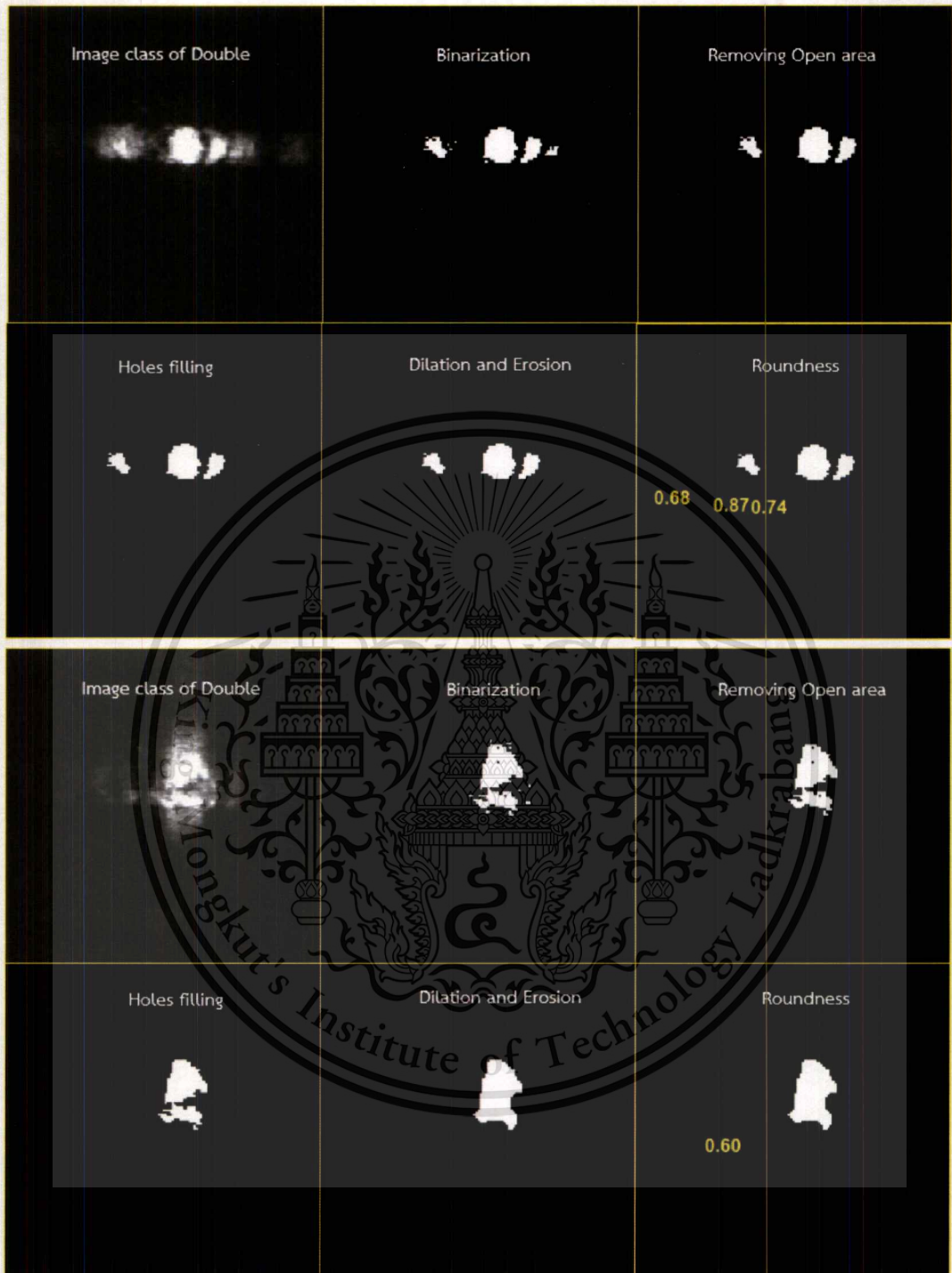


Figure 4.2 Results of Image preprocessing (cont.)

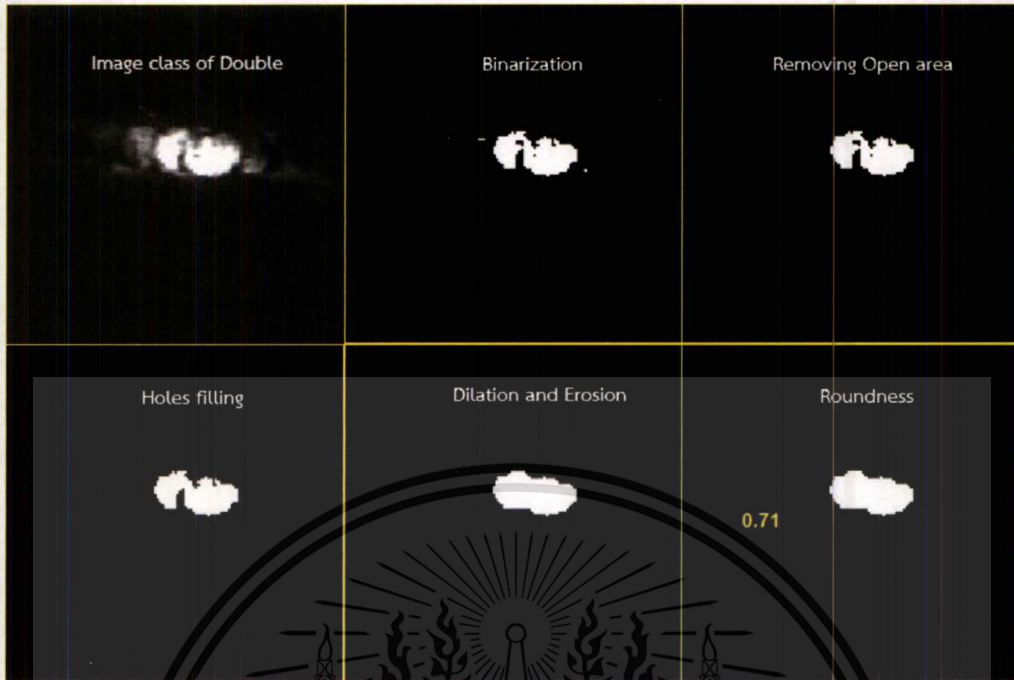


Figure 4.2 Results of Image preprocessing (cont.)

4.1.2 Image decomposition by Discrete Wavelet Transform

The transformation is using built-in function in MATLAB 7.11.0 (R2010b) and running in Windows 7 enterprise service pack 1, 64-bit operational system with Intel® Core™ i5-3320M CPU @ 2.60HGZ Processor and 4.00 GB memory. The result is compared in qualitative vision and executed times of decomposition in each level. The chosen wavelet filters are Haar, Daubechies2, and Symlets then decomposed in level 2 to level 5. The comparison of executed time is shown in table 4.1. The executed time of level 5 decomposition is increased about 60% from level2 for Haar wavelet filter and about 70% for Daubechies and Symlets wavelet filter. The detail and approximated coefficient are also significant better in higher composition levels. But actually, the purpose of this experiment is not required much high detail at level 5 while weighted with executed time. The image of laser spot is defined value in grey scale level that it is not as much detail as color image so the level 2 decomposition is preferred in this experiment.

Table 4.1 Comparison of executed time of image decomposition

Wave name	Level	Elapsed time (Second)	% of db2
Haar	2	0.013048	95
Haar	3	0.015056	110
Haar	4	0.018479	135
Haar	5	0.021253	155
db2	2	0.013682	100
db2	3	0.015994	117
db2	4	0.018618	136
db2	5	0.023138	169
sym2	2	0.013075	96
sym2	3	0.016349	119
sym2	4	0.019913	146
sym2	5	0.022676	166

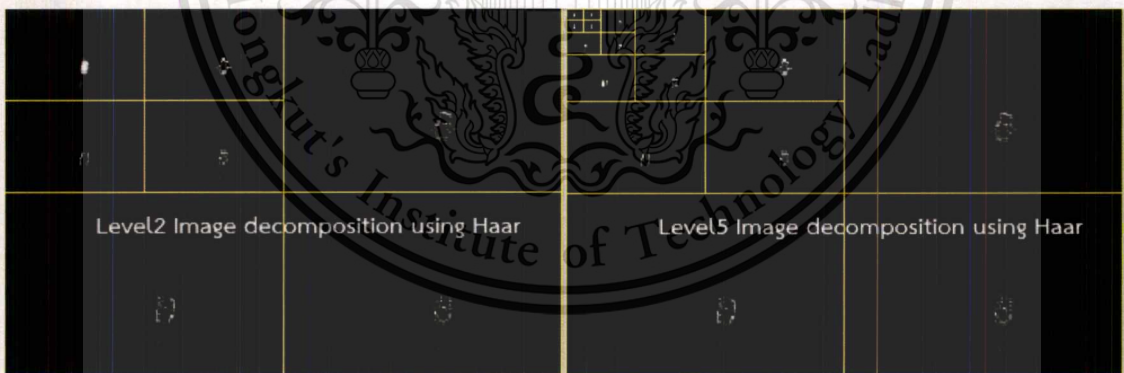


Figure 4.3 Comparison of level 2 and level 5 image decomposition using Haar wavelet transform



Figure 4.3 Comparison of level 2 and level 5 image decomposition using Haar wavelet transform (cont.)

4.1.3 Image fusion result

The result shows sample images before fusion and the last obtained images after post image processing. Steps of post image processing shows in Figure 4.4 is similar to pre image processing.

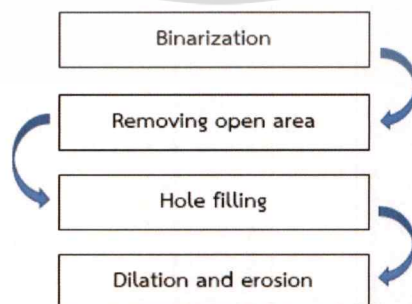


Figure 4.4 Steps of post image processing

The results are observed to be better in qualitative term of circularity. The centroids in X, Y coordination are also calculated then plotted in the images. Some of them are not perfect circular but they are shown much better than the original input images as shown in Figure 4.5

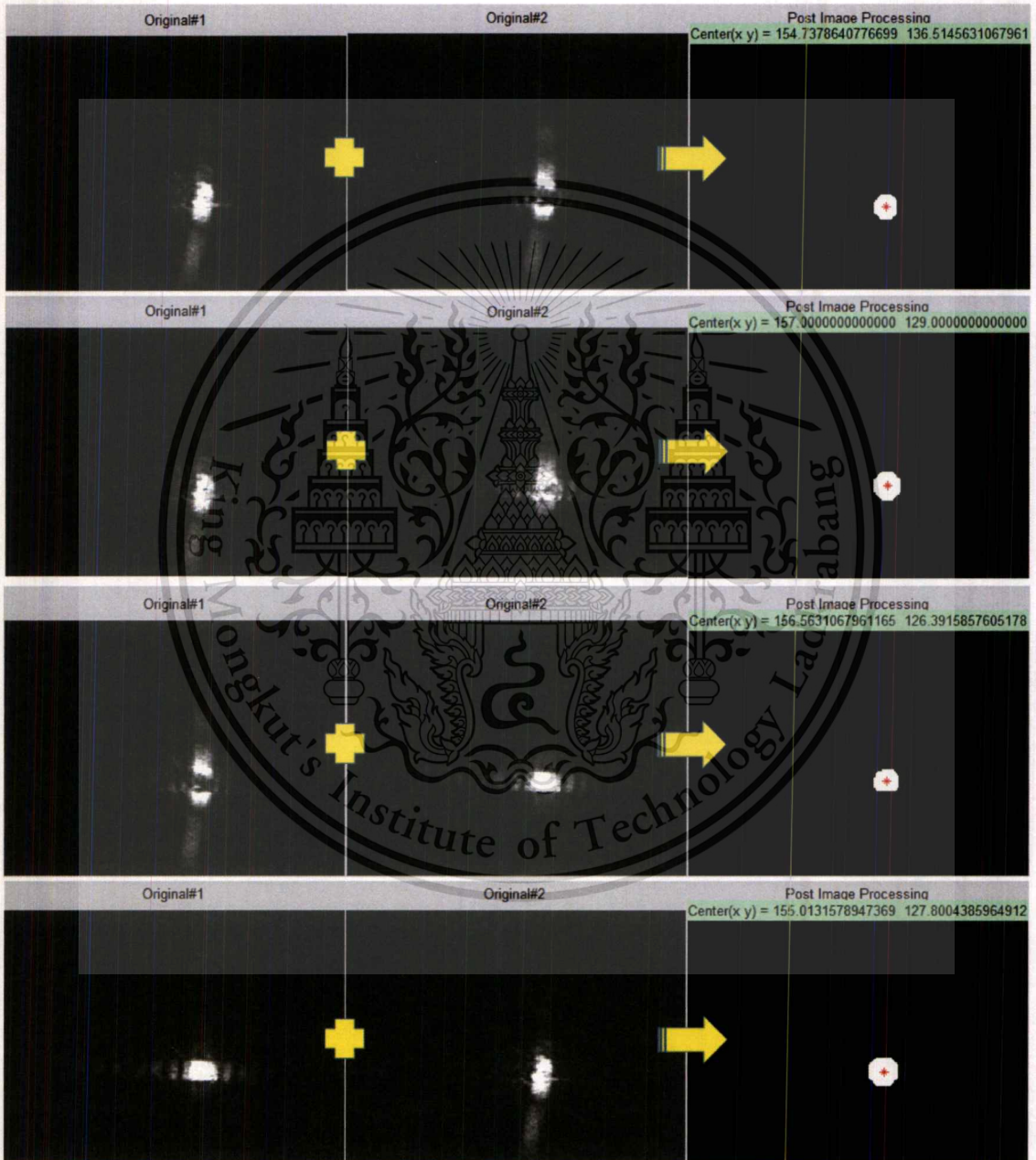


Figure 4.5 Results of post image processing with centroids displayed

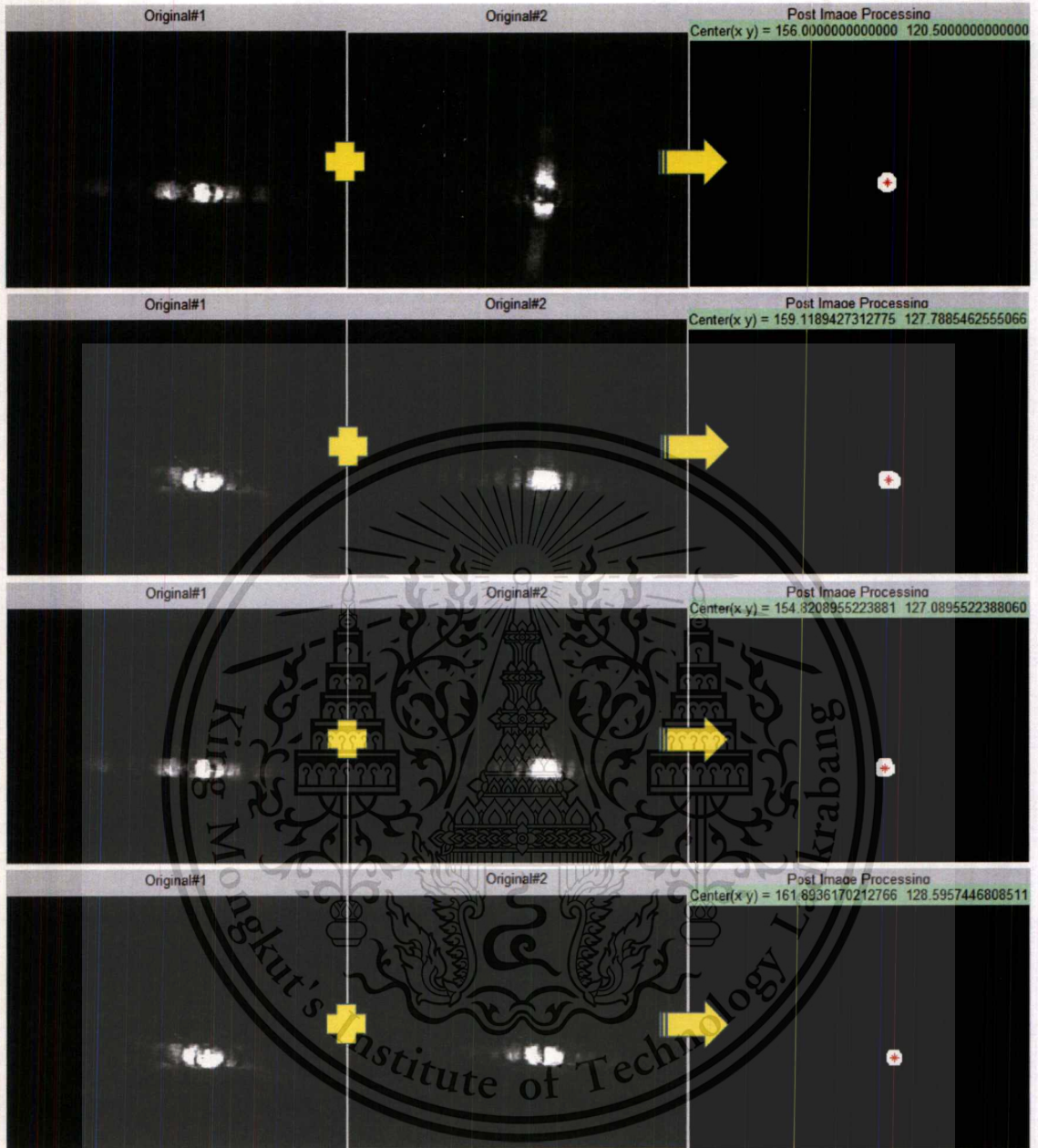


Figure 4.5 Results of post image processing with centroids displayed (cont.)

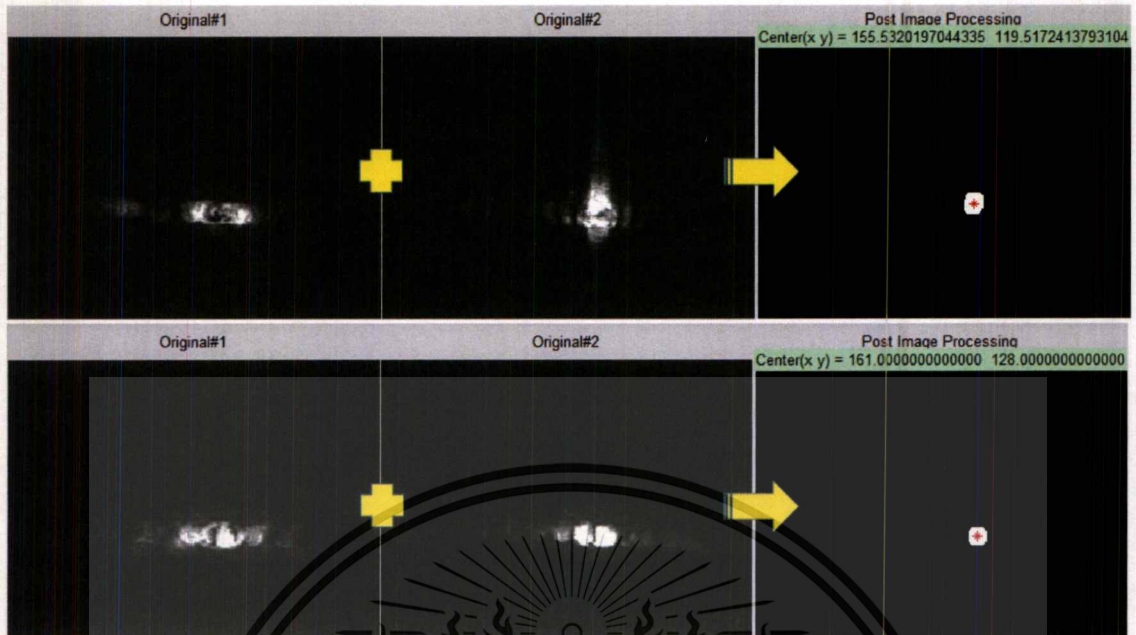


Figure 4.5 Results of post image processing with centroids displayed (cont.)

4.2 Measurement phase

The result of measurement phase will be shown into three sections. The first section is transfer function interpolation from the centroid of the gauge's images. Then PSA and RSA value will be calculated from transfer function and compared to the reading of the machine in the second section. The third section will be shown the correlation between PSA and RSA getting by calculation and reading of the machine then translate the result.

The angle value are catalogued by up tab PSA, down tab PSA, up tab RSA and down tab RSA. The angle of slider on the tip of HGA is defined the directions as illustrated in Figure 3.10 and the reason of machine offset value biasing so that is the reason why the measurement ranges have been separated into positive and negative.

The process of image pre-processing is also applied to these set of images before find their centroid. It can be seen that the image quality of hard gauge is much better than the obtained image of the slider, due to very smooth and flat surface. The samples of the centroid positions of gauge are plotted on the original images are shown in Figure 4.6

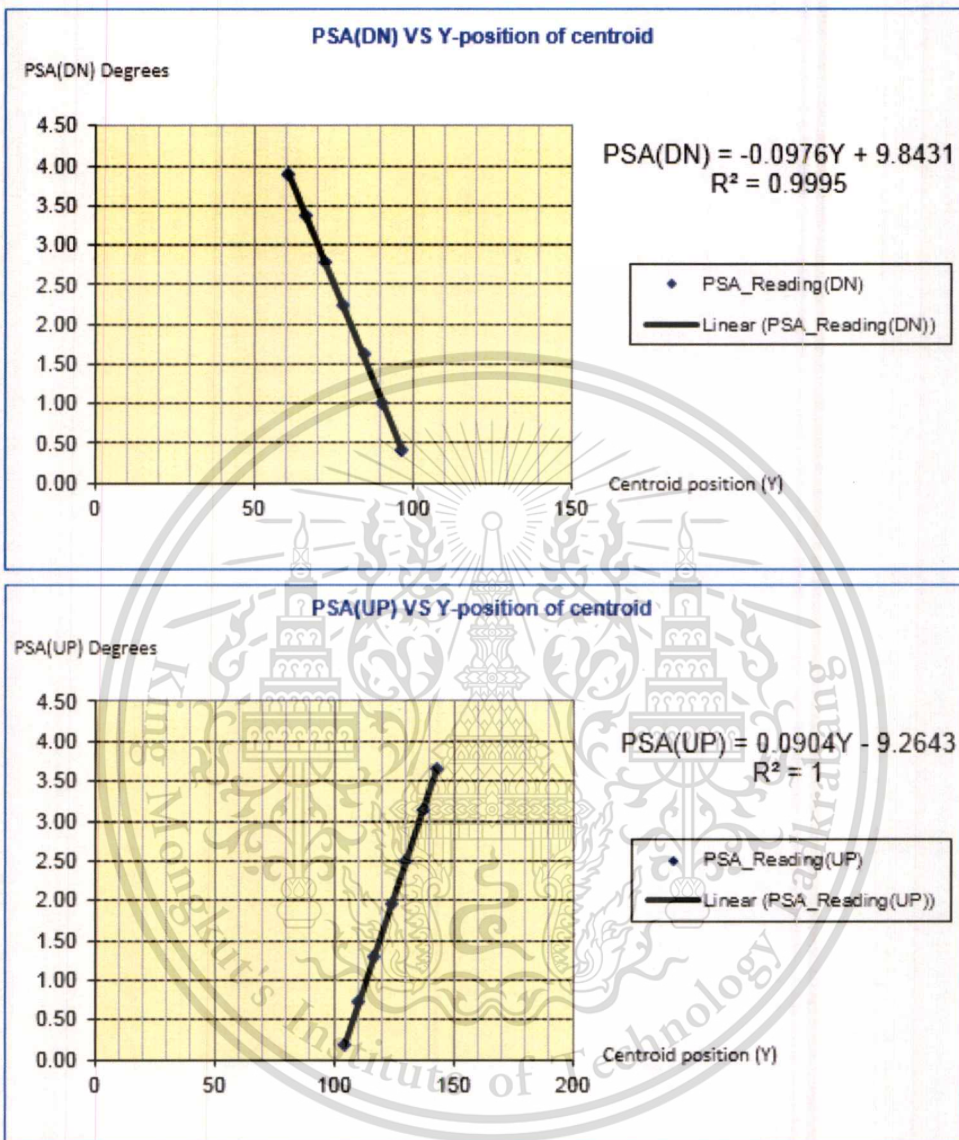


Figure 4.7 Correlation plot and transfer function of centroid position to PSA

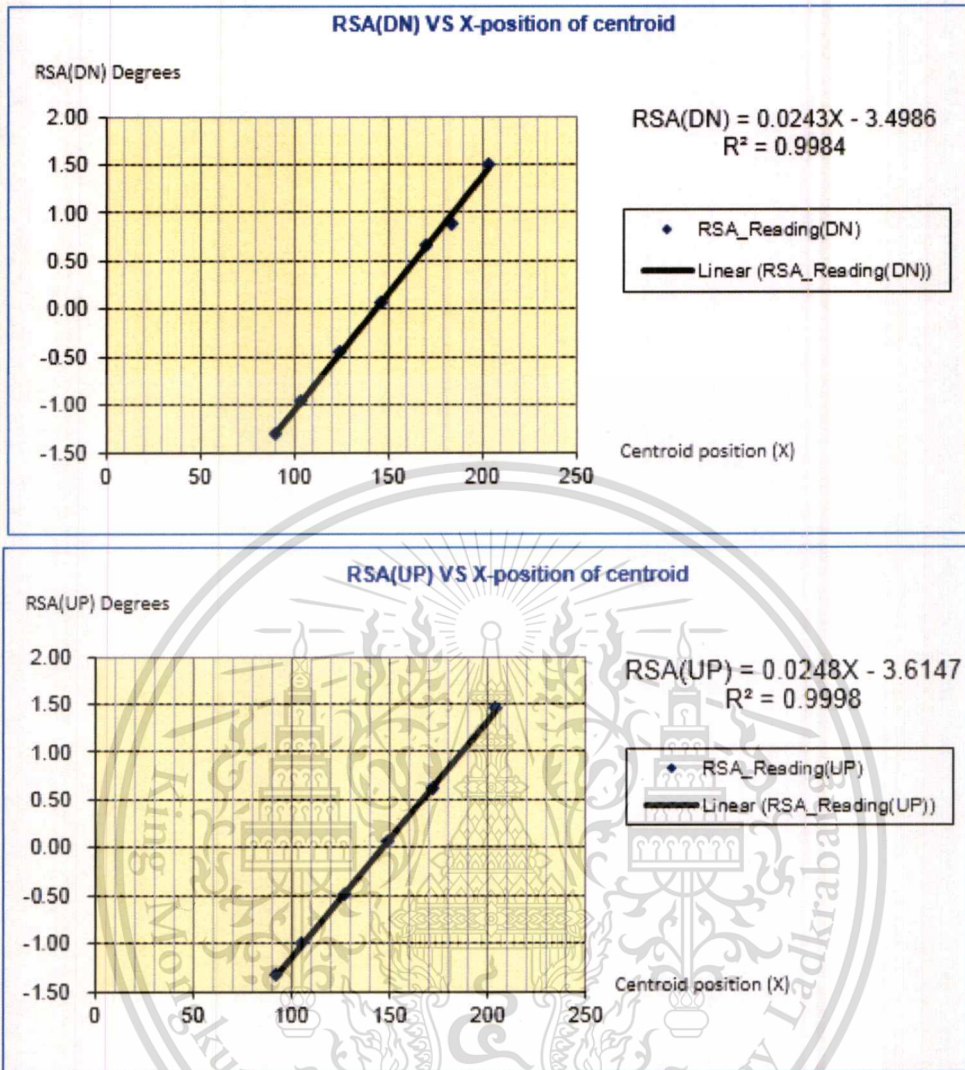


Figure 4.8 Correlation plot and transfer function of centroid position to RSA

The 4 functions in Figure 4.7 and Figure 4.8 are used to calculate PSA and RSA by using MATLAB. They are used to translate centroid position to angle value which show as equation (4.1) to (4.4).

Then the calculated PSA and RSA are compared to reading values from the current using machine. The value and the error are separated into upside and downside then reported in the following Table 4.2. The positive error means calculation value is higher than reading from machine and vice versa.

The impact of error could be adjusted reasonably but it is regarding with the correlation. More than 99% correlation is significant acceptable and the error just need to be biased by constant value.

$$PSA(DN) = -0.0976Y + 9.8431 \quad (4.1)$$

$$PSA(UP) = 0.0904Y - 9.2643 \quad (4.2)$$

$$RSA(DN) = 0.0243X - 3.4986 \quad (4.3)$$

$$RSA(UP) = 0.0284X - 3.6147 \quad (4.4)$$

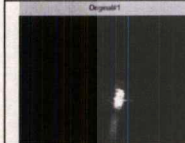
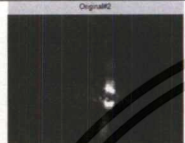
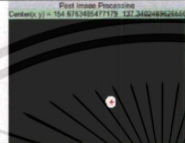

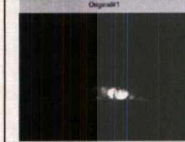



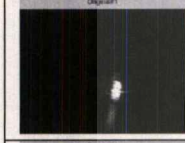



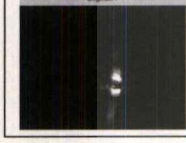



Table 4.2 MATLAB Calculation value VS reading value from current in used machine

Tab	Centroid position		MATLAB calculation		Reading from Machine		Error	
	X	Y	PSA(deg)	RSA(deg)	PSA(deg)	RSA(deg)	PSA(deg)	RSA(deg)
DN	118.29683	132.02594	-3.04263	-0.62399	-2.80875	-0.63169	-0.23388	-0.00770
DN	148.80342	135.97721	-3.42828	0.11732	-3.45066	0.12927	0.02238	0.01194
DN	138.69322	135.49853	-3.38156	-0.12835	-3.76883	-0.13650	0.38728	-0.00815
DN	154.08264	139.77410	-3.79885	0.24561	-3.83345	0.24235	0.03459	-0.00326
DN	155.73727	126.90617	-2.54294	0.28582	-2.62561	0.33162	0.08267	0.04581
DN	112.87042	140.89859	-3.90860	-0.75585	-3.71107	-0.76192	-0.19754	-0.00607
UP	160.83643	123.54275	1.90396	-0.37404	1.88765	0.33387	0.01632	-0.04017
UP	181.01075	122.89964	1.84583	0.87437	1.82247	0.86398	0.02336	-0.01039
UP	179.21691	122.93382	1.84892	0.82988	1.87450	0.77192	-0.02558	-0.05796
UP	158.85714	112.98730	0.94975	0.32496	0.97679	0.29346	-0.02704	-0.03150
UP	184.66901	121.13028	1.68588	0.96509	1.68779	0.96250	-0.00192	-0.00259
UP	161.37162	125.64865	2.09434	0.38732	2.16335	0.36876	-0.06901	-0.01856

The usage time of overall fusion process for level 2 and level 5 decomposition is compared in Table 4.3. The usage time of level 5 deposition is increased about 20% of level 2. In term of angel values, it is varied about 0.3 degrees at worst when calculated by equation (4.1) to (4.4).

However, the original slider could not be measured so it could not be defined the exactly error from the right value in this thesis. So that Daubechies2 wavelet filter is still in used at level 2 decomposition in this research.

Table 4.3 Images and executed times comparison between processes of using level2 and level5 Daubechies2 wavelet filter.

Original#1	Original#2	Image fusion		Executed time(Sec)		
		LVL 2	LVL 5	LVL 2	LVL 5	%of LVL 2
				0.442142	0.546963	124
				0.468105	0.549773	117
				0.466882	0.548263	117
				0.462911	0.553378	120

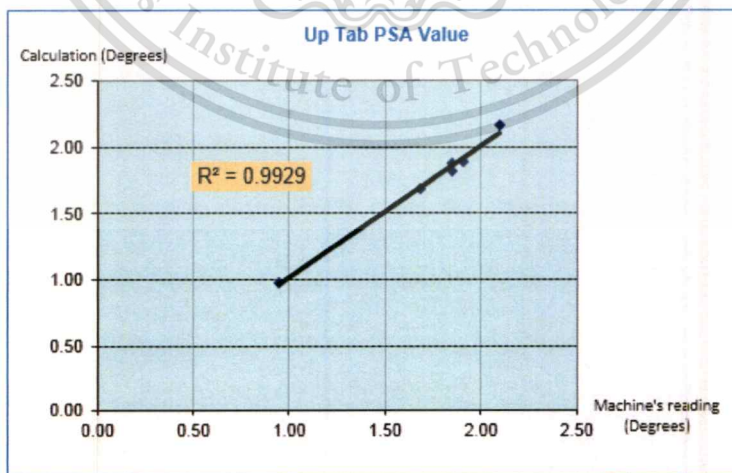


Figure 4.9 Correlation of reading value PSA and calculated value of up tab PSA

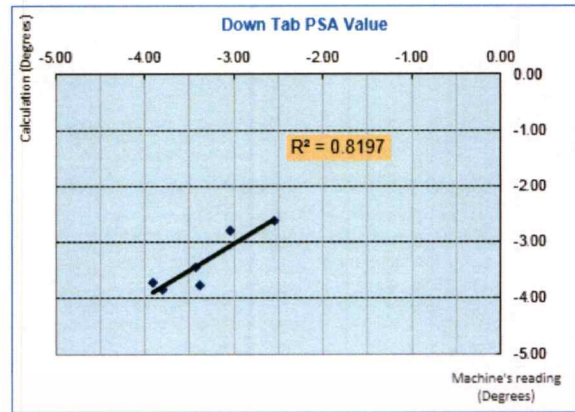


Figure 4.10 Correlation of reading value and calculated value of down tab PSA

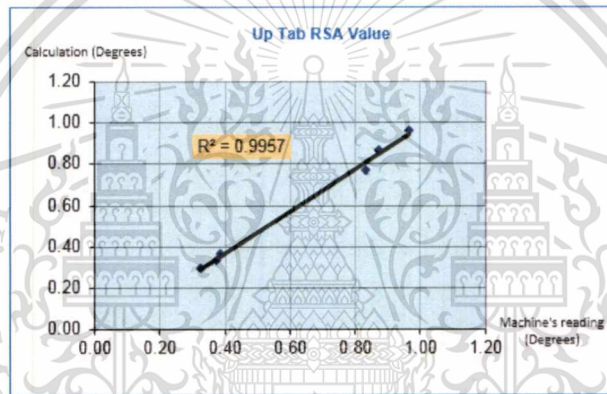


Figure 4.11 Correlation of reading value and calculated value of up tab RSA

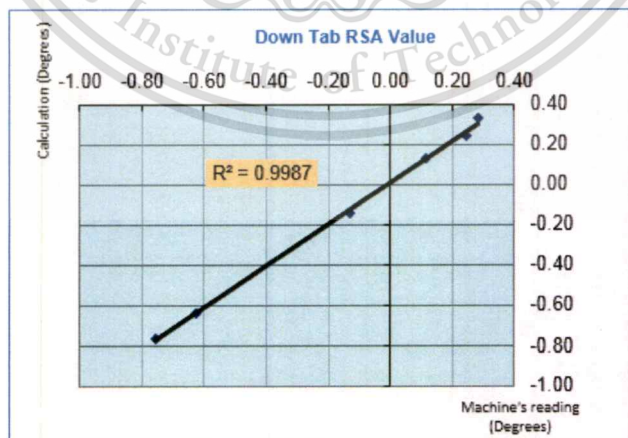


Figure 4.12 Correlation of reading value and calculated value of down tab RSA

From the correlation result in Figure 4.9 to Figure 4.12, it is observed that only down tab PSA has a big error. When consider the transfer function in Figure 4.7, noticed that the position using for interpolation of PSA down tab is ranged around 60 to 100 but the actual Y position of centroid from the image of PSA down tab range around 120 to 140 so this might be one reason of much error in this PSA down tab group. The equation (4.1) might need to recalculate due to the interpolation value is not cover actual range of down tab PSA then prone to have more error.



CHAPTER 5

CONCLUSIONS AND SUGGESTION

5.1 Conclusions

The good result brings us to the conclusion that image fusion using wavelet transform technique is capable to solve the distortion of obtained images from the light scattering or in some cases, grooves on air bearing surface of the slider.

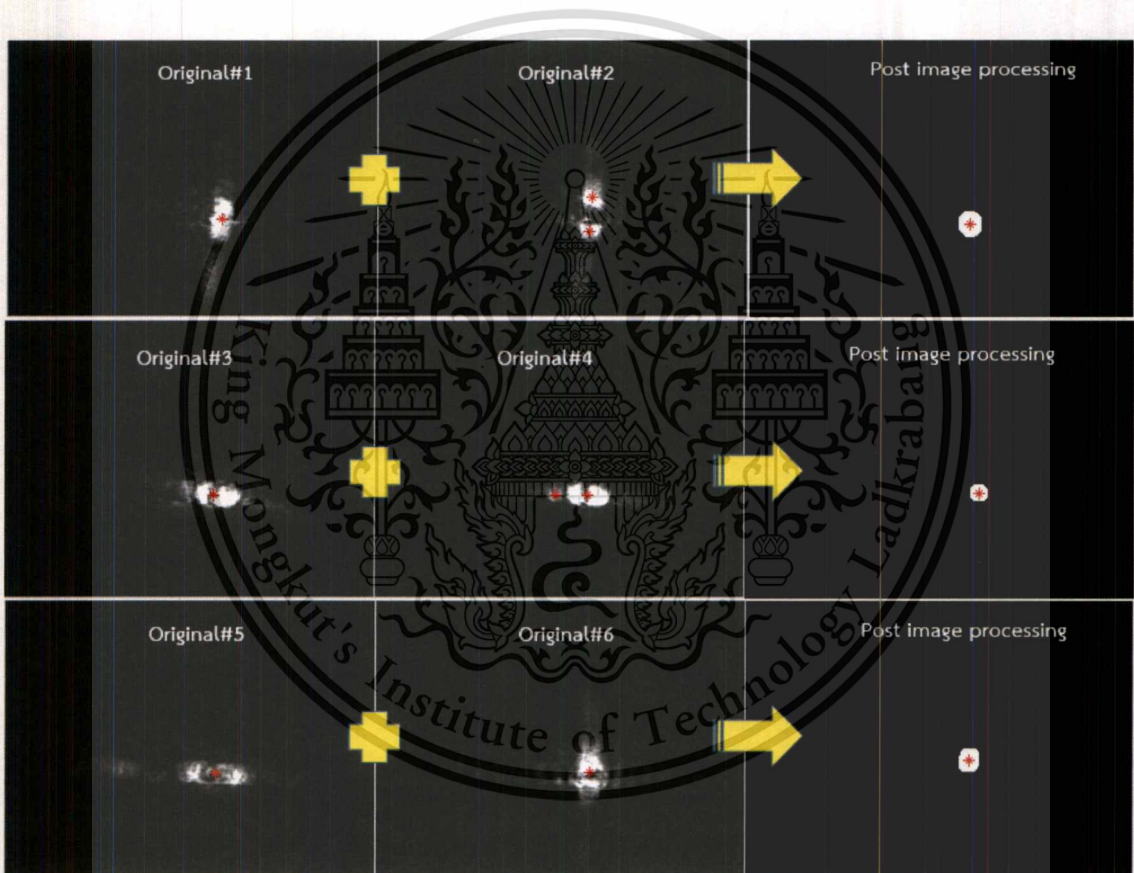


Figure 5.1 Centroid position plotted on original images compared to post image processing

In image fusion section the quality of original images and post processing image are compared in Figure 5.1. The centroid positions plotted on the image are one indicator to assure that the result images are better than original images.

For the measurement phase, the transfer functions interpolated by the image of standard parts are good correlation between position of the calculated centroid and angle value. Then they are well acceptable and use for angle value calculation. The results also show good correlation between calculation value and the machine reading value. The more error of PSA down tab in the verification phase will be solved by re-calculation the transfer function which using cover range standard gauge. At the bottom line, however, the proposed method give more confidence in measuring PSA and RSA due to the imperfect input images compared to the currently used method. The main conclusion can be made as the following lists

- Image fusion using wavelet transform technique can solve the issue of distorted obtained images that cannot be measured by current in used laser base measurement system.
- The measurement accuracy can be improved by image processing in the proposed system.
- The image of reflection of laser spot is processed in binary mode so it does not have much detail as color image or satellite or medical captures as in literature reviews.
- Level 2 image decomposition using wavelet transform is sufficient to get the information of the image in this purpose methodology.
- Centroid position shows good correlation to angle value then precise transfer function can be obtained.
- The proposed system needs standard parts by product that have cover range of centroid position to calculate their transfer function of angle value.
- Transfer functions are separated to PSA by tab and RSA by tab the same as current in used.

5.2 Suggestions for further work

Although this work is finished, there are some suggestions to the work for further study on application of image fusion using wavelet transform in slider orientation measurement.

- Wavelet transform by modern decomposition method. In this research the input images are reflection of laser spot which required the circular result and it is also processed in binary mode so that the detail of wavelet frequency might be studied to get the best optimized result for the coefficient matrices.
- The image capture from another area on the tip of HGA could be studied whether it might be good correlation then just bias a constant to the system to calculate the angle value of the slider.
- The fusion strategy could be studied to improve and optimize the method. For some of the separated type input images, sometimes it does not work for the automatic system then need to operate manually.
- Flexibility of measuring system such as measuring on another area of HGA instead of slider surface.

REFERENCES

- [1] Thoatsarlope, K. Surachate, Ch. and Jukkaphun, P., "The improvement of deformations and characteristics of HGA during clamping using finite element analysis", Proceedings of the 2008 Winter Simulation Conference, pp. 1335-1343.
- [2] Hong, Z. and David B., "Effect of Pitch static attitude and Roll static attitude on the Steady performance of Air Bearing sliders", Proceedings of World Tribology Congress III (WTC2005), Sep. 2005, Paper no.WTC2005-63320, pp. 693-694.
- [3] Ronald, S., "High-Resolution, Non-contact Angular measurement system for PSA/RSA" A Thesis presented to the Faculty of California Polytechnic State University, Mar.2011, pp. 1-7.
- [4] Jair, G.L. and Miguel, A.A., "CMOS vision Chip for Lase spot Position Detection", Proceedings of Electronics, Robotics and Automotive Mechanics Conference, IEEE2010, pp. 759-764
- [5] Pajares, G. and Manuel, C., "A wavelet-based image fusion tutorial", Proceedings of pattern Recognition 37, 2004, pp. 1855-1872.
- [6] Siffuzzaman, M. Islam, M.R. and Ali, M.Z., "Application of Wavelet Transform and its Advantages Compared to Fourier Transform", Journal of Physical Sciences, ISSN 0972-8791, www.vidyasagar.ac.in/journal, 2009, Vol.13, pp. 121-134.
- [7] Yufeng, Z. Edward, E. and Bruce, H., "An Advanced Image Fusion Algorithm Based on Wavelet Transform -Incorporation with PCA and Morphological Processing", Literature of Department of Psychological & Brain Sciences, University of Louisville, Louisville, KY 40292, USA

- [8] Albert, B. and Francis N., "A First course in Wavelets with Fourier Analysis", Texas A&M university, Texas, Prentice Hall, pp. 155-260.
- [9] Ivan, S., "Wavelet Transforms-A Quick Study", Physics Today magazine, Polytechnic University, Brooklyn, NY, Oct. 2007.
- [10] Martin, V. and Jelena, K., "Wavelets and Subband Coding", Prentice Hall, 1995, Reissued 2007.
- [11] Eduardo, C., "Image Fusion", Project report for the Master degree in Electrical and Electronics engineering, University of Bath, Claverton down, UK, Jun. 2002.
- [12] Susmitha, V. and Pancham, S., "A Novel Architecture for Wavelet based Image Fusion", Proceedings of World Academy of Science, Engineering and Technology 57, 2009, pp. 372-377.
- [13] Otsu, N., "A Threshold Selection Method from Gray-Level Histograms," IEEE Transactions on Systems, Man, and Cybernetics, Vol. 9, No. 1, 1979, pp. 62-66.
- [14] Wang, A. Haijing, S. and Yueyang, G., "The application of wavelet transform to Multi-modality Medical Image fusion", Proceedings of 2006 IEEE International Conference, pp. 270-274.
- [15] Vincent, L., "Morphological Grayscale Reconstruction in Image Analysis: Applications and Efficient Algorithms," IEEE Transactions on Image Processing, Vol. 2, No. 2, April, 1993, pp. 176-201.

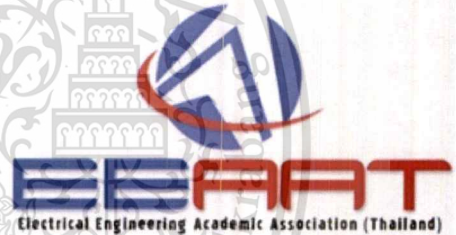
APPENDIX A

PUBLICATION

This work has also been published and presented in The 2014 International Electrical Engineering Congress (IEECON2014) in Pattaya city, Thailand during March 19-21, 2014 and also in the international conference of information science and computer applications (ICISCA2012) at Bali Dynasty Resort, Bali, Indonesia during November 19-20, 2012.

iEECON 2014

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Image Fusion Using Wavelet Transform for Slider Orientation Measurement

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Abstract— In order to measure the orientation of head stack assembly (HSA) a laser-based measurement system is used. The system projects a laser beam onto a work piece and the reflected beam is captured by the camera. Usually, the system produces a good round light dot which used further for measuring the orientation of the work piece. However, there are some areas in which the laser beam is scattered. This leads to undesirable measurement results.

For this reason, an attempt to improve the quality of image before taking measurement is proposed. Instead of using only one picture to produce the measurement result, the proposed method used several of pictures from the same area of work piece. It then uses the wavelet transform to fuse these images to produce one representation of image for further measurement. This work shows the experimental view of the area where the laser beam is scattered. It is obvious that using only one image from this area could not obtain accurate measurement. However, by applying the image fusion techniques mentioned previously to the images of reflection of laser spot from the other areas of head stack assembly (HSA), more accurate measurement can be obtained. The desired measured values for this work are pitch static attitude (PSA) and roll static attitude (RSA).

The images of standard parts are also used for references of the proposed method. It is used to find the relationship between the location of the light dot and the orientation of the work piece. MATLAB is selected to be the tool used for experiment in this work. It has been found that the proposed method can greatly improve the quality of the resulted image and hence lead to a more accurate measurement results.

Index Terms—PSA/RSA; HSA; HGA orientation; angular measurement system; image processing, wavelet transform

I. INTRODUCTION

A magnetic read/write element, slider, is an element attached to trace gimbal assembly (TGA). The combination of the slider and TGA is known as head gimbal assembly (HGA). Two or more HGAs which are assembled in both upside and downside form the head stack assembly (HSA). Figure 1 illustrates the HSA and positions of slider, base plate and arm. In order to guarantee the slider orientation of HSA to be within the specification before being assemble into the hard disk drive

(HDD), laser-based measurement system is used. This is the current measurement system used to obtain the orientation of the slider.

A laser-based measurement system is shown in Fig. 2. It consists of two laser sources for both up and down side surfaces. There are five cameras installed on the platform along with 3-axes step motor system. The HSA will be fixed on a jig for measurement. In order to measure the orientation of the slider, the system captures a picture of the laser beam reflection from the slider and sends the image to display on the computer screen. The software then calculates the measured values of pitch static attitude (PSA), roll static attitude (RSA) and Z from the obtained picture.

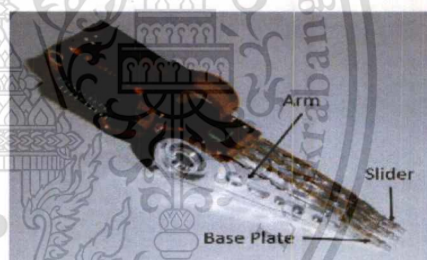


Figure 1. Head Stack Assembly

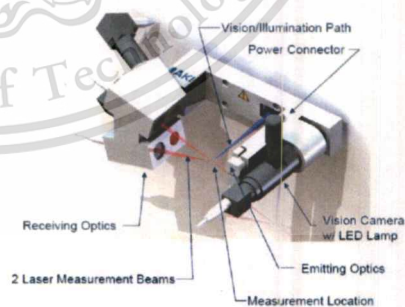


Figure 2. Laser-based measurement system for HSA orientation

This paper is organized as follows. Section II discusses in details about the problems and the proposed method. The experiment procedure is illustrated in section III. Section IV gives experiment results and finally, section V concludes and discusses about future works.

II. PROBLEM STATEMENT AND PROPOSED METHOD

It should be noted that, in general, there are some grooves or some non-removal contamination on slider surface. This might results in light scattering on reflection that leads to a low quality of captured images. For this reason, inaccurate values of slider orientation occur in some measurement cases. In the worst-case scenario, the laser-based measurement system is not working at all. Apart from the slider, this phenomenon also happens in the non-smooth surface area of the HSA, e.g. base plate and arm.

To overcome such problem, the image processing technique is introduced. The image processing technique is proposed because its cost is lower compared to other high performance hardware replacement solutions. The technique of image fusion using wavelet transform has particularly been chosen for the proposed system. In [11] this approach has been used to solve undesired light scattering issue on the slider's surface. The results show good correlation to the current in used system.

To measure the orientation of a slider using the laser-based measurement system, the laser sources are usually set to aim at the slider surface on HGA. The surface of slider is diamond like carbon coating material. This surface is also not flat due to grooves of air bearing which will help in flying performance of slider. The area nearby slider such as base plate of HGA or arm of HSA is flatter than surface of slider.

So far, there is no study showing the measurement results of aiming laser on any other areas except surface of the slider. This paper studies the measurement of slider orientation by measuring the orientation of other areas of HSA. The measurement values are PSA and RSA as in the slider cases. However, the area in study is now base plate of HGA and arm of HSA. Baselines or value of orientation is expected to be different from measuring on slider. For this reason, it is not set in this research. The image fusion technique is then applied on those captured images from such areas.

As previously mentioned, the current measurement system uses a single image to measure PSA and RSA value. This approach presents no difficulty if the captured image is of good quality. That is the captured image is a clear round light dot. However, in case of light scattering, the captured image is of poor quality. In such cases, the captured image can have high scattering light dot, the shape of the dot itself is not round, or there will be two light dots captured on the screen. To overcome this problem, several images are captured from the very same area of the work piece. These images are then undergoes the image processing technique to improve the quality before being measured. The image fusion using wavelet transform is chosen for this work.

In general, image fusion refers to the method, which combines information from multiple images into a single image. The result image then has useful information extracted from a set of input images on some given fusion rules. In this scenario, the effect of containing less information of some input images might not be significant because of redundant information and complement information from a set of input images. A concept of image fusion is shown in Fig.3.

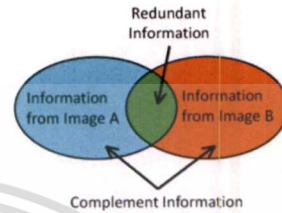


Figure 3. Image fusion concept

Given a set of input images, the concept of image fusion using wavelet is governed by the following equation

$$I(x,y) = W^{-1}\{F\{W\{I_1(x,y)\}, W\{I_2(x,y)\}\}\}. \quad (1)$$

while $I_1(x,y)$ and $I_2(x,y)$ are the original images which would be transformed by a wavelet transform W . F is some fusion rules which applied to the transformed images $I_1(x,y)$ and $I_2(x,y)$. The result image is obtained from the wavelet inverse transform W^{-1} . The result image $I(x,y)$ is then used further for further measurement.

2D images have been applied by the 2D wavelet transform. The fusion rule of roundness is the strategy to combine transformed images. For details see [11]. Roundness of laser spot is defined by the following equation

$$\text{Roundness} = \frac{4 \times \pi \times \text{area}}{\text{perimeter}^2} \quad (2)$$

This paper shows the experiment on measuring the slider orientation on some other area of HSA apart from the surface of slider. A base plate of HGA and an arm of HSA are candidate of this paper. After obtaining several images from these areas, image fusion using wavelet transform technique is applied to fuse images. Quality of images after fusion shows significant improvement compared with the original images. However, the values of angle are not concluded due to different baselines and standard parts are also needed for a new reference method.

III. EXPERIMENTAL PROCEDURE

The proposed experiment is designed to study the possibility of slider orientation measurement system, which measured on some other possible areas of HSA apart from

slider's surface. In this work, the area of arm of HSA and base plate of HGA are chosen for the experiment.

There are two parts in order to obtain the experimental result. The first part is to get a set of images from different areas that concern to the hardware. The second part is the image processing which is software concerning part. The set of laser and CCD camera is moving by small steps to capture images of reflection from desired areas. The set of obtained images are then analyzed by discrete wavelet transform. The coefficient matrices and sub-images are formed. These pictures are then fused by the rule of roundness see [11] for details description. The fused image is then synthesized by inverse discrete wavelet transform. The diagram of proposed algorithm to get the fused image is shown in Fig.4

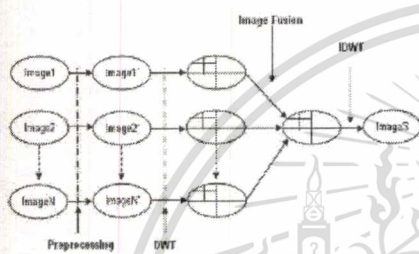


Figure4. Diagram of proposed algorithm

Image pre-processing and image post processing are also applied to the fused image as appropriate. After that the set of camera is moving to capture the other sets of images in different area of HGA base plate and arm of HSA consequently. The set of images will then be applied and processed as aforementioned procedures. The Daubechies decomposition method is selected to transform the sets of images in this experiment. Two levels Daubechies decomposition image fusion is shown in Fig.5.

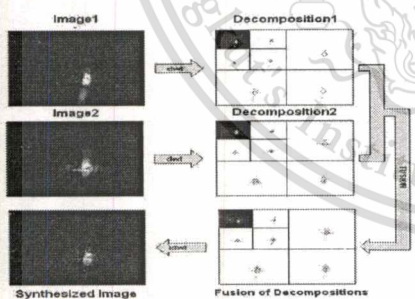


Figure5. Illustrated 2 images fusion by 2 level Daubechies decomposition

IV. EXPERIMENTAL RESULTS

Slider surface material is made from diamond like carbon coating while HGA base plate and HSA arm are made from different kind of metal. The reflection of laser spot on HSA arm is found to have the same characteristics as from base plate. Thus, the results could be referred from the base plate.

The base plate when exposes to light results in light scattering much more than the slider. The input image from reflection of slider surface could be distorted, noisy or separated images [11] while images of the reflection of base plate are almost noisy from light scattering. Fig.6 illustrates images obtained from slider and base plate for comparison purpose.

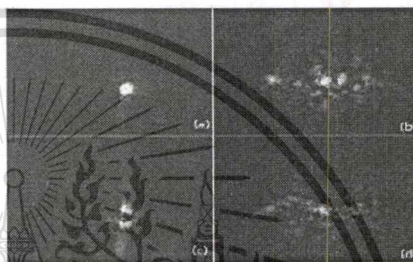


Figure 6. (a) and (c) images from slider. (b) and (d) images from base plate.

Image 6(a) shows nearly perfect image of reflection from slider surface while image 6(c) is distorted due to non-smooth surface of the slider. Image 6(b) seems to be circular when observing by naked eyes. However, it might be miscalculated by the system because of the same level of brightness of the scattering spots. Image 6(d) is also found to have much light scattering. The contours of the light scattering areas are shown in Fig.7. It is obvious that none of these images is appropriate for the measurement system since the inaccuracies will be large.

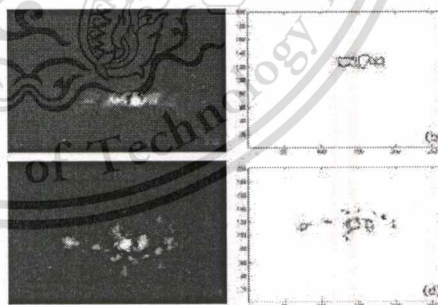


Figure 7. The top is contour of image form reflects of slider surface, The bottom is contour of image from reflect of base plate.

In order to overcome this problem, a set of images has been processed to improve image quality by fusion technique using wavelet transform. The reflection images obtained from sliders surface is found to have good results and the angle can be measured accurately. This is shown in the previous research [11]. The images obtained from reflection of base plate are also shown good results after they undergo the proposed fusion method. The result of post image processed is shown in the Fig.8.

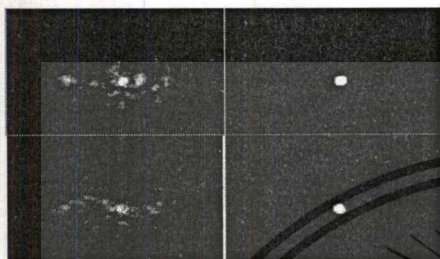


Figure 8. Base plate image before (right column) and after (left column) image processing

The resulted images are shown to have improvement in quality and more suitable for angle values calculation. The result of PSA and RSA values are not shown in this experiment. The centroid determination method as in [11] could be applied to the fused images. However, the hard gauge or stand parts have not yet been prepared. Thus reference could not be measured. The transferred function of angle values is thus still in process. However, the good circular final images can be guaranteed. From this point of view, it can be said that the obtained fused image is more appropriate for the currently used laser-based measurement system.

V. CONCLUSION AND FUTURE WORKS

It is found that a base plate and an arm of HSA will have light scattering more than surface of slider. This is due to the metal material used in these parts. However, the work in this paper shows that image fusion using wavelet transform technique is able to improve the image quality obtained from these areas as well. The good circular of final fused image is shown to be a satisfied result suitable to angle value calculation in further procedures. However, the transferred function of

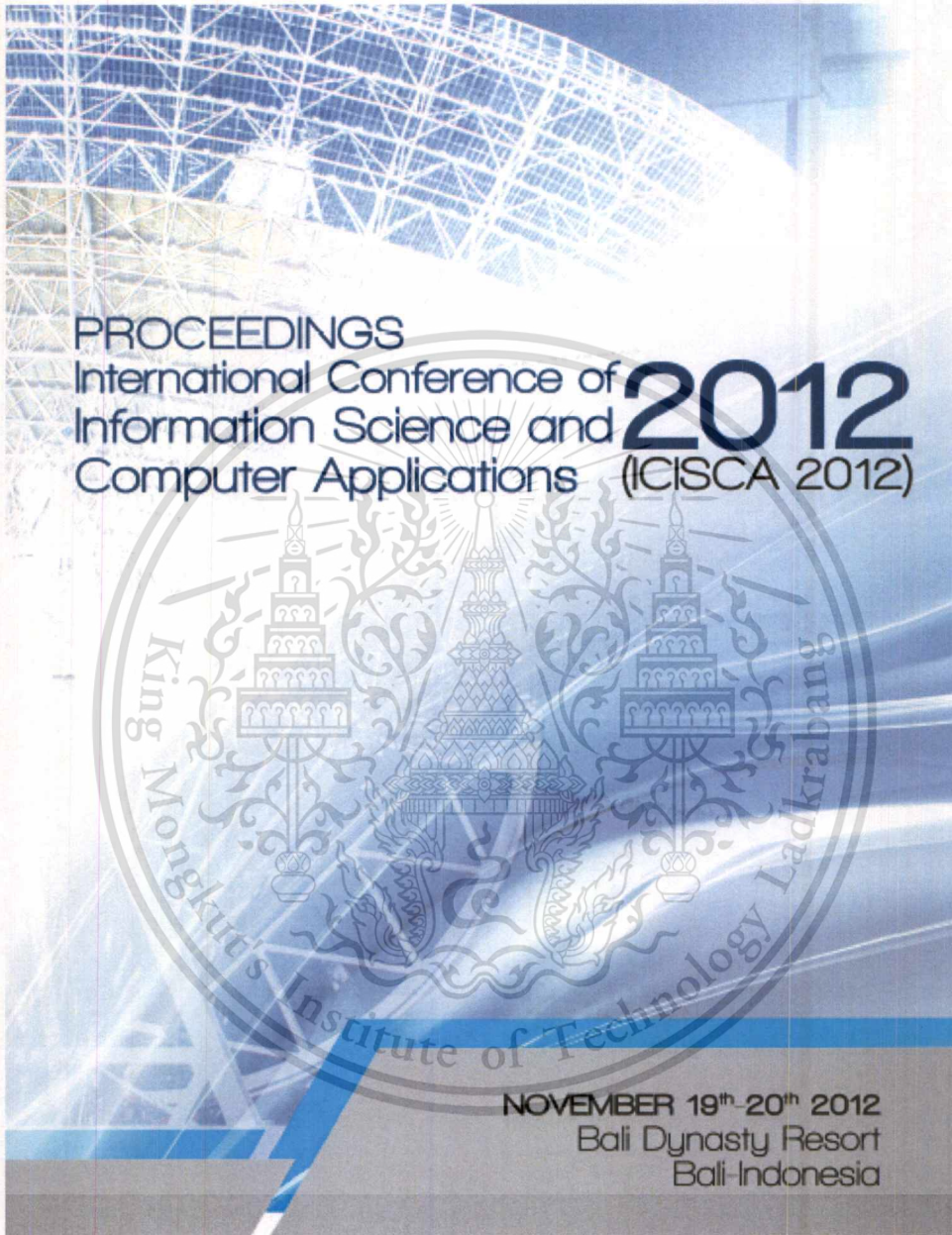
image from the base plate has not yet been done. Furthermore, the standard parts are also needed to prepare for references.

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REFERENCES

- [1] Thoatsanope K, Surachate Ch, Jukkaphun P, "The improvement of deformations and characteristics of HGA during clamping using finite element analysis", Proceedings of the 2008 Winter Simulation Conference, pp. 1335-1343
- [2] Hong Zhu, David B. Bogy, "Effect of Pitch static attitude and Roll static attitude on the Steady performance of Air Bearing sliders", Paper no. WTC2005-63320 pp.693-694, World Tribology Congress III (WTC2005) September 12-16, 2005, Washington, D.C., USA
- [3] Ronald Sloat, "High-Resolution, Non-contact Angular measurement system for PSA/RSA" A Thesis presented to the Faculty of California Polytechnic State University, San Luis Obispo, March 2011, pp.1-7
- [4] Jair Garcia-Lamont, Miguel Aleman-Arce, "CMOS vision Chip for Laser spot Position Detection", 2010 Electronics, Robotics and Automotive Mechanics Conference, IEEE 2010, doi: 10.1109/CERMA.2010.90
- [5] Wang, A. Haijing Sun, Yueyang Guan, "The application of wavelet transform to Multi-modality Medical Image fusion", Proc. 2006 IEEE International Conference, pp. 270-274, doi: 10.1109/ICNSC.2006.1673156
- [6] Hongbo Wu, Yanqiu Xing, "Pixel-based Image fusion using wavelet transform for spot and ETM+ image", progress in Informatics and Computing (PIC), 2010 IEEE International Conference, pp. 936-940, doi: 10.1109/PIC.2010.5687880.
- [7] Hongbing Zhang, "Research on the application of image fusion in material evidence photography", Multimedia Technology (ICMT), 2010 International Conference, pp. 1-3, doi: 10.1109/ICMULT.2010.5631114
- [8] Otsu, N., "A Threshold Selection Method from Gray-Level Histograms," IEEE Transactions on Systems, Man, and Cybernetics, Vol. 9, No. 1, 1979, pp. 62-66.
- [9] Vincent, L., "Morphological Grayscale Reconstruction in Image Analysis: Applications and Efficient Algorithms," IEEE Transactions on Image Processing, Vol. 2, No. 2, April, 1993, pp. 176-201.
- [10] G. Pajares, J. Manuel de la Cruz, "A wavelet-based image fusion tutorial", pattern Recognition 37 (2004), pp. 1855 - 1872, doi:10.1016/j.patcog.2004.03
- [11] N. Chalocmlap, N. Chaiwat, "application of image fusion using wavelet transform in slider orientation" Advances in Information Technology and Applied Computing, 2010, pp.84-88.



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Applications of Images Fusion using Wavelet Transform in Slider Orientation Measurement

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Abstract—The current pitch static attitude and roll static attitude measuring systems are of laser-based. A charge-coupled device (CCD) sensor installed in this system detects a reflected laser spot on the screen. The captured image of laser spot is then used to calculate the slider orientation. One of the concerned issues of laser spot captured image, which is reflected at the Head Gimbal Assembly (HGA), is that this image sometimes has inadequate information for the measuring process. In general, the captured image should appear in a perfect circle for accurate measurements. However, this might not be the case for some reasons such as grooves on the slider. Hence, in some cases the obtained image has a shape of distorted circle. This results in measurement inaccuracy. In addition, other area of HGA is found to be not suitable due to light scattering problem. This very problem also occurs in height measurement. Image fusion is the matching of solutions to solve the unclearness of captured images for measurements. The information of a set of images from the same surface will be combined by the appropriate fusion rule to obtain the better-fused image with pre-image processing. Then the resulting fused image will be calculated to obtain the value of slider orientation correlated to the position of the standard hard gauges. MATLAB has been used to prove the proposed concept.

Keywords—Image fusion; PSA/RSA; HGA orientation; angular measurement system; image processing, wavelet transform

I. INTRODUCTION

A slider is an important component in hard disk drive (HDD). It is located at the tip of a head gimbal assembly (HGA) and responsible for reading/writing information from/to the media [1]. The orientation of the slider has crucial effect on the flying height that has to be kept as small as possible. Two important parameters of the slider orientation are pitch static attitude (PSA) and roll static attitude (RSA) [2]. These two parameters are being controlled in the hard disk drive process at head gimbal assembly (HGA) as well as at head stack assembly (HSA) level.

A non-contact angular measurement system of hard disk drive's sliders or a laser based measurement system is currently used for quality assurance. The machine is composed of a laser source which generates laser beam and

emits directly to the slider surface. The beam of laser is then reflected to the CCD camera. As a result, the position of the laser spot can be detected. The position of detected laser spot is then calculated to angle value by the some calculation of built in software [3].

The surfaces of sliders are of various coating materials, together with the effects of air bearing or other undesired contamination; they might in some cases result in light scattering as the laser beam reflected from them. Furthermore, the captured images sometimes do not appear in a perfect circle as they should for a perfect calculation. These factors are all make the measurements inaccurate. A replacement of a measuring system with higher performance could be one of a possible way to solve the aforementioned issues. As for example, a position sensitive detector (PSD) system has been replaced CCD as discussed in [3]. In [4], a new CMOS vision chip has been developed especially for laser spot position detection [4]. However, the cost of such solutions is very high. For this reason, this paper proposed another method in attempt to circumvent this difficulties using image processing.

An image has its own information and once the information is processes as digital data, it can be analyzed or managed as desired. This also applied to the captured laser spot images. In general, the captured images from the same slider surface or HSA surface are likely to give the same measurement results. It is also assumed that more images contain more information compared to just only one image. It should be noted that the desired information is still obtained from the same source. Since each captured image might not hold all the essential information for measurement, therefore image fusion is the proposed solution which attempts to solve the unclearness of captured images for better measurement accuracy. Hence, the proposed technique will use a set of images instead of only one image for measurements. This set of images will be fused by using wavelet transform techniques. Image fusion by wavelet transform is widely used and has satisfied results in many fields such as medical, satellites, and material evidences [5-7]. Therefore this paper will proposed a method which makes use of this technique to solve the concern issue.

The paper is divided into two main parts; the first part is concerning image fusion using wavelet transform technique. Appropriate fusion rule or synthesis coefficient will be applied on to the set of images, and the fused image with more complete information will be obtained. To do so a pre-image processing is necessary. After the fused image is matched to the measurement system, the value will be calculated from the fused image to the angle value in the second part. Images of standard parts are also needed as a reference such that the value calculated from the synthesized images could be compared for more accurate measurement.

II. PROPOSED ALGORITHM

The images obtained from a CCD camera are sometimes distorted. This might lead to inaccurate position calculation in measuring process. For example, in case two center points of laser spot are detected, the system will fail to measure. The proposed solution is to use multi-capturing images of the same plane. This can be obtained by moving a set of camera by small steps. This set of images will go through an image pre-processing before getting analyzed by wavelet transform. After that they will be fused by fusion strategy. The fused image is then synthesized by inverse wavelet transform. A diagram of the proposed algorithm is shown in Fig.1.

The detail of each block will be discussed in the following parts.

A. Image pre-processing

In some cases the captured image from the CCD camera are not perfect. This can be seen as light scatter or distorted circle in Fig.2 (b)-(d). In order to measure the PSA and RSA accurately, the input images should be pre-processed before analyzed by wavelet transform. In this research Imcomplement technique is eventually chosen after studied on many image processing techniques. The idea of Imcomplement is to convert the darker zone of image to be brighter and vice versa. The laser spot is normally brighter than background area and the purpose of this method is to emphasize the laser spot area in the image. Then background area will less important when the images are fused and the result is shown more satisfied.

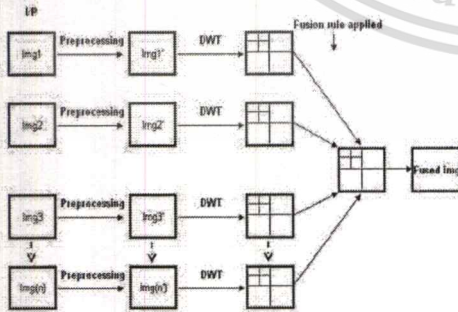


Figure 1.The diagram of proposed algorithm.

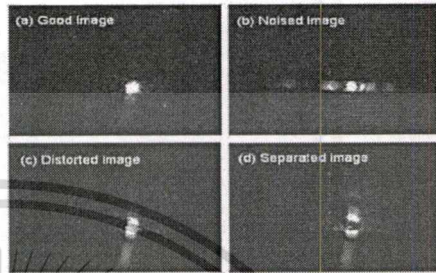


Figure 2. Input images from CCD camera. (a) Good image, (b) Noised image, (c) Distorted image, (d) Separated image.

B. Discrete wavelet transform

The two dimension (2D) wavelet transforms W of the two registered input images $I_1(x,y)$ and $I_2(x,y)$ are operated by filtering and down-sampling process. Fused strategy F is used to combine their coefficient matrices. The result image $I(x,y)$ is obtained from the inverse wavelet transformation, W^{-1} . The result fused image $I(x,y)$ can then be used for further purpose. The concept of image fusion using wavelet is governed by equation (1)

$$I(x,y) = W^{-1}\{F[W(I_1(x,y)), W(I_2(x,y))]\} \tag{1}$$

In detail, the 2D wavelet transform horizontally filters and down-samples using the 1-D low pass filter L and high pass filter H to each row of the image I . The coefficient matrices have then been produced. After that, following by vertically down-sampling using low pass and high pass filters L and H to each column and the sub-images have been produced [10]. The coefficient matrices and sub-images will be used for the proposed fusion rule in the following step. One stage of 2D-DWT multi resolution image decomposition is shown in the Fig.3.

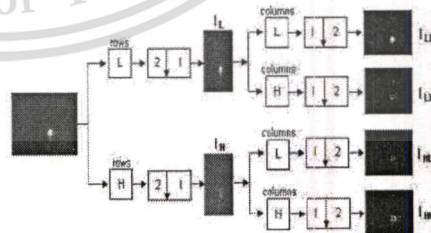


Figure 3.One stage of 2D-DWT multi resolution image decomposition.

C. Fused strategy

The purpose of fusion is to make the final image as circular as possible before measuring its angle values. The circular or roundness comparison is desired for the fused strategy. Roundness of laser spot is defined by equation (2).

$$\text{Roundness} = \frac{4 \times \pi \times \text{area}}{\text{perimeter}^2} \quad (2)$$

Roundness is equal to one only for a circle and it is less than one for any other shape. The multi value in case of separated input image is ignored. Then image which has the closest roundness to one will be the main template of fusion process. The example of roundness is shown in Fig.4.

In Fig.4 the roundness of (a) is 0.90 which is the closest to one, (b) is multi value so will be ignored and not choose to be the template, (c) is 0.85 which closer to one than (d) at 0.65 so the template of fusion will be prior to (a), (c) and (d) respectively. Post image process, binarization which use Otsu's method [8], noise elimination, erosion and dilation processed by the morphological grayscale reconstruction algorithm [9], are done after fusion.

D. Angle value calculation

In the proposed method, a centroid of an image is referred to as its angle position. The position of the centroid is reported in two elements. The first element of the centroid has horizontal coordinates (or x-axis) at the center of the image, and the second element has vertical coordinates (or y-axis). The x-coordinate represents PSA values and the y-coordinate represents RSA values. The directions of PSA and RSA are represented by coordination, as shown in Fig.5. The hard standard gauges, which were built by a very high precision machine, are used to collect the laser spot images reflected from the gauges. Their centroids were calculated and correlated to the reading value, which were received from the machine.

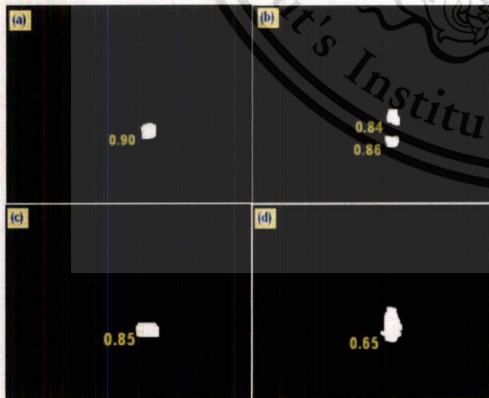


Figure 4. Defined Roundness of images

The interpolation method is used to calculate and get the transfer function of the centroids of the images to the angle values. The transfer function equations are separated in range of positive and negative values from both PSA and RSA since it is easier to compensate the offset value at the machine, which is the same as the current measuring system.

III. EXPERIMENTAL RESULT

There are various products of sliders. They differ in properties of materials on the surface and the groove pattern of the air bearing. Therefore only one product and a corresponding standard hard gauge image of laser spot has been collected for this experiment.

A. Fusion phase

The Imcomplement technique helps to emphasize the laser spot area in the image and makes the background area less important when they are fused. The example of imcomplement is shown in Fig.6. The resulting images are thus more suitable for analyze after preprocessing. In this work, the Symlets wavelet family is found to be more suitable compared to another wavelet family e.g the Daubechies [5]. For this reason Symlets wavelet functions have been selected for wavelet decomposition. The coefficients matrices are obtained after the input images have been decomposed. The Symlet2 wavelet function at level5 decomposition is desired in this paper. The example decomposition are shown in Fig.7 and also the final result after inversed wavelet transform are shown in Fig.8

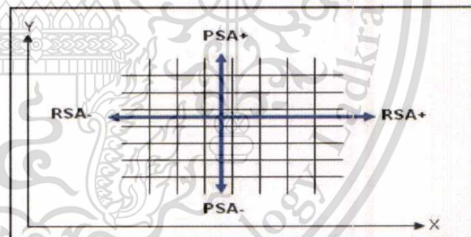


Figure 5. Fused PSA and RSA directions on X-Y coordinate.



Figure 6. Image preprocessing. (a) and (c) are original image, (b) and (d) are imcomplement processed images

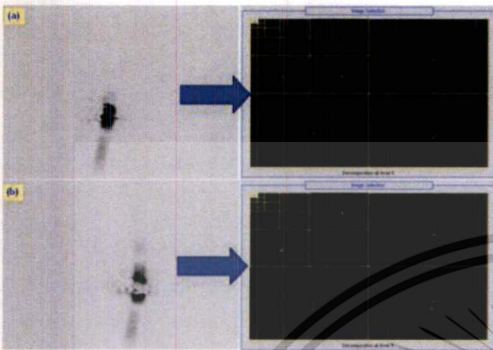


Figure 7. Symlet2 wavelet transform at level15

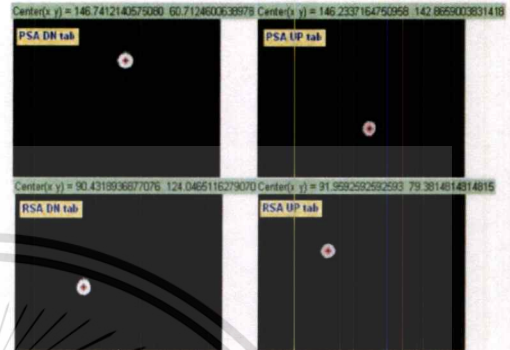


Figure 9. Centroids calculation of PSA and RSA plotted on original images.



Figure 8. Result of image fusion. (a3) is output of (a1) and (a2), (b3) is output of (b1) and (b2), (c3) is output of (c1) and (c2)

B. Measurement phase

The images obtained from the standard part, the hard gauge made by high precise machines, have been collected. The parts catalogued by up tab PSA, down tab PSA, up tab RSA and down tab RSA. Almost all of the products do not have the cover range of the angle values so this is why ranges have been separated into positive and negative.

The process of image pre-processing is also applied to these set of images in order to find the centroid. It can be seen that the image quality of hard gauge is much better than the obtained image of the slider, due to very smooth and flat surface. The samples of the centroid, the position of gauge, that are plotted on the original images are shown in Fig.9

The position of these centroids correlated to the machine angle readings. So that transfer function is established by linear interpolation. Correlation plot and transfer equations are shown in Fig.10.

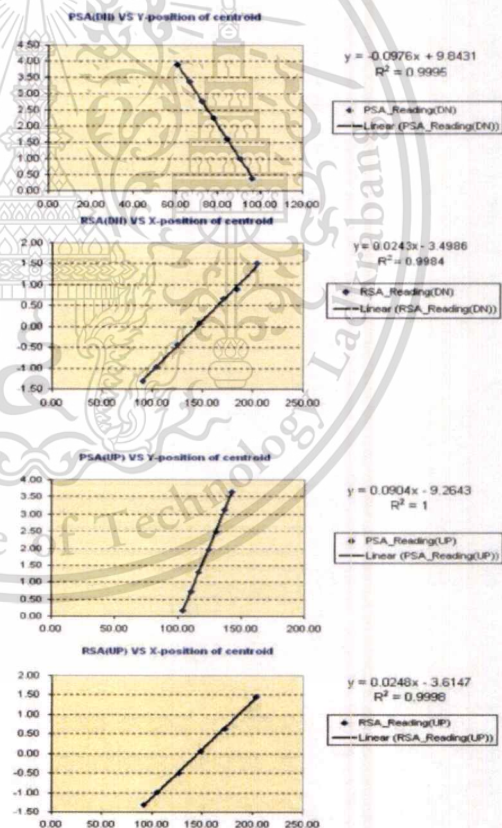


Figure 10. Correlation plotted and transfer equation of centroid to angle value.



Figure 11. Centroid of original image VS after fused image.

Fig.11 illustrates a comparison of the centroid of the original images and of the fused images. Note that the original (b) could not be measured by the current system and the original (d) might be able to measure but prone to error compared to the fused image (c). The fused image (a) is likely to be more accurate in angle reading value when compared to input (a1) or (a2) in Fig.8.

IV. CONCLUSION

Image fusion using wavelet transform technique is capable to solve the distortion of obtained images from the light scattering or in some cases, grooves on air bearing surface of the slider. The results shown in Fig.11 strongly assure that the proposed method work very well compared to the current method. However, the better-fused strategy needs to be studied for better results. The contrast and brightness of the images have also not been mentioned at this time. The qualitative measurement of the fused image could be shown in some ways in further study. At the bottom line, however, the proposed method give more confidence in measuring PSA and RSA due to the imperfect input images compared to the currently used method.

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REFERENCES

- [1] Thoatsanope K, Surachate Ch, Jukkaphun P, "The improvement of deformations and characteristics of HGA during clamping using finite element analysis", Proceedings of the 2008 Winter Simulation Conference, pp. 1335-1343
- [2] Hong Zhu, David B. Bogy, "Effect of Pitch static attitude and Roll static attitude on the Steady performance of Air Bearing sliders", Paper no. WTC2005-63320 pp.693-694, World Tribology Congress III (WTC2005) September 12-16, 2005, Washington, D.C., USA
- [3] Ronald Sloat, "High-Resolution, Non-contact Angular measurement system for PSA/RSA" A Thesis presented to the Faculty of California Polytechnic State University, San Luis Obispo, March 2011, pp.1-7
- [4] Jair Garcia-Lamont, Miguel Aleman-Arce, "CMOS vision Chip for Laser spot Position Detection", 2010 Electronics, Robotics and Automotive Mechanics Conference, IEEE2010, doi: 10.1109/CERMA.2010.90
- [5] Wang, A, Haijing Sun, Yueyang Guan, "The application of wavelet transform to Multi-modality Medical Image fusion", Proc. 2006 IEEE International Conference, pp. 270-274, doi: 10.1109/ICNSC.2006.1673156
- [6] Hongbo Wu, Yanqiu Xing, "Pixel-based Image fusion using wavelet transform for spot and ETM+ image", progress in Informatics and Computing (PIC), 2010 IEEE International Conference, pp. 936-940, doi: 10.1109/PIC.2010.5687880.
- [7] Hongbing Zhang, "Research on the application of image fusion in material evidence photography", Multimedia Technology (ICMT), 2010 International Conference, pp. 1-3, doi: 10.1109/ICMULT.2010.5631114
- [8] Otsu, N., "A Threshold Selection Method from Gray-Level Histograms", IEEE Transactions on Systems, Man, and Cybernetics, Vol. 9, No. 1, 1979, pp. 62-66.
- [9] Vincent, L., "Morphological Grayscale Reconstruction in Image Analysis: Applications and Efficient Algorithms", IEEE Transactions on Image Processing, Vol. 2, No. 2, April, 1993, pp. 176-201.
- [10] G. Pajares, J. Manuel de la Cruz, "A wavelet-based image fusion tutorial", pattern Recognition 37 (2004), pp. 1855 - 1872, doi:10.1016/j.patcog.2004.03

APPENDIX B

MATLAB CODE

Main section

```

clear all
close all
clc

[pic1 , R1] = PrePro; figure, imshow(pic1);title('Original#1');
[pic2 , R2] = PrePro; figure, imshow(pic2);title('Original#2');

%% Wavelet Transform
wname = 'db2'; % wavename = db2
[cI1,sI1] = wavedec2(pic1,2,wname); % wavelet transform for image 1
[cI2,sI2] = wavedec2(pic2,2,wname); % wavelet transform for image 2

% Approximate Coefficients
% for pic1
cI1a2 = appcoef2(cI1,sI1,wname,2); % approximate coefficient level 2
cI1a1 = appcoef2(cI1,sI1,wname,1); % approximate coefficient level 1

% for I2
cI2a2 = appcoef2(cI2,sI2,wname,2); % approximate coefficient level 2
cI2a1 = appcoef2(cI2,sI2,wname,1); % approximate coefficient level 1

% Detail Coefficients
% for I1
[cI1hd2, cI1vd2, cI1dd2] = detcoef2('all',cI1,sI1,2); % detail coefficient level 2
[cI1hd1, cI1vd1, cI1dd1] = detcoef2('all',cI1,sI1,1); % detail coefficient level 1

% for I2
[cI2hd2, cI2vd2, cI2dd2] = detcoef2('all',cI2,sI2,2); % detail coefficient level 2
[cI2hd1, cI2vd1, cI2dd1] = detcoef2('all',cI2,sI2,1); % detail coefficient level 1

%% Fusion Coefficient matrices

% Circular weighted rules

Rall = R1 + R2;
cA2Cir = (R1/Rall)*cI1a2 + (R2/Rall)*cI2a2;
cH2Cir = (R1/Rall)*cI1hd2 + (R2/Rall)*cI2hd2;
cV2Cir = (R1/Rall)*cI1vd2 + (R2/Rall)*cI2vd2;
cD2Cir = (R1/Rall)*cI1dd2 + (R2/Rall)*cI2dd2;

cH1Cir = (R1/Rall)*cI1hd1 + (R2/Rall)*cI2hd1;
cV1Cir = (R1/Rall)*cI1vd1 + (R2/Rall)*cI2vd1;
cD1Cir = (R1/Rall)*cI1dd1 + (R2/Rall)*cI2dd1;

```

Main Section (cont.)

```

%% Reconstruction Image

% Circular Weighted Rule
% Fused coefficients level 2
cA2C = cA2Cir(:);
cH2C = cH2Cir(:);
cV2C = cV2Cir(:);
cD2C = cD2Cir(:);

% Fused coefficients level 1
cH1C = cH1Cir(:);
cV1C = cV1Cir(:);
cD1C = cD1Cir(:);

% Image Reconstruction
cFusedC = [cA2C, cH2C, cV2C, cD2C, cH1C, cV1C, cD1C];
IfusedC = waverec2(cFusedC,sI1,wname);
figure, imshow(IfusedC); title('Fused Image');

%% Post Image Processing
PostPro(IfusedC);

```

Image Preprocessing section

```

function [img1 , R_AVG] = PrePro(image)

%%Load image
Getimg1=imread(uiigetimage);
img1=im2double(Getimg1);

%% Image processing

threshold = graythresh(img1);
bw = im2bw(img1,threshold);
% remove all object containing fewer than 50 pixels
bw = bwareaopen(bw,50);
bw = imfill(bw,'holes');
se = strel('disk',5);
bw = imclose(bw,se);
[B,L] = bwboundaries(bw,'noholes');

```

Image Preprocessing section (cont.)

```

stats = regionprops(L,'Area','Centroid');

for k = 1:length(B)

    % obtain (X,Y) boundary coordinates corresponding to label 'k'
    boundary = B{k};

    % compute a simple estimate of the object's perimeter
    delta_sq = diff(boundary).^2;
    perimeter = sum(sqrt(sum(delta_sq,2)));

    % obtain the area calculation corresponding to label 'k'
    area = stats(k).Area;

    % compute the roundness metric
    Roundness(k) = 4*pi*area/perimeter^2;
end

R_AVG = 0;

for i = 1:length(B)

    % compute the roundness average
    R_AVG = R_AVG+Roundness(i);

end

R_AVG = R_AVG/k;
sprintf('%2.3f',R_AVG);

end

```

Image Post processing section

```

function [Centroid , binary3] = PostPro(img)
%% Image processing Section

binary = im2bw(img,graythresh(img));
binary2 = bwareaopen(binary,30); %----- Remove all image that area < 30
se = strel('disk',7); %----- strel function ----Disc radius
bbb = imcomplement(binary2);
ccc = imclose(bbb,se); %----- fill area ---
binary3 = imcomplement(ccc);

%figure,imshow(binary2); %----- if function error,need to check this*--
%figure,imshow(bbb);
%figure,imshow(ccc);
%figure,imshow(binary3);

```


Function get image location in drive (cont.)

```

[fname, fpath] = uigetfile(ftype, titl, 'MultiSelect', 'on');
% To restrict selection to a single file, uncomment the next line, and
% delete the previous one above
% [fname, fpath] = uigetfile(ftype, titl);

fclass = class(fname);
if strcmp(fclass, 'double')==1;
    disp('No file chosen');
    return
% If output argument, fpath, is not asked for, fname contains full path
elseif nargin>2
    if iscell(fname) ~==1;
        fname = [fpath, fname];
    else for ii=1:length(fname)
        fname[ii]= [fpath, fname{ii}];
    end
end
end

%[filename, fpath] = UIGETIMAGE(titl)
% Use of UIGETFILE tailored for selection of image file(s) with formats
% supported by IMREAD. A dialog box is displayed for the user to fill in,
% and returns the filename and path strings.
%
% You can choose a single file, or several using the Shift and Ctrl keys
% in the usual way supported by the operating system.
%
% titl = [optional] title or request, e.g., 'Please select first image'
% fname = file name, char variable for single file, or
%         cell array of file names if several are chosen.
% fpath = [optional] file path (directory of folder) for chosen file(s)
%         if fpath is not asked for, then fname contains the full path
%         for each file chosen.
%
% NEEDS: UIGETFILE
%
% Example usage:
% Returns full file path to selected file(s)
%> fn = uigetimage('Pick a picture file')
%
% Returns names and path for file(s) selected with default title
%> [fn, fpath] = uigetimage;
%
% Peter Burns, 22 April 2011

```

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- Chaloeplap, N. Chaiwat N., "APPLICATION OF IMAGE FUSION USING WAVELET TRANSFORM IN SLIDER ORIENTATION MEASUREMENT". ICISCA 2012, The proceedings of International Conference of Information Science and Computer Application 2012 at Bali, Indonesia, November 14-15, 2012.

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