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Automated localisation of the optic disc, fovea, and retinal blood vessels from digital colour fundus images¹

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ABSTRACT — **Aim--** To recognise automatically the main components of the fundus on digital colour images. **Methods--** The main features of a fundus retinal image were defined as the optic disc, fovea and blood vessels. We describe methods for their automatic recognition and location. 112 retinal images were pre-processed via adaptive, local, contrast enhancement. The optic discs were located by identifying the area with the highest variation in intensity of adjacent pixels. Blood vessels were identified by means of a multilayer perceptron neural net, for which the inputs were derived from a principal component analysis of the image and edge detection of the intensity. The foveas were identified using matching correlation together with characteristics typical of a fovea—for example, darkest area in the neighbourhood of the optic disc. The main components of the image were identified by an experienced ophthalmologist for comparison with computerised methods. **Results--** The sensitivity and specificity of the recognition of each retinal main component was as follows: 99.1% and 99.1% for the optic disc; 83.3% and 91.0% for blood vessels; 80.4% and 99.1% for the fovea. **Conclusions--** In this study the optic disc, blood vessels and fovea were accurately detected. The identification of the normal components of the retinal image will aid the future detection of diseases of these regions. In diabetic retinopathy, for example, an image could be analysed for retinopathy with reference to sight threatening complications such as disc neovascularisation, vascular changes or foveal exudation.

Key Words -- Image Analysis, Image Recognition, Neural Network, Diabetic Diagnosis, Retinopathy

บทคัดย่อ-- วัตถุประสงค์: การใช้เทคโนโลยีคอมพิวเตอร์หาส่วนประกอบหลักๆ ของเรตินาอย่างอัตโนมัติจากภาพสีที่ถ่ายจากกล้องถ่ายภาพเรตินาระบบดิจิทัล **หลักการ--** ภาพเรตินาประกอบด้วย ออฟติคดิสก์ โฟเวีย และเส้นเลือด หลักการที่จะกล่าวต่อไปจะใช้อธิบายการหาตำแหน่งอย่างอัตโนมัติของส่วนประกอบหลักๆ นี้ กับ 112 ภาพ เริ่มต้นด้วยการทำให้ภาพคมชัดขึ้นโดยเทคนิค Adaptive Local Contrast Enhancement จากนั้นหาตำแหน่งของออฟติคดิสก์โดยการวัดความแปรผันของ Intensity ณ.จุดนั้นกับบริเวณใกล้เคียง เส้นเลือดในตาสามารถวิเคราะห์ โดยใช้เทคนิคโครงข่ายประสาทเทียมแบบ Multilayer perceptron โดยที่ข้อมูลที่ป้อนเข้าไปนามาจากเทคนิค Principal component analysis (PCA) และ Edge detection ของ PCA โฟเวียสามารถหาได้โดยใช้เทคนิค Matching correlation และลักษณะเฉพาะของโฟเวียอาทิเช่น ลักษณะมืดคล้ายบริเวณข้างๆ ออฟติคดิสก์สุดท้ายวัดความถูกต้อง โดยเปรียบเทียบตำแหน่งของส่วนประกอบหลักๆ ที่ได้จากคอมพิวเตอร์กับการบอกตำแหน่งโดยแพทย์ผู้เชี่ยวชาญ **ผลที่ได้--** ค่า Sensitivity และค่า Specificity ของการหาส่วนประกอบของภาพเรตินาแต่ละส่วนอย่างอัตโนมัติ เป็นไปดังนี้ 99.1% และ 99.1% สำหรับตำแหน่งออฟติคดิสก์, 83.3% และ 91.0% สำหรับตำแหน่งเส้นเลือดในตา และ 80.4% กับ 99.1% สำหรับตำแหน่งโฟเวีย **บทสรุป--** จากการศึกษาที่คอมพิวเตอร์สามารถหาตำแหน่งออฟติคดิสก์ เส้นเลือด และโฟเวียได้อย่างถูกต้อง การหาส่วนประกอบหลักๆ ของเรตินานี้จะช่วยวิเคราะห์บริเวณผิดปกติที่เกิดขึ้นในอนาคต ในตาของคนที่เป็นโรคเบาหวาน อาการที่อาจจะมียผลกระทบร้ายแรง เช่น disc neovascularisation, vascular changes หรือ foveal exudation เป็นต้น

¹ This article is a reprint of the article appeared in the British Journal of Ophthalmology (Br J Ophthalmol 1999 83: 902-910)

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1. Introduction

The patterns of disease that affect the fundus of the eye are varied and usually require identification by a trained human observer such as a clinical ophthalmologist. The employment of digital fundus imaging in ophthalmology provides us with digitised data that could be exploited for computerised detection of disease. Indeed many investigators use computerised image analysis of the eye, under the direction of a human observer [1-4]. The management of certain diseases would be greatly facilitated if a fully automated method was employed [5]. An obvious example is the care of diabetic retinopathy, which requires the screening of large numbers of patients (approximately 30,000 individuals per million total population [6,7]). Screening of diabetic retinopathy may reduce blindness in these patients by 50% and can provide considerable cost savings to public health systems [8,9]. Most methods, however, require identification of retinopathy by expensive, specifically trained personnel [10-13]. A wholly automated approach involving fundus image analysis by computer could provide an immediate classification of retinopathy without the need for specialist opinions.

Manual semiquantitative methods of image processing have been employed to provide faster and more accurate observation of the degree of macula oedema in fluorescein images [14]. Progress has been made towards the development of a fully automated system to detect microaneurysms in digitised fluorescein angiograms [15,16]. Fluorescein angiogram images are good for observing some pathologies such as microaneurysms which are indicators of diabetic retinopathy. It is not an ideal method for an automatic screening system since it requires an injection of fluorescein into the body. This disadvantage makes the use of colour fundus images, which do not require an injection of fluorescein, more suitable for automatic screening.

The detection of blood vessels using a method called 2D matched filters has been proposed [17]. The method requires the convolution of each image with filter of size 15×15 for at least 12 different kernels in order to search for directional components along distinct orientations. The large size of the convolution kernel entails heavy computational cost. An alternative method to recognise blood vessels was

developed by Akita and Kuga [18]. This work does not include automatic diagnosis of diseases, because it was performed from the viewpoint of digital image processing and artificial intelligence.

None of the techniques quoted above has been tested on large volumes of retinal images. They were found to fail for large numbers of retinal images, in contrast with the successful performance of a neural network.

Artificial neural networks (NNs) have been employed previously to examine scanned digital images of colour fundus slides [19]. Using NNs, features of retinopathy such as haemorrhages and exudates were detected. These were used to identify whether retinopathy was present or absent in a screened population but allowed no provision for grading of retinopathy. The images with retinopathy still require grading by a trained observer. Grading greatly improves the efficiency of the screening service because only those patients with sight threatening complications are identified for ophthalmologic management. This task is more complex than identifying the presence of retinopathy because the computer programme must be able to detect changes such as neovascularisation, cotton wool spots, vascular changes and perifoveal exudation [20]. The first step for achieving this aim is to be able to automatically locate the main regions of the fundus—that is, the optic disc, fovea and the blood vessels. The data from these regions can then be analysed for features of sight threatening disease. Identification of the regions of the fundus may also aid analysis of images for other diseases that preferentially affect these areas preferentially—for example, glaucoma and senile macular degeneration.

In this study, a variety of computer image analysis methods, including NNs, were used to analyse images to detect the main regions of the fundus.

2. Methods

In all, 112 TIF (tagged image format) images of the fundi of patients attending a diabetic screening service were obtained using a TOPCON TRC-NW5S non-mydriatic retinal camera. Forty degree images were used.

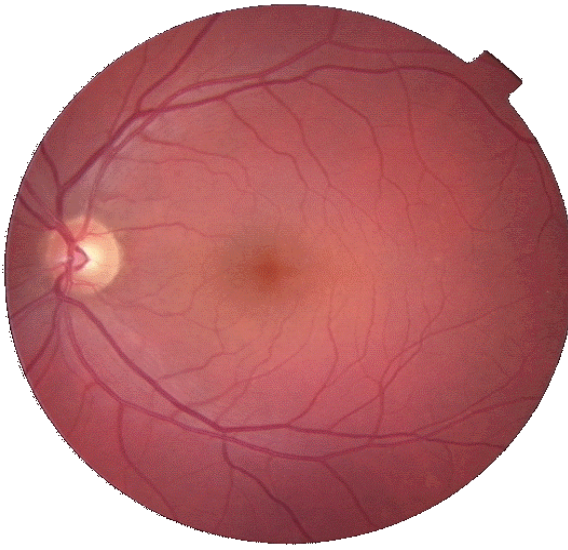


Figure 1: Digital Colour Retinal Image.



Figure 2: Retinal image after pre-processing by local colour contrast enhancement.

2.1 Pre-processing of Colour Retinal Images

The captured fundus images were of dimensions 570×550 pixels. Each pixel contained three values, red, green, and blue, each value being quantised to 256 grey-levels. An example can be seen in Figure 1. The contrast of the fundus images tended to diminish as the distance of a pixel from the centre of the image increased. The objective of pre-processing was to reduce this effect and to normalise the mean intensity. The intensities of the three colour bands were transformed to an intensity-hue-saturation representation [21]. This allowed the intensity to be processed without affecting the perceived relative colour values of the pixels. The contrast of the intensity was enhanced by a locally adaptive transformation. Consider a sub-image, $W(i, j)$, of size $M \times M$ pixels centred on a pixel located at (i, j) . Denote the mean and standard deviation of the intensity within $W(i, j)$ by $\langle f \rangle_W$ and σ_W respectively. Suppose that f_{max} and f_{min} were the maximum and minimum intensities of the whole image.

The adaptive local contrast enhancement transformation was defined by equations (A1) and (A2) of appendix A.

Figure 2 shows the effect of pre-processing on a fundus image, Figure 1.

2.2 Recognition of the Optic-Disc

The optic-disc appeared in the fundus image as a yellowish region. It typically occupied approximately one seventh of the entire image, 80×80 pixels. The appearance was characterised by a relatively rapid variation in intensity because the

“dark” blood vessels were beside the “bright” nerve fibres. The variance of intensity of adjacent pixels was used for recognition of the optic disc.

Consider a sub-image $W(i, j)$ of dimensions $M \times M$ centred on pixel (i, j) . Let $\langle f \rangle_W$ as defined by equation (A3) be the mean intensity within $W(i, j)$. (If $W(i, j)$ extended beyond the image, then undefined intensities were set to zero and the normalisation factor was correspondingly reduced.)

A variance image was formed by the transformation

$$g(i, j) \rightarrow p(i, j) = \langle f^2 \rangle_W - (\langle f \rangle_W)^2, \quad (1)$$

where the sub-image was 80×80 pixels. An image of the average variance within sub-images was then obtained as

$$p(i, j) \rightarrow q(i, j) = \langle p \rangle_{W(i, j)} \quad (2)$$

The location of the maximum of this image was taken as the centre of the optic-disc, (i_d, j_d) .

$$(i_d, j_d) = \arg \max_{W(i, j)} \langle p \rangle_{W(i, j)} \quad (3)$$

The variance image of Figure 2 is shown in Figure 3 and the location of the optic-disc in Figure 7.

2.3 Recognition of Blood-Vessels

Blood vessels appeared as networks of either deep red or orange-red filaments that originated within the optic disc and were of progressively diminishing width. A multilayer perceptron NN was used to classify each pixel of the image [22-24]. Pre-processing of the image was necessary before presentation to the input layer of

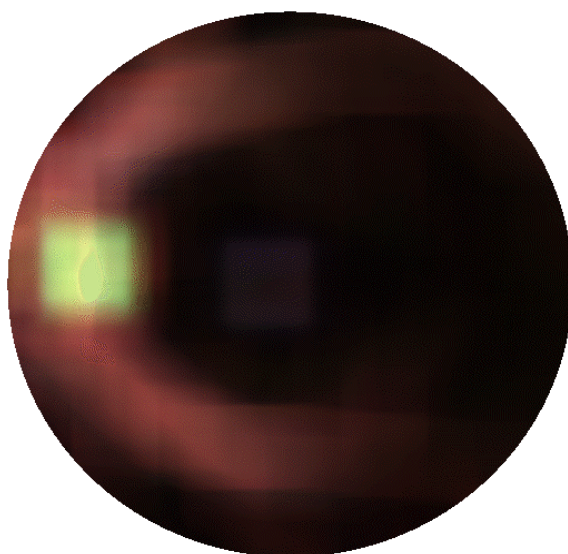


Figure 3: The variance image of Figure 2.

the NN. Pattern classifiers are most effective when acting on linearly separable data in a small number of dimensions. More details are described in appendix B.

The values of the three spectral bands of a pixel were strongly correlated. The principal component transformation [25] was used to rotate the axes from red-green-blue to three orthogonal axes along the three principal axes of correlation, thus diagonalising the correlation coefficient matrix. The values along the first axis exhibited the maximum correlated variation of the data containing the main structural features. Uncorrelated noise was concentrated mainly along the third axis, while, in general, texture tended to be along the second. The original data was reduced in dimensionality by two thirds by the principle component transformation.

A measure of edge-strength was obtained for each pixel by processing the image from the first principal component using a Canny edge-operator [26-28]. This was used to enhance vessel / non-vessel separability.

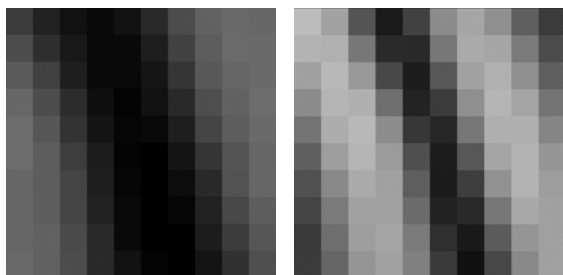


Figure 4: An example of the data input to the net, of size $2 \times 10 \times 10$ pixels. In this example, the pattern was classified as vessel.

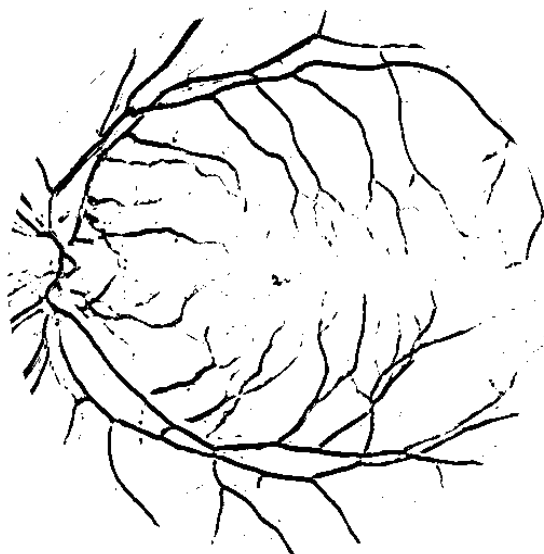


Figure 5: Classification of the image Figure 2 into vessels/non-vessels.

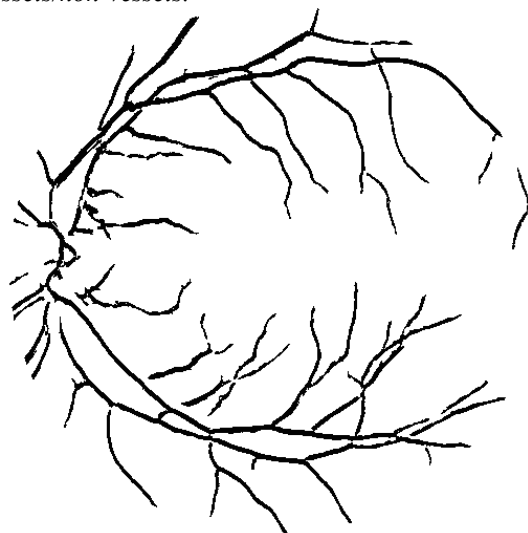


Figure 6: The classified image after post-processing to remove small regions.

2.4 Neural Network Algorithm

Each pixel of a fundus image was classified as vessel or non-vessel. The data input to the NN were the first principal component [29] and edge strength values from a sub-image of 10×10 pixels localised on the pixel being classified, as shown in Figure 4. The net was a three-layer perceptron having 200 input nodes, 20 hidden nodes and two output nodes.

A training/validation data set of 25,094 examples, comprising 8,718 vessel and 16,376 non-vessel, was formed by hand and checked by a clinician. The back propagation algorithm with

early stopping was applied [30,31], using 5/6 of the data for training and 1/6 for validation.

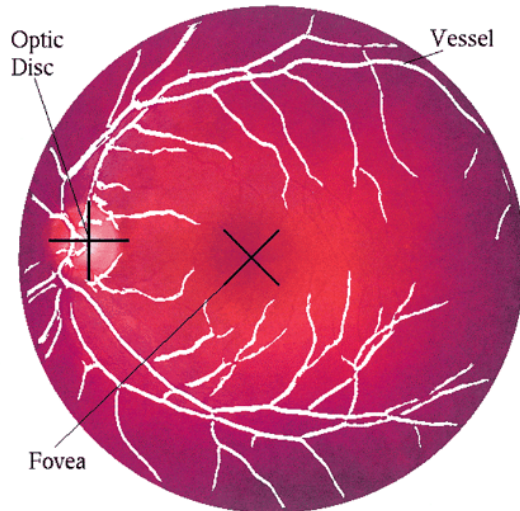


Figure 7: The results of automatic recognition of the main components of the fundus from digital fundus colour image.

2.5 Postprocessing [32,33]

Figure 5 shows the classification of the entire image into vessel and non-vessel, denoted as black and white respectively.

The performance of the classifier was enhanced by the inclusion of contextual (semantic) conditions. Small isolated regions of pixels that were misclassified as blood vessels were reclassified using the properties that vessels occur within filaments, which form networks. Three criteria were applied -- size, compactness and shape. Regions smaller than 30 pixels were reclassified as non-vessels. The compactness of a region may be expressed using the ratio of the square of the perimeter to the area [34] -- for example, circular discs have a ratio of 4π . Regions whose ratios were less than 40 were reclassified as non-vessels. Approximating a region by an elliptical disc yields a measure of shape in terms of the ratio of the major and minor axes [35]. Regions smaller than 100 pixels with a ratio smaller than 0.95 were reclassified as non-vessels as can be seen in Appendix C. Figure 6 shows the effect of such post-processing on an image.

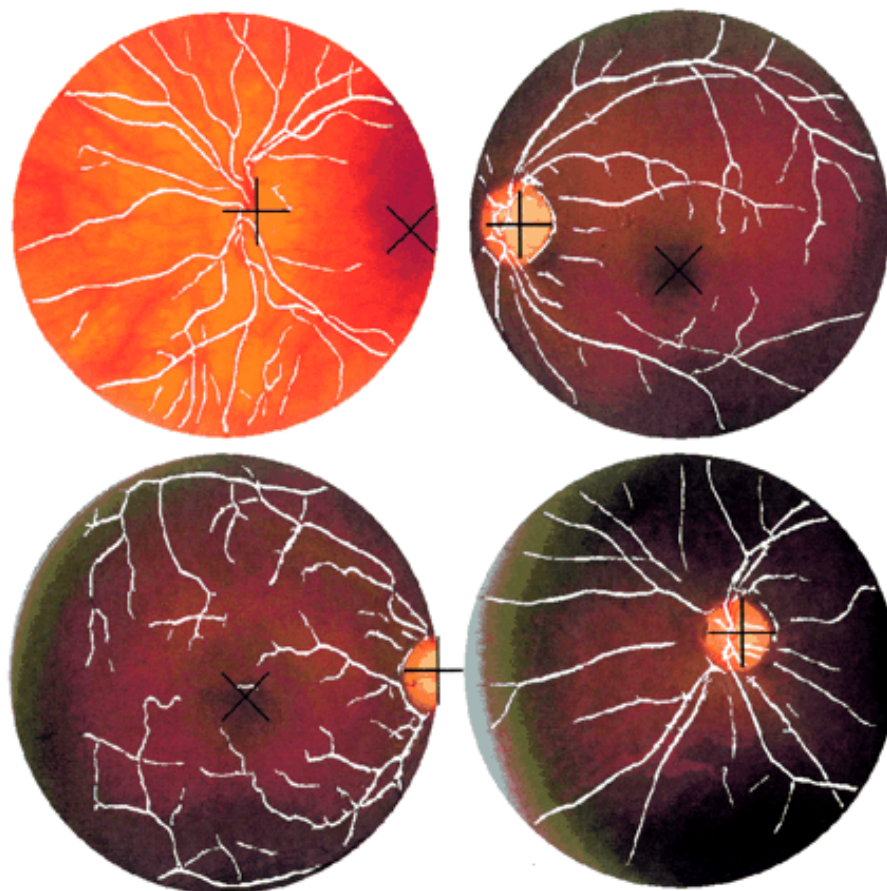


Figure 8: A sample of images showing the results of the recognition of the main components from digital fundus colour images.

2.6 Recognition of the Fovea

The centre of the fovea was usually located at a distance of approximately 2.5 times the diameter of the optic-disc, from the centre of the fundus image, with approximately the same intensity as the blood vessels. The fovea was first correlated to a template of intensities. The template was chosen to approximate a typical fovea and was defined by;

$$g(i, j) = 128 \left[1 - \frac{1}{2} \exp \left(\frac{-(i^2 + j^2)}{2\sigma^2} \right) \right] \quad (4)$$

Where (i, j) are relative to the centre of the template. A template of size 40×40 pixels was employed, the standard deviation of the Gaussian distribution being $\sigma = 22$. Given a sub-image $W(i, j)$ centred on pixel (i, j) of dimensions $M \times M$ with

intensities $g(k, l), (k, l) \in W(i, j)$, the correlation coefficient of W at (i, j) with an image having intensities $f(i, j)$ is [21]

$$\gamma(i, j) = \frac{\sum_{k,l} [f(k, l) - \langle f \rangle_W] [g(i - k, j - l) - \langle g \rangle_W]}{\left\{ \sum_{k,l} [f(k, l) - \langle f \rangle_W]^2 \sum_{k,l} [g(i - k, j - l) - \langle g \rangle_W]^2 \right\}^{1/2}} \quad (5)$$

The correlation coefficient $\gamma(i, j)$ is scaled to the range $[-1 \leq \gamma \leq 1]$, and is independent of mean or contrast changes in $f(i, j)$ and $g(i, j)$. The range of values runs from anti-correlation, -1, through no correlation, 0, to perfect correlation +1.

The location of maximum correlation between the template and the intensity image, obtained from the intensity-hue-saturation

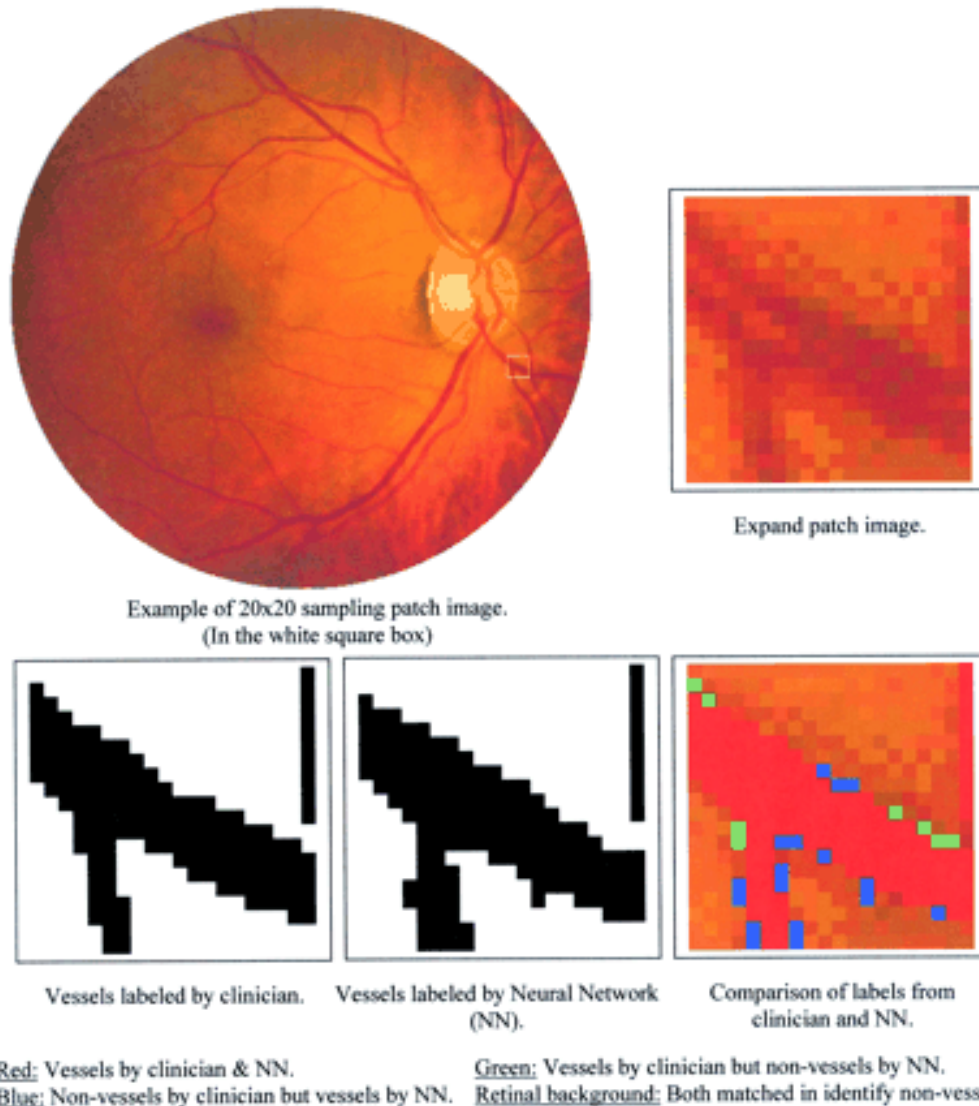


Figure 9: Example of patch of size 20x20 pixels used to measure the accuracy of vessels recognition.

transformation, was chosen as the location of the fovea, subject to the condition that it be an acceptable distance from the optic-disc and in a region of darkest intensity.

The criteria deciding the existence of the fovea were a correlation coefficient more than 0.5 and a location at the darkest area in the allowed neighbourhood of the optic disc.

Figure 7 and 8 give examples of foveal location, the cross indicates the located position in each example.

2.7 Validation of the Accuracy of Detection of Regions

An experienced ophthalmologist observed the localisation of the optic disc and fovea by the algorithms. In order to provide independent test data for the blood vessels, the same ophthalmologist manually traced the vessels of 73 randomly selected patches of 20 x 20 pixels taken from the images. The traced vessels were then compared with the positions of the vessels identified by the neural network. An example of a random patch is shown in Figure 9.

3. Results

The recognition rates for optic disc, blood vessels and fovea were as follows:

- (1) The optic disc was identified incorrectly in one image. The sensitivity and specificity for the detection of the optic disc recognition were 99.1% and 99.1% respectively.
- (2) The recognition rate of blood vessels by the neural network was 99.56% for training and 96.88% for validation data respectively. The sensitivity and specificity of the detection of blood vessels were calculated for each of the 73 patches. The overall sensitivity and specificity for the detection of the blood vessels were 83.3% (SD 16.8%) and 91.0% (SD 5.2%) respectively.
- (3) To assess the accuracy of recognition of the fovea, the images were separated into three groups: *Group 1*: 71 images presented all of the fovea of within the image. In 60 the fovea was detected correctly (84.5%) but in 11 (15.5%) the fovea was unidentified; *Group 2*: in 29 retinal images the fovea was at the edge of the image but more than half was present on the image. In 18 images the correct position of the fovea was located (62.1%). In one image the fovea was detected inaccurately in the nasal retina (3.4%). The fovea was not identified in 10 images (34.5%); *Group 3*: 12 retinal images either presented no fovea or less than half of the foveal area was within the image. The

algorithm did not identify a fovea in these images.

The overall sensitivity and specificity of the detection of the fovea were 80.4% and 99.1% respectively.

4. Discussion

In this study computer based algorithms were used to detect the main regions of the fundus without any intervention from an operator. The accuracy of the detection was high for the optic disc, blood vessels and the fovea (especially when the image contained the whole foveal area). It is hoped that the detection of these regions will aid the examination of fundal disorders. The optic disc was particularly reliably detected and may be examined in the future for patterns of disease such as glaucoma [36]. The fovea was missed in a number of cases but usually when there was poor centration of the fovea in the image. This can be easily remedied by more careful fundus photography. The detection of the major blood vessels was performed using NN analysis. NNs have been employed in the past in other areas of medicine [37] and ophthalmology [38,39] because of the capability of these programs to cope with highly variable images. Indeed, NN have already been used before to detect features of retinopathy but employing minimal pre-processing [40]. The pre-processing and post-processing used in this study reduces the reliance upon the NN and improves the efficiency of the computer analysis. The smaller blood vessels were more difficult to detect. However, the method used to calculate the accuracy of the detection of the blood vessels by comparing vessels recognised by the NN technique with the vessels traced by the ophthalmologist may introduce some errors. It was technically difficult for the ophthalmologist to locate subjectively the exact position of vessels, especially at their edges. Therefore, the accuracy of the ophthalmologists' identification of blood vessels may have been variable. Other methods may need to be explored in order to detect all of the blood vessels—for example, active contour models (SNAKES) [41,42], to avoid confusion with features such as retinal haemorrhages. There may be other applications for this technology—for example, the accurate detection of the major blood vessels may allow the “fingerprint” of the blood vessels to be used for identifying individuals in a way similar to that in which iris crypts have been utilised [43].

In this study it was possible to detect the main regions of the fundus image. Once these have been identified, the data from these regions can be analysed for abnormality. Of course some

of the diseases that we would propose to study may alter the appearance of these regions, reducing their detection. However, the algorithms were designed to minimise this risk, particularly for disease processes such as diabetic retinopathy. In diabetic retinopathy further algorithms will be required to detect features which indicate risk to the patients' sight such as neovascularisation, cotton wool spots, venous changes and parafoveal exudation. The detection of other features of retinopathy in diabetes (haemorrhages and exudates), and other disorders such as senile macular degeneration, will be facilitated by the removal from the image data set of complex regional features such as the blood vessels and the optic disc. In diabetes, grading of a patient's retinopathy by fundus imaging and computer analysis, at the site of acquisition of the image, would allow an immediate opinion for the patient on the urgency of referral for an ophthalmologic opinion.

In conclusion, computer algorithms were able to detect regions of the fundus. These may be exploited for the examination of patterns of disease. This may have particular relevance to the management of common ophthalmologic disorders such as diabetic retinopathy.

Appendix A: colour local contrast enhancement

The *RGB* colours, where *R*, *G*, and *B* are abbreviated from the colours *Red*, *Green*, and *Blue* respectively, represent the colour model used for computer graphics or image analysis. Another colour model, which will be used in this work, is the *IHS* model, where *I*, *H*, and *S* are abbreviations for *Intensity*, *Hue*, and *Saturation* respectively. The *RGB* and *IHS* have an invertible relation between them [21].

The importance of an *RGB* model is to display colour images. To present the full colour techniques for image enhancement in some detail, we are interested in the *IHS* model. The *IHS* model is best suited to present full colour techniques for image enhancement in detail. It is important that once the *IHS* model is applied to enhance an image, it must be converted back to *RGB* for visual display. The *IHS* model is suitable for image enhancement because the intensity component is decoupled from the colour information of the image. Applying the local contrast enhancement technique to the intensity component and converting the result to *RGB* for display will not affect the colour content of the image.

Local Contrast Enhancement [44]

Let the intensity, f , of the picture elements (pixels) of an $N \times N$ digital image be indexed by

(i, j) $1 \leq i, j \leq N$. Consider a subimage of size $M \times M$ centred on (i, j) in this paper $M=49$. Denote the mean and standard deviation of the intensity within W by $\langle f \rangle_W$ and $\sigma_W(f)$ respectively.

The objective is to define a point transformation dependent on W such that the distribution is localised around the mean of the intensity and covers the entire intensity range. The implicit assumption is that W is large enough to contain a statistically representative distribution of the local variation of grey levels, yet small enough to be unaffected by the gradual change of contrast between the centre and the periphery of the fundus image. The adaptive contrast enhancement transformation is defined by

$$f(i, j) \rightarrow g(i, j) = 255 \frac{[\Psi_W(f) - \Psi_W(f_{\min})]}{[\Psi_W(f_{\max}) - \Psi_W(f_{\min})]} \quad (A1)$$

Where the sigmoidal function was

$$\Psi_W(f) = \left[1 + \exp\left(\frac{\langle f \rangle_W - f}{\sigma_W}\right) \right]^{-1} \quad (A2)$$

while f_{\max} and f_{\min} are the maximum and minimum values of intensity within the whole image with

$$\langle f \rangle_{W(i, j)} = \frac{1}{M^2} \sum_{(k, l) \in W(i, j)} f(k, l) \quad (A3)$$

$$\sigma_W^2(f) = \frac{1}{M^2} \sum_{(k, l) \in W(i, j)} (f(k, l) - \langle f \rangle_W)^2 \quad (A4)$$

The local contrast enhancement function provides large contrast enhancement for an initially small σ (poor contrast) and little contrast enhancement for an initially large σ (high contrast).

As a result of local contrast enhancement, the dark area is brighter and clearer showing more detail. However, the technique of local contrast enhancement not only adjusts the contrast of the image but also increases the noise. Hence, a 2D Gaussian smoothing filter or median filter has been applied in order to reduce the noise before the local contrast enhancement process.

Appendix B: prepare data for NN

First Principal Component [45]

The PCA (principal component analysis) technique is the same as the Karhunen Loeve transform technique, also known as Hotelling transform, which aims to form linear combinations of the image bands in order to maximise the information content in the highest order bands. Giving a set of K image bands, denoted by the intensities of N^2 pixels $f_a(i)$ for $i=1, \dots, N$ $a = 1, \dots, K$.

We first form a set of *zero mean* images by subtracting off the mean of each band

$$g_a = f_a(i) - \langle f_a(i) \rangle \quad (B1)$$

Where

$$\langle f_a(i) \rangle = \frac{1}{N^2} \sum_{i=1}^{N^2} f_a(i) \quad (B2)$$

To simplify the formulation, it is convenient to write the set of K image bands $g_a(i)$ as a $N^2 \times K$ matrix, where each image of the spectral band forms a column of the matrix normally,

$$G = \begin{bmatrix} g_1(1) & g_2(1) & \dots & g_K(1) \\ g_1(2) & g_2(2) & \dots & g_K(2) \\ \vdots & \vdots & \ddots & \vdots \\ g_1(N^2) & g_2(N^2) & \dots & g_K(N^2) \end{bmatrix} \quad (B3)$$

We define a K by K matrix C as

$$C = G^T G, \quad (B4)$$

where G^T is the transpose of G . The matrix C , can be expressed in terms of the input image $g_a(i)$ as having elements,

$$\begin{aligned} c_{ab} &= \sum_{i=1}^{N^2} g_a(i) g_b(i) \\ &= \sum_{i=1}^{N^2} (f_a(i) - \langle f_a(i) \rangle) (f_b(i) - \langle f_b(i) \rangle) \quad (B5) \\ &= \sum_{i=1}^{N^2} f_a(i) f_b(i) - \frac{1}{N^2} \sum_{i=1}^{N^2} f_a(i) \sum_{i=1}^{N^2} f_b(i) \end{aligned}$$

This is the un-normalised correlation between the a th and the b th image bands.

Hence C is the spectral correlation matrix of the images. We form a matrix H of uncorrelated images by the orthogonal $K \times K$ matrix transform B .

$$H = GB \quad (B6)$$

Since the columns of H are uncorrelated

$$H^T H = \Lambda \quad (B7)$$

where Λ is a diagonal matrix

$$\Lambda = \begin{bmatrix} \lambda_1 & 0 & \dots & 0 \\ 0 & \lambda_2 & \dots & 0 \\ \vdots & \vdots & \ddots & \vdots \\ 0 & 0 & \dots & \lambda_K \end{bmatrix} \quad (B8)$$

it follows that

$$CB = BA \quad (B9)$$

The above equation is just the familiar eigen vector/value problem where the λ_a are the eigenvalues of the matrix C and the columns of the

matrix B are the corresponding eigenvectors. Since the matrix C is symmetric, $c_{ab} = c_{ba}$, the eigenvector problem involves finding the eigenvalues and vectors of a real symmetric matrix. Hence we can solve for the eigenvalues and vectors by applying Jacobi transformations [46]. Finally, the transform of the set of K orthogonal images $h_a(i)$, being linear combinations of the normalised images $g_a(i)$, is given by

$$h_a(i) = \sum_{b=1}^K b_{ab} g_b(i) \quad (B10)$$

for $a = 1, \dots, K$ and $h_1(1), h_1(2), \dots, h_1(N)$ will be the first component of the set of principal components which will be used together with the edge gradient as the pattern data for classification by a neural network.

Edge Gradient

In this paper we applied the edge operator to the first component of a *PCA* image. Canny has defined an edge detection operator, which is optimal for step edges corrupted by white noise. The operator that we use in this work is the implementation of operator obtained by Spacek. The reasons that we use Spacek's solution because Canny was unable to construct a solution of the defining conditions and so approximated one by a Difference of gaussians. Spacek demonstrated that performance of his solution was superior to Canny's approximation. Since the operator satisfies the conditions proposed by Canny we refer to it as the Canny edge operator.

The Spacek method that we use takes the form [28].

$$h(x) = 16.9564 \sin(x) + 13.0161 \cos(x) - 18.8629 \exp(x) + 4.8468 \exp(-x) + 1 \quad (B11)$$

$h(x)$ has been defined in the interval $(-1, 0)$. Values in the range $(0, 1)$ may be obtained from the anti-symmetry of the edge operator. For our application, we have modified to use the Canny edge filter in two dimensions by smoothing the operator in the orthogonal direction, hence yielding two dimensional edge kernels $h_x(x, y)$ and $h_y(x, y)$ for edge strengths in the x, y directions respectively. Now we apply the 2D edge filter in x and y directions. The response of the filters to the image is given by a 2D-convolution integral.

The response an image to an edge kernel is given by a 2D discrete convolution, the edge strength in the x direction

$$e_x(x, y) = \sum \sum h_x(\xi, \eta) f(x - \xi, y - \eta) d\xi d\eta \quad (B12)$$

with a similar equation for $e_y(x, y)$. The intensity of the edge image intensity is defined by

$$e(x, y) = [(e_x(x, y))^2 + (e_y(x, y))^2]^{1/2} \quad (B13)$$

Appendix C: post-processing

Area

The simplest and most natural property of a region is its area, given by the number of pixels of which the region is comprised. This method was used to remove the small regions of the output vessels/non-vessels classification from neural net, small regions with less than 30 pixels were removed.

Compactness [33]

Compactness is a commonly used shape descriptor independent of linear transformations given by

$$compactness = \frac{(region\ border\ length)^2}{area} \quad (C1)$$

The most compact region in Euclidean space is a circle. Compactness assumes values in the interval (1, ∞) in digital images if the boundary is defined as an inner boundary. The limit value of compactness in this work is 40, within the region less than 100 pixels will be determined.

Ellipse Parameter

The ellipse parameter used is the ratio between the major and the sum of the two (major and minor) axes of an ellipse. This parameter describes the shape of the region and lies between 0.5 (a circle) and 1 (a line). The method that we used to calculate this parameter is the same as employed in PCA. Considering a region, with two variables, x variable (positions of the region pixels in x co-ordinate) and y variable (positions of the region pixels in y co-ordinate). The major and minor axes of the region can be calculated as the eigen values of the covariance matrix:

$$c = \left[\frac{\sum (x_i - \langle x \rangle)^2}{\sum (x_i - \langle x \rangle)(y_i - \langle y \rangle)} \quad \frac{\sum (x_i - \langle x \rangle)(y_i - \langle y \rangle)}{\sum (y_i - \langle y \rangle)^2} \right] \quad (C2)$$

where x_i, y_i are co-ordinates in the x, y directions of the region and $\langle x \rangle, \langle y \rangle$ are the average value of the region's x, y co-ordinates. From this property, the ellipse parameter of circle, ellipse, and line are 0.5, $0.5 < \text{ellipse param} < 1$, and 1 respectively. From our experiments with the test images of variable shapes, we decided to use an ellipse parameter of less than 0.95 the small regions (less than 100 pixels) to classify then as non-vessels.

Acknowledgments:

We acknowledge the help of Professor Sonksen, Robin Edwards, and Shirley Smith of the

Department of Medicine, St Thomas's Hospital, London, for the use of their images.

Grant support organisation:

1. The Development and Promotion of Science and Technology Talent's Project (Thailand)
2. Overseas Research Student Awards (UK).

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Robust Stabilization of Uncertain Linear System with Distributed State Delay*

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Jongkol Ngamwiwit and Yothin Prempraneerach*

ABSTRACT – In this paper, we present the theoretical development to stabilize a class of uncertain time-delay system. The system under consideration is described in state space model containing distributed delay, uncertain parameters and disturbance. The main idea is to transform the system state into an equivalent one, which is easier to analyze its behavior and stability. Then, a computational method of robust controller design is presented in two parts. The first part is based on solving a Riccati equation arising in the optimal control theory. In the second part, the finite dimensional Lyapunov min-max approach is employed to cope with the uncertainties. Finally, we show how the resulting control law ensures asymptotic stability of the overall system..

KEY WORDS -- Robust Stabilization, Time-delay System, Control System Design.

1. Introduction

It is well known that uncertain parameters and disturbance in practical control system such as modeling errors, linearization approximations, etc., are always found and disturb the system. On the other hand, the time delay which commonly encountered in various engineering systems is frequently a source of instability. Therefore, the problem of robust stabilization of state delayed system with uncertain parameters have received considerable attention of many researchers, and many solution approaches have been proposed, see, for example [1~9] and reference therein. One approach which frequently applied to deterministic robust control is by means of the so-called “second method” of Lyapunov. The design is based on a nominal linearization of given system with time-varying, non-linear uncertain elements of the system and the extraneous disturbances grouped into an unknown but bounded function. Only knowledge of compact sets bounding the system uncertainties is required. Furthermore, if they satisfy certain matching conditions, complete insensitivity to the system variations can be achieved, see, for example [1~8] and reference therein. Other often-used approach is based on H_∞ control theory of which resulting control law is linear [9][10]

In this paper, A class of linear system containing constant known distributed state delay, uncertain parameters and additive disturbances are presented. Determination of controller parameters can be divided into two parts. First, base on the improved Fiagbedzi and Pearson theorem [11~13], the linear transformation is utilized to reduce the original problem into an equivalent one which is easier to find the solution. Next, by using the well-known Lyapunov min-max approach of Gutman [14], a suitable stabilizing control law is derived.

This paper is organized as follow. In the next section, we introduce the uncertain system considered here and the state-feedback based transformation technique. In section 3, we derive the required robust control law. A numerical example in section 4 demonstrates the proposed control method. Some final remarks and conclusion appear in Section 5.

2. Problem Formulation

Consider a class of uncertain time-delay systems (S_d) which is defined by the following state equations

$$\begin{aligned} \dot{x}(t) = & [A + \Delta A(t)]x(t) + [A_h + \Delta A_h(t)]x(t-h) \\ & + \int_{-r}^0 A_r(\theta)x(t-r-\theta)d\theta \end{aligned}$$

* This paper is reprinted from the same title of IEICE TRANS. FUNDAMENTALS, Vol.E82-A, No. 9 SEPTEMBER 1999, pp1911-1918

$$\begin{aligned} & + \int_{-r}^0 \Delta A_r(t) x(t-r-\theta) d\theta \\ & + [B + \Delta B(t)] u(t) + Bw(t) \end{aligned} \quad (2.1)$$

where $x \in R^n$ is the current value of the system state, $u(t) \in R^m$ is the control function, $\omega(t) \in R^l$ is the additive disturbance A, A_h, B are known constant matrices of appropriate dimensions, $A_r \in L_1([-r, 0]; R^{n \times n})$ is a matrix whose elements are integrable functions on $[-r, 0]$, $\Delta A(t), \Delta A_h(t), \Delta A_r(t), \Delta B(t)$ are matrices whose elements are continuous, unknown but bounded functions, $h, r \in R^+$ is a known constant delay time and the initial function of system be specified as $x_0(\eta) \in C_d([-t_f, 0]; R^n)$, $t_f = \max(h, r)$.

Assumptions

Before proposing our controllers, the following assumptions are made throughout here.

Assumption 2.1: The nominal system of (S_d) ; i.e., the system (S_d) which $\Delta A(t) = \Delta A_h(t) = \Delta A_r(t) = 0$, $\Delta B(t) = 0$, $w(t) = 0$ are spectrally stabilizable.

Assumption 2.2: For all $t \in R^+$, there are exist continuous matrix functions $H(t), H_h(t), H_r(t)$, and $E(t)$ of appropriate dimensions such that

- $\Delta A(t) = BH(t)$,
- $\Delta A_h(t) = BH_h(t)$,
- $\Delta B(t) = BE(t)$,
- $I + \frac{1}{2}(E(t) + E^T(t)) \geq \delta I$ for some scalar $\delta > 0$,
- $\Delta A_r(t) = BH_r(t)$
- there are scalar $\mu(x_t)$ and $\mu_E(t)$ such that $\mu(x_t) \geq \|H(t)x(t) + H_h(t)x(t-h) + \int_{-r}^0 H_r(t)x(t-r-\theta)d\theta + \omega(t)\|$,

and

$$\mu_E(t) \geq \|E(t)\|$$

- information δ, μ and μ_E are available

Note here that physical meaning of matching conditions defined in Assumption 2.2 is all disturbance and uncertainty effects disturb into the system though the same channel as the control. And if matching conditions are satisfies, we can rewrite system (S_d) to the form

$$\begin{aligned} \dot{x}(t) &= Ax(t) + A_h x(t-h) + \int_{-r}^0 A_r(\theta) x(t-r-\theta) d\theta \\ &+ B(u(t) + v(t)) \end{aligned} \quad (2.2)$$

where

$$\begin{aligned} v(t) &= H(t)x(t) + H_h(t)x(t-h) \\ &+ \int_{-r}^0 H_r(t)x(t-r-\theta) d\theta + E(t)u(t) + w(t) \end{aligned} \quad (2.3)$$

Transformation Technique

We begin with the linear transformation T_c defined by

$$\begin{aligned} z(t) &= (T_c(x))(t) \\ &= x(t) + \int_{-h}^0 e^{A_c \theta} A_h x(t-h-\theta) d\theta \\ &+ \int_{-r}^0 \int_{-\theta}^0 e^{A_c \tau} A_r(-r-\theta) x(t-r+\theta) d\tau d\theta \end{aligned} \quad (2.4)$$

where $A_c \in R^{n \times n}$ is a matrix yet to be defined.

Proposition 2.1 :

Let the matrix A_c be defined by

$$\begin{aligned} A_c &= A + e^{-hA_c} A_h \\ &+ \int_{-r}^0 e^{-(r+\theta)A_c} A_r(\theta) d\theta, \end{aligned} \quad (2.5)$$

and

$$\sigma_u(S_d) \subset \sigma(A_c) \subset \sigma(S_d) \quad (2.6)$$

where

$$\begin{aligned} \sigma(S_d) &= \{s \in C; \det(sI - A - e^{-hs} A_h \\ &- \int_{-r}^0 e^{-(r+\theta)s} A_r(\theta) d\theta) = 0\}, \end{aligned}$$

and

$$\sigma_u(S_d) = \{s \in \sigma(S_d); \operatorname{Re}(s) \geq 0\},$$

Then, $\dot{x}(t)$ satisfies (2.1) and hence (2.2), if and only if $\dot{z}(t)$ satisfies the system of the form (S_o)

$$\dot{z}(t) = A_c z(t) + B(u(t) + v(t)) \quad (2.7)$$

Furthermore, the following properties are true:

- (A_c, B) is a stabilizable pair,
- if $\lim_{t \rightarrow \infty} \|z(t)\| = 0$, then $\lim_{t \rightarrow \infty} \|x(t)\| = 0$
- if $\lim_{t \rightarrow \infty} \|z(t)\| \leq k_1, \exists k_1 < \infty$, then $\lim_{t \rightarrow \infty} \|x(t)\| \leq k_2, \exists k_2 < \infty$,

Proof:

By using the *Leibniz's formula* [15], it is straightforward to verify that (2.2) in conjunction

with the transformation (2.4) yields (2.7); see Appendix. Property (a) follows from Theorem 3.2 of [8]. To show the property (b) and (c), are obtained using Laplace transform (2.4) to obtain, after some rearrangement,

$$X(s) = \Delta^{-1}(s)(sI - A_c)Z(s) + \Delta^{-1}(s)(sI - A_c)\Psi(s) \quad (2.8)$$

where $\Delta(s) = [sI - A - e^{-hs} A_h]$, and

$$\Psi(s) = \int_{-h}^0 e^{A_c \theta} A_h \int_{-(h+\theta)}^0 e^{-s(\tau+h+\theta)} x_0(\tau) d\tau d\theta.$$

Next by setting $t = \tau + h + \theta$, Observe that

$$\int_{-(h+\theta)}^0 e^{-s(\tau+h+\theta)} x_0(\tau) d\tau = \int_0^{(h+\theta)} e^{-st} x_0(t-h-\theta) dt$$

Since $x_0(\tau) = 0, \forall \tau \in [-h, 0]$, we have

$$\int_{-(h+\theta)}^0 e^{-s(\tau+h+\theta)} x_0(\tau) d\tau = \int_0^\infty e^{-st} x_0(t-h-\theta) dt = L\{x_0(t-h-\theta)\}.$$

where the operator $L\{\cdot\}$ is defined as the Laplace Transform.

Furthermore, by setting $t = \tau + r + \alpha + \theta$,

$$\int_{-(r+\alpha+\theta)}^0 e^{-s(\tau+r+\alpha+\theta)} x_0(\tau) d\tau = \int_0^{(r+\alpha+\theta)} e^{-st} x_0(t-r-\alpha-\theta) dt$$

Since $x_0(\tau) = 0, \forall \tau \in [-t_f, 0]$, we have

$$\begin{aligned} \int_{-(r+\alpha+\theta)}^0 e^{-s(\tau+r+\alpha+\theta)} x_0(\tau) d\tau &= \int_0^\infty e^{-st} x_0(t-r-\alpha-\theta) dt \\ &= L\{x_0(t-r-\alpha-\theta)\} \end{aligned}$$

This implies that

$$\begin{aligned} \psi(t) &= L^{-1}\{\Psi(s)\} \\ &= L^{-1}\left\{\int_{-h}^0 e^{A_c \theta} A_h L\{x_0(t-h-\theta)\} d\theta\right\} \\ &\quad + L^{-1}\left\{\int_{-r}^0 \int_{-(r+\theta)}^0 e^{A_c \alpha} A_r(\theta) L\{x_0(t-r-\alpha-\theta)\} d\alpha d\theta\right\} \\ &= \int_{-h}^0 e^{A_c \theta} A_h x_0(t-h-\theta) d\theta \\ &\quad + \int_{-r}^0 \int_{-(r+\theta)}^0 e^{A_c \alpha} A_r(\theta) x_0(t-r-\alpha-\theta) d\alpha d\theta \end{aligned}$$

and hence,

$$\psi(t) = 0, \forall t > t_f = \max(h, r).$$

Note here that (2.6) implies that all eigenvalues of the transfer function $\Delta^{-1}(s)(sI - A_c)$ are stable. Consequently, it can be verified that

$$\begin{aligned} \lim_{t \rightarrow \infty} \|x(t)\| &\leq \lim_{t \rightarrow \infty} \|L^{-1}\{\Delta^{-1}(s)(sI - A_c)Z(s)\}(t)\| \\ &\quad + \lim_{t \rightarrow \infty} \|L^{-1}\{\Delta^{-1}(s)(sI - A_c)\Psi(s)\}(t)\| \\ &= \lim_{t \rightarrow \infty} \|L^{-1}\{\Delta^{-1}(s)(sI - A_c)Z(s)\}(t)\|. \end{aligned}$$

The above analysis imply that $\psi(t)$ does not influence stability of $x(t)$. Furthermore, asymptotic stability of $z(t)$ implies asymptotic stability of $x(t)$ since $\Delta^{-1}(s)(sI - A_c)$ is stable. \square

3. Controller Design

In this section we present a suitable controller design, which is based on the Min-Max Approach of Gutman, to stabilize $z(t)$. Next we will proof that the controller can make the system asymptotically stable.

Theorem 3.1 : Suppose there exists a transformation satisfying the hypothesis of proposition 2.1. Then, for given $Q > 0$, there exist a positive definite solution P to the Riccati equation

$$A_c^T P + P A_c - P B B^T P + Q = 0 \quad (3.1)$$

Furthermore, a control law, which render closed-loop systems asymptotically stable, is given by

$$u(t) = u_L(t) + u_N(t) \quad (3.2)$$

where

$$u_L(t) = -\frac{1}{2} B^T P z(t) \quad (3.3)$$

and

$$u_N(t) = -\frac{\rho^2(x_t) B^T P z(t)}{\delta(\rho(x_t)) \|B^T P z(t)\| + e^{-\phi t}} \quad (3.4)$$

where the nonlinear gain

$$\rho(x_t) = \mu_E \|u_L(t)\| + \mu(x_t), \quad (3.5)$$

and $\phi \in R^+$ and δ is the positive scalar defined in Assumption 2-d.

Proof:

First, we take the positive definite function

$$V_z(t) = z^T(t)Pz(t) \quad (3.6)$$

as Lyapunov function candidate for the system (2.7) with control (3.2). Applying with the Riccati equation, the following is obtained of the derivative of V_z

$$\dot{V}_z = -z^T(t)[A_c^T P + P A_c]z(t) + 2z^T(t)PB(u(t) + v(t))$$

Substitute $u_L(t)$ in the above equality to get

$$\begin{aligned} \dot{V}_z &= -z^T(t)[A_c^T P + P A_c - P B B^T P]z(t) \\ &\quad + 2z^T(t)PB(u_N(t) + v(t)) \\ &= -z^T(t)Qz(t) + 2z^T(t)PB(u_N(t) + v(t)) \end{aligned}$$

since $v(t)$ still has same value as defined in (2.3), we have

$$\dot{V}_z = -z^T(t)Qz(t) + \alpha(t) + \beta(t)$$

where

$$\alpha(t) = 2z^T(t)PB(I + E(t))u_N(t)$$

and

$$\begin{aligned} \beta(t) &= 2z^T(t)PB \left\{ H(t)x(t) + H_h(t)x(t-h) \right. \\ &\quad \left. + \int_{-r}^0 H_r(t)x(t-r-\theta)d\theta + \omega(t) + E(t)u_L(t) \right\} \end{aligned}$$

Consequently from $u_N(t)$ defined in (3.4), $\alpha(t)$ becomes

$$\begin{aligned} \alpha(t) &= -2k(t)z^T(t)PB(I + E(t))B^T Pz(t) \\ &= -2k(t)z^T(t)PB \left(I + \frac{1}{2}(E^T(t) + E(t)) \right) B^T Pz(t) \\ &\leq -2k(t)z^T(t)PB\delta B^T Pz(t) \end{aligned}$$

where

$$k(t) = \frac{\rho^2(x_t)}{\delta(\rho(x_t)\|B^T Pz(t)\| + e^{-\phi t})} \quad (3.7)$$

Hence

$$\alpha(t) \leq -2k(t)\delta\|B^T Pz(t)\|^2 \quad (3.8)$$

On the other hand,

$$\beta(t) \leq 2\|B^T Pz(t)\|\rho(x_t) \quad (3.9)$$

Combining (3.8) with (3.9) to get

$$\begin{aligned} \alpha(t) + \beta(t) &\leq 2 \left(-k(t)\delta\|B^T Pz(t)\|^2 \right. \\ &\quad \left. + \rho(x_t)\|B^T Pz(t)\| \right) \quad (3.10) \end{aligned}$$

(3.7) and (3.10) imply that

$$\alpha(t) + \beta(t) \leq 2 \left(-\frac{\rho^2\|B^T Pz(t)\|^2}{\rho\|B^T Pz(t)\| + e^{-\phi t}} \right)$$

$$+ \rho(x_t)\|B^T Pz(t)\|)$$

$$\begin{aligned} &\leq 2 \left(\frac{e^{-\phi t}\rho\|B^T Pz(t)\|}{\rho\|B^T Pz(t)\| + e^{-\phi t}} \right) \\ &\leq 2e^{-\phi t} \end{aligned}$$

Therefore,

$$\begin{aligned} \dot{V}_z(t) &= -z^T(t)Qz(t) + \alpha(t) + \beta(t) \\ &\leq -z^T(t)Qz(t) + 2e^{-\phi t} \end{aligned}$$

By using [17], It can be verified that closed-loop system (2.7) with control law (3.2) is asymptotically stable. \square

4. Numerical Example and Simulation

Consider the following uncertain system with distributed time delay with its linear part as defined in

$$\begin{aligned} \dot{x}(t) &= Ax(t) + [A_h + \Delta A_h(t)]x(t-h) \\ &\quad + \int_{-r}^0 A_r(\theta)x(t-r-\theta)d\theta + Bu(t) + \omega(t) \quad (4.1) \end{aligned}$$

where

$$\begin{aligned} A &= \frac{8e^{-\frac{\pi}{4}} - 8}{65}, \quad A_h = e, \quad A_r(\theta) = \sin(8\theta), \quad B = 1, \\ |\Delta A_h(t)| &\leq 3, \quad |\omega(t)| \leq 0.5, \quad h = 1, \quad r = \frac{\pi}{4} \end{aligned}$$

Therefore, it can be verified by using the numerical algorithm proposed in [15] that $\sigma_u = \{1\}$, consequently A_c has chosen to be 1. Next, we choose Q to be 3 then P becomes 3 and the nonlinear gain

$$\rho(x_t) = \mu(x_t) = \|3 \cdot x(t-h) + 0.5\| \quad (4.2)$$

Using the controller described and let ϕ be 0.15, the response of the system (4.1) with controller are given in the figure 1 shown below

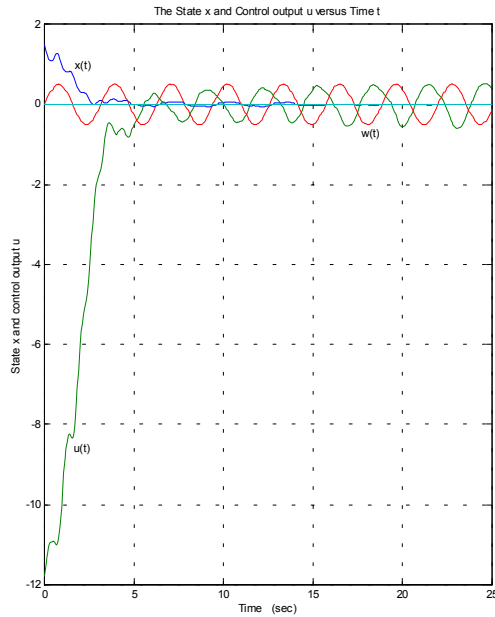


Fig 1. Simulation Result,

Furthermore, figure 2 shows the response of system (4.1) with only linear control law (3.3). It can be observed that the control law without nonlinear part can not stabilize the system. In the other hand, the nonlinear part is sufficient to control the effect of uncertainties and disturbance for stabilizing the system

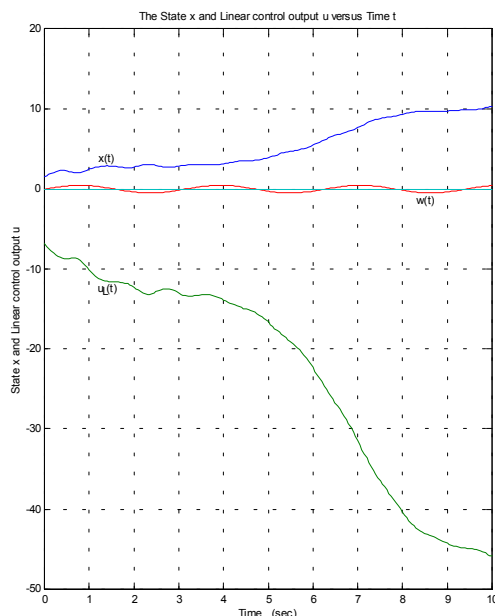


Fig 2. Simulation Result without nonlinear control law

5. Concluding Remarks

We have presented a method to stabilize uncertain system with distributed time delay. By using matching condition defined in *Assumption 2.2*, we can change system model (2.1) into new model (2.7) that easier to be applied with the special linear transformation. The transformation is used to reduce the system state model so that we can obtain a stabilizing condition as shown in *Proposition 2.1*. In the other word, choosing A_c , such that $\Delta^{-1}(s)(sI - A_c)$ stable, paves the way to feasible design of the robust controller. And it explains why stability of $z(t)$ can imply stability of $x(t)$. As a consequence, we obtain a new design of robustly stabilizing controller for the system.

In General, the problem of determining the roots of systems has been considered by many authors. Base on Manitus method [16], Fiagbedzi and Pearson had proposed the solution for distributed systems in 1987, see [13] for references.

Finally, we note that the applicability of our approach is not limited to stabilization problem. For instance, it is feasible to extend our result in section 3 to cope with the model-following control of which concept is proposed in [7].

6. Appendix

Supplementary proof of Proposition 2.1

From the hypothesis of Proposition 2.1, we have

$$\dot{x}(t) = Ax(t) + A_h x(t-h) + \int_{-r}^0 A_r(\theta) x(t-r-\theta) d\theta + B(u(t) + v(t)) \quad (\text{A.1})$$

with the auxiliary output

$$\begin{aligned} z(t) &= (T_c(x))(t) \\ &= x(t) + \int_{-h}^0 e^{A_c \theta} A_h x(t-h-\theta) d\theta \\ &\quad + \int_{-r}^0 \int_{-\theta}^0 e^{A_c \tau} A_r(-r-\theta) x(t-r+\theta) d\tau d\theta \quad (\text{A.2}) \end{aligned}$$

where the matrix A_c be defined by

$$A_c = A + e^{-hA_c} A_h + \int_{-r}^0 e^{-(r+\theta)A_c} A_r(\theta) d\theta, \quad (\text{A.3})$$

By using the *Leibniz's formula* [12], it can be verified that

$$\begin{aligned} \frac{d}{dt} \int_{-h}^0 e^{A_c \theta} A_h x(t-h-\theta) d\theta \\ = e^{-hA_c} A_h x(t) - A_h x(t-h-\theta) \\ + A_c \int_{-h}^0 e^{A_c \theta} A_h x(t-h-\theta) d\theta \end{aligned}$$

and

$$\begin{aligned} \frac{d}{dt} \int_{-r}^0 \int_{-\theta}^0 e^{A_c \tau} A_r (-r-\theta) x(t-r+\theta) d\tau d\theta \\ = \int_{-r}^0 \left[e^{-\theta A_c} A_r (-r-\theta) x(t) - A_r (-r-\theta) x(t+\theta) \right. \\ \left. + A_c \int_{-\theta}^0 e^{A_c \tau} A_r (-r-\theta) x(t-\tau+\theta) d\tau \right] d\theta \end{aligned}$$

Hence,

$$\begin{aligned} \dot{x}(t) &= x(t) + \frac{d}{dt} \int_{-h}^0 e^{A_c \theta} A_h x(t-h-\theta) d\theta \\ &+ \frac{d}{dt} \int_{-r}^0 \int_{-\theta}^0 e^{A_c \tau} A_r (-r-\theta) x(t-r+\theta) d\tau d\theta \\ &= Ax(t) + A_h x(t-h) \\ &+ \int_{-r}^0 A_r(\theta) x(t-r-\theta) d\theta + B(u(t) + v(t)) \\ &+ e^{-hA_c} A_h x(t) - A_h x(t-h-\theta) \\ &+ A_c \int_{-h}^0 e^{A_c \theta} A_h x(t-h-\theta) d\theta \\ &+ \int_{-r}^0 \left[e^{-\theta A_c} A_r (-r-\theta) x(t) - A_r (-r-\theta) x(t+\theta) \right. \\ &\quad \left. + A_c \int_{-\theta}^0 e^{A_c \tau} A_r (-r-\theta) x(t-\tau+\theta) d\tau \right] d\theta \\ &= A_c \left[x(t) + \int_{-h}^0 e^{A_c \theta} A_h x(t-h-\theta) d\theta \right. \\ &\quad \left. + \int_{-r}^0 \int_{-\theta}^0 e^{A_c \tau} A_r (-r-\theta) x(t-r+\theta) d\tau d\theta \right] \\ &+ B(u(t) + v(t)) \\ &+ \left[A + e^{-hA_c} A_h + \int_{-r}^0 e^{-(r+\theta)A_c} A_r(\theta) d\theta - A_c \right] x(t) \end{aligned}$$

which is equivalent to

$$\dot{x}(t) = A_c z(t) + B(u(t) + v(t))$$

owning to (A.2) and (A.3).

Next, to show (2.8), Laplace transform (A.2) to obtain

$$Z(s) = L\{z(t)\}$$

$$\begin{aligned} &= L \left\{ x(t) + \int_{-h}^0 e^{A_c \theta} A_h x(t-h-\theta) d\theta \right. \\ &\quad \left. + \int_{-r}^0 \int_{-\theta}^0 e^{A_c \alpha} A_r (-r-\theta) x(t-\alpha+\theta) d\alpha d\theta \right\} \\ &= X(s) + \int_{-h}^0 e^{A_c \theta} A_h L\{x(t-h-\theta)\} d\theta \\ &\quad + \int_{-r}^0 \int_{-\theta}^0 e^{A_c \alpha} A_r (-r-\theta) L\{x(t-\alpha+\theta)\} d\alpha d\theta \end{aligned}$$

Consequently,

$$\begin{aligned} Z(s) &= X(s) + \int_{-h}^0 e^{A_c \theta} A_h e^{-s(h+\theta)} d\theta X(s) \\ &\quad + \int_{-h}^0 e^{A_c \theta} A_h \int_{-(h+\theta)}^0 e^{-s(\tau+h+\theta)} x_0(\tau) d\tau d\theta \\ &\quad + \int_{-r}^0 \int_{-(r+\theta)}^0 e^{A_c \alpha} A_r(\theta) e^{-s(r+\alpha+\theta)} d\alpha d\theta X(s) \\ &\quad + \int_{-r}^0 \int_{-(r+\theta)}^0 e^{A_c \alpha} A_r(\theta) \int_{-(r+\alpha+\theta)}^0 e^{-s(r+\alpha+\theta)} x_0(\tau) d\tau d\alpha d\theta \\ &= \left[I + \int_{-h}^0 e^{A_c \theta} A_h e^{-s(h+\theta)} d\theta \right. \\ &\quad \left. + \int_{-r}^0 \int_{-(r+\theta)}^0 e^{A_c \alpha} A_r(\theta) e^{-s(r+\alpha+\theta)} d\alpha d\theta \right] X(s) \\ &\quad + \int_{-h}^0 e^{A_c \theta} A_h \int_{-(h+\theta)}^0 e^{-s(\tau+h+\theta)} x_0(\tau) d\tau d\theta \\ &\quad + \int_{-r}^0 \int_{-(r+\theta)}^0 e^{A_c \alpha} A_r(\theta) \int_{-(r+\alpha+\theta)}^0 e^{-s(r+\alpha+\theta)} x_0(\tau) d\tau d\alpha d\theta \end{aligned} \quad (A.4)$$

Note here that

$$\begin{aligned} I + \int_{-h}^0 e^{A_c \theta} A_h e^{-s(h+\theta)} d\theta + \int_{-r}^0 \int_{-(r+\theta)}^0 e^{A_c \alpha} A_r(\theta) e^{-s(r+\alpha+\theta)} d\alpha d\theta \\ = (sI - A_c)^{-1} \Delta(s) \end{aligned} \quad (A.5)$$

where

$$\Delta(s) = \left[sI - A - e^{-hs} A_h - \int_{-r}^0 e^{-(r+\theta)A_c} A_r(\theta) d\theta \right],$$

This can be verified easily by direct integration and then using (A.3). Finally, direct substitution (A.5) in (A.4) yields the required result.

7. Acknowledgment

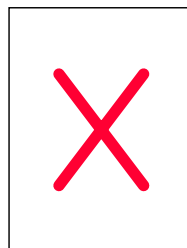
The authors gratefully acknowledge for the helpful comment of reviewers especially concerning in section 3

This work is partly supported by National Science and Technology Development Agency. Ministry of

Science Technology and Environment. The Thai Royal Government.

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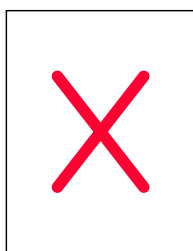
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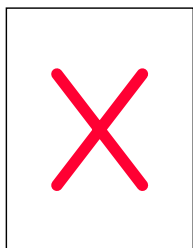
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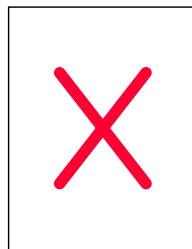
manufacturing automation and telemedicine. His responsibility is mainly project leading to develop prototypes of several products; e.g., calcium scoring software, medical image converter, and CNC simulator. As an invited lecture of KMITL, he also conducts course on stability theory and robust control. He has a broad research background with expertise in such areas as practical applications of modern control theory, development of electromechanical systems, computed tomography and medical informatics. He has authored over 20 publications in these areas.



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Introduction to Micro-Electro-Mechanical Systems (MEMS) with Emphasis on Optical Applications

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ABSTRACT -- Micro-Electro-Mechanical Systems, or MEMS, are integrated micro devices or systems combining electrical and mechanical components. They are fabricated using integrated circuit (IC) batch processing techniques and can range in size from micrometers to millimeters. These systems can sense, control and actuate on the micro scale, and function individually or in arrays to generate effects on the macro scale. This paper presents an overview of MEMS technology with emphasis on optical applications. Applications of MEMS devices vary in many fields from automotive transducers, biomedical technologies, communication systems, robotics, aerospace, micro-optics, industrial sensors and actuators. The applications of MEMS in optics include display systems, optical switching, optical communication, optical data storage, optical processing and interconnection, and adaptive optics. Examples of micro-optical components and systems are described in this paper.

KEY WORDS: MEMS, MOEMS, micromachining, micro-optics, sensor, actuator

บทคัดย่อ -- ระบบจุลภาคไฟฟ้า - เครื่องกล (MEMS) คือประดิษฐ์กรรมขนาดไมโครมิเตอร์ซึ่งรวมส่วนประกอบของระบบไฟฟ้าและเครื่องกลเข้าด้วยกัน ระบบจุลภาคไฟฟ้าเครื่องกลสร้างโดยอาศัยเทคโนโลยีการผลิตวงจรทรานซิสเตอร์ซึ่งมีขนาดตั้งแต่ไมโครมิเตอร์ถึงมิลลิเมตร ระบบดังกล่าวนี้สามารถตรวจวัด, ควบคุมและกระตุ้นในระดับต่ำและสามารถทำงานทั้งในแบบอิสระหรือแบบขนานเพื่อให้ผลในระดับสูงขึ้น บทความนี้กล่าวถึงภาพรวมของเทคโนโลยีระบบจุลภาคไฟฟ้า-เครื่องกลและการนำไปใช้ประโยชน์โดยเน้นการใช้ประโยชน์ทางด้านแสง การใช้ประโยชน์ของระบบนี้สามารถใช้ได้ในหลายสาขา อาทิ เทคโนโลยีย่นตกรรม เทคโนโลยีการแพทย์ชีวภาพ เทคโนโลยีระบบสื่อสาร ระบบหุ่นยนต์ ระบบอากาศยาน เป็นต้น การใช้ประโยชน์ทางด้านแสงสามารถนำไปสร้างระบบการแสดงผล ระบบการสับเปลี่ยนทางแสง การสื่อสารด้วยแสง การเก็บข้อมูลด้วยแสง การประมวลและเชื่อมต่อข้อมูลด้วยแสง รวมทั้งการปรับปรุงภาพทางดาราศาสตร์ ในบทความนี้ได้อธิบายถึงตัวอย่างของอุปกรณ์และระบบขนาดเล็กเกี่ยวกับแสง

คำสำคัญ -- ระบบจุลภาคไฟฟ้า - เครื่องกล, ระบบจุลภาคไฟฟ้าเครื่องกลทางแสง, กลจักรขนาดเล็ก, อุปกรณ์ขนาดเล็กเกี่ยวกับแสง, อุปกรณ์ตรวจวัด, อุปกรณ์กระตุ้น

1. Introduction

Trend toward smaller size, higher performance, and greater functionality for electronic devices is made possibly by the success of solid-state microelectronics technology. In the late 1980s, the silicon Very-Large-Scale-Integrated (VLSI) design and manufacturing was developed for use in field of

Micro-Electro-Mechanical System (MEMS)[1]. This field is called by a wide variety of names in different parts of the world: micro-electro-mechanical systems (MEMS), microsystem technology (MST), micromechanics, and micro total analysis systems (μ -TAS) etc. These systems interface with both electronic and non-electronic signals and interact with non-electrical physical

world as well as the electronic world by merging signal processing with sensing and/or actuation. Instead of dealing only electrical signals, MEMS also deals with moving-part mechanical elements, making miniature systems possible such as accelerometers, fluid-pressure and flow sensors, gyroscopes, and micro-optical devices. MEMS are designed using computer-aided design (CAD) techniques based on VLSI and mechanical CAD tools and typically batch-fabricated using VLSI-based fabrication process [1]. The commercial available surface and bulk micromachining such as Multi-User-MEMS process (MUMPs) at MCNC and MOSIS service respectively are widely used to fabricate prototype MEMS devices due to their low cost and short turn-around time. Post-processing such as cavity etching, silicon bonding and flip chip soldering can be applied to produce the more complex mechanical structures for suitable applications. An early application of MEMS was in the field of microsensor and microactuator for measuring or driving position, pressure, velocity, acceleration, force, torque, flow, magnetic field, temperature, gas composition, humidity, pH, fluid ionic concentration, and biological gas/liquid-/Molecular concentration. Some applications have been successfully commercialized in market such as thermal inkjet printer, automotive accelerometer, and high-resolution display projector.

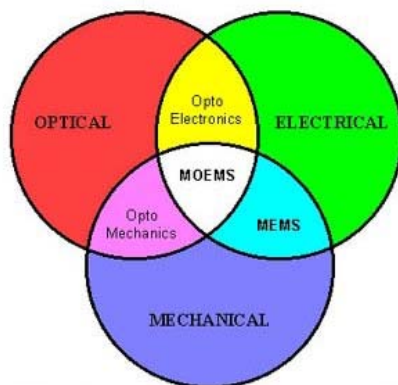


Figure 1. Schematic diagram shows interdisciplinary field of MOEMS

MEMS is also widely used to fabricate micro optical components or optical systems such as deformable micromirror array for adaptive optics, optical scanner for bar code scanning, optical

switching for fiber optical communication etc. This special field of MEMS is called 'Micro-Opto-Electro-Mechanical Systems (MOEMS)'. This interdisciplinary field has to combine knowledge in optics, electronics, and mechanics to design and fabricate devices as shown in Fig.1.

2. Fabrication Technology

Batch IC fabrication technology is used to fabricate mechanical microstructures such as beam, spring, diaphragms, orifices, grooves, gears, linkages, and complex mechanical suspended flexure. MEMS devices can be divided into two fabrication classes: Surface micromachining and bulk micromachining.

2.1 Surface micromachining

Surface micromachining is an additive fabrication technique that involves the building of devices on the top surface of substrates. Specific structure parts of a device are encased in layers of a sacrificial material during fabrication process. The structural parts are released by chemical etchant dissolving of the sacrificial layers. Surface micromachining can be used to fabricate not only relatively conventional mechanical structure such as beams or diaphragms, but also more sophisticated ones such as gears, linkages, and micro-motors. Commercial polycrystalline silicon surface micromachining processes such as MUMPs (Multi-User-MEMS-Process) and SUMMiT (Sandia Ultra-planar Multi-level MEMS Technology) are available for prototyping MEMS designs. Multi-levels of doped or undoped polysilicon layers are used to form the mechanical structures and silicon dioxide layers are used as the sacrificial material. The schematic layout diagrams of MUMPs and SUMMiT surface micromachining fabrication were shown in Fig. 2 [2]. Electrostatic micromotor fabricated by surface micromachining was shown in Fig.3.

2.2 Bulk micromachining

Bulk micromachining is a subtractive fabrication technique that uses the substrate to form mechanical structure of MEMS devices. The single crystal substrate is etched in anisotropic

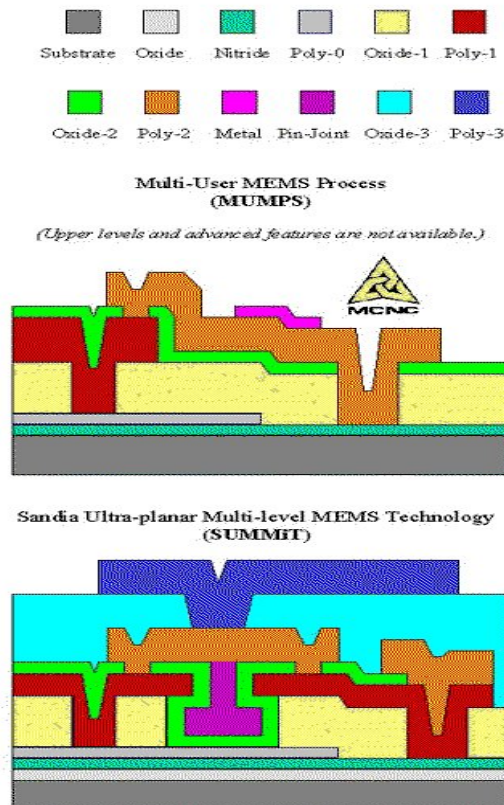


Figure 2. Surface micromachining fabrication (MUMPs and SUMMiT)

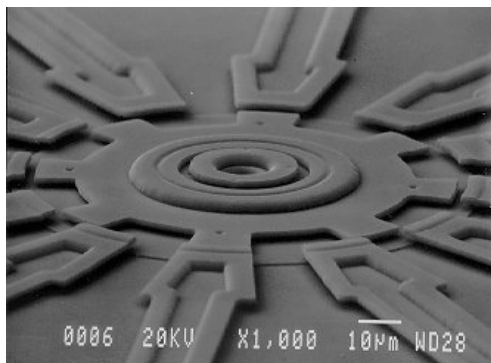


Figure 3. Electrostatic micromotor fabricated by MUMPs: diameter is 80 μm . (Courtesy of MCNC) (For reference, human hair diameter is 70-80 μm)

etchants such as potassium hydroxide (KOH) or ethylene-diamine pyrocatechol (EDP) along given crystal planes. The process is based on the fact that anisotropic etchants etch the $\langle 100 \rangle$ and $\langle 110 \rangle$ crystal plane significantly faster than the $\langle 111 \rangle$ crystal planes. In a $\langle 100 \rangle$ silicon substrate, anisotropic etching proceeds along $\langle 100 \rangle$ plane but practically stop etching at $\langle 111 \rangle$ plane, making a 54.7 degrees angle slanted wall in the etched

cavity. The final size of etched cavity is controlled by the etch-mask opening or heavily boron-doped silicon etch-stop. Under-etching occurring where etch masks are misaligned with $\langle 110 \rangle$ direction can be used to fabricate suspended microstructure. The Miller indices indicated the plane of silicon crystal was shown in Fig.4. Fig. 5 shows the cavity anisotropically etched by EDP.

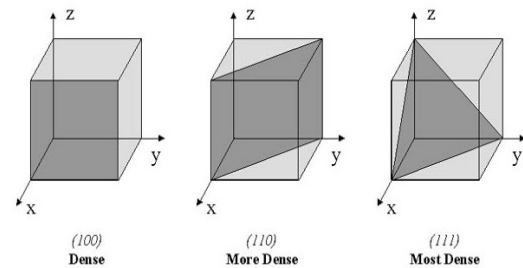


Figure 4. The Miller indices of silicon crystal plane

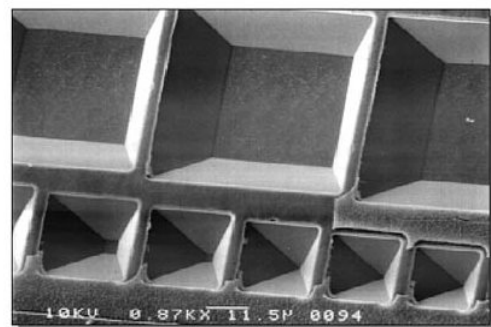
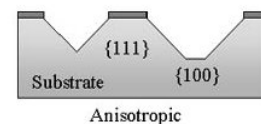


Figure 5. The etched cavity from anisotropic etching: cavity size ranges from 10-100 μm . (Bulk micromachining)

The design of MEMS device is limited by planar geometry of IC fabrication process. Three-dimensional structure or high aspect ratio (height to width) is difficult to fabricate by conventional IC process. The x-ray photolithography technique (LIGA) was developed to fabricate high aspect ratio structure over 100. Microgear and motor fabricated by LIGA were shown in Fig.6.

Post-fabrication processes such as bonding or flip chip soldering permit a silicon substrate to be attached to another substrate to provide added design flexibility and packaging possibility.

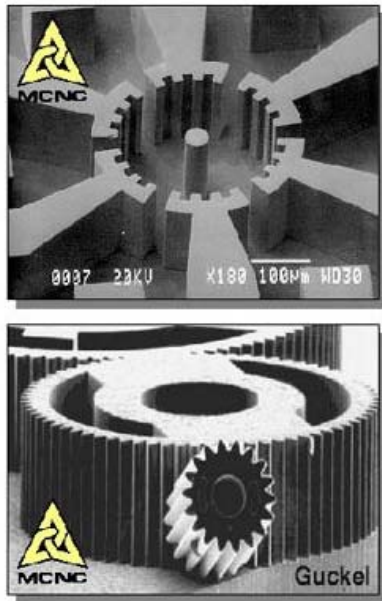


Figure 6. Micromotor components fabricated by high aspect ratio LIGA. Stator (upper figure) and rotor (lower figure). (Courtesy of MCNC)

3. Computer-Aided Design for MEMS

Computer-Aided Design and Engineering programs (CAD and CAE) have been recently developed to assist MEMS design easier. In MEMS technology, the design complexity is compounded by intimacy between mechanical and electronic performance.

Several commercially available software tools such as L-EDIT, Cadence, and MEMCAD can provide the layout tool for MEMS design. The MEMS-specific tools that are integrated into an environment where complete structural, as well as operational, analysis such as MEMCAD, CAEMEMS, and IntelliSuite have used to be design verification tools (e.g., solid modeling, finite element analysis, discretization, and visualization). These software tools have also proven useful for modeling a variety of parameters (e.g., displacement, stress, electric field, magnetic field, temperature, and fluid velocity) under a wide variety of conditions. Fig. 7 shows computer-users interface of MEMS CAD tool available in market.

Finite-element analysis (FEA) is one very powerful technique to model a variety of static and dynamic phenomena for a complex microstructure. Among them are mechanical stress-strain distribution, thermal distribution, frequency response, fluid flow, electromagnetic field and resonant frequency. Several commercially available software packages

such as Ansys, Nastran, Cosmo, and Abaqus provide sophisticated modeling capabilities.

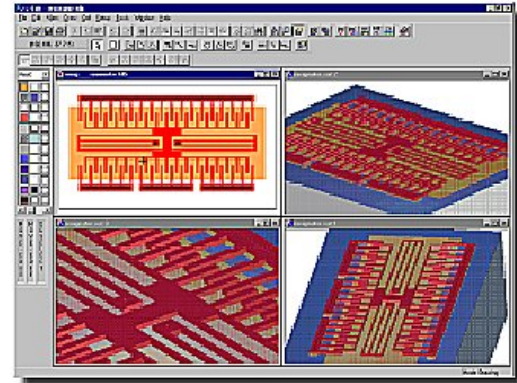


Figure 7. MEMS CAD tool for design, layout, and simulation (Courtesy of Tanner EDA)

4. Microactuators, Microsensors and Microsystems

4.1 Microactuator

Microactuators are component that converts energy into appropriate action capable of producing micron-scale motion. Microactuators can be classified into two classes: rigid microstructure and deformable microstructures. Rigid-type microactuators such as micromotors provide displacement and force through rigid-body motion [1].

Deformable microstructures such as beams and diaphragms provide displacement and force through mechanical deformation. Currently, the microactuation methods in common use are electrostatic, electromagnetic, piezoelectric and thermal. Fig.8 shows deformable mirror driven by electrostatic mechanism.

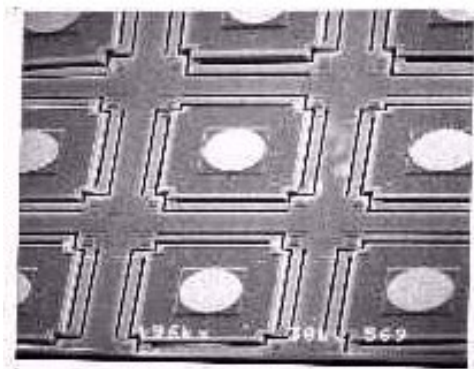


Figure 8. Electrostatic deformable micromirror array [4]

The electrostatic actuation uses the nature of electrostatic force provided by parallel plate capacitor structures or comb-finger structures. The attractive and repulsive forces generated by electric charge distribution are used to convert electrical to mechanical energy. The electrostatic actuated devices (e.g., micromirror array, microswitch, scanner, microshutter, micromotor) are widely used in varieties of fields. Fig.9 shows the commercially available micromirror array for display projection developed by Texas Instrument, USA.

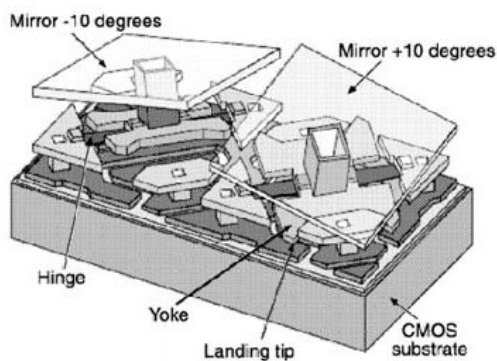


Figure 9. Texas Instrument's micromirror display projector (Courtesy of TI DSP)

Electromagnetic actuator has been demonstrated in conjunction with both mechanical classes of microactuators but electro-magnetic systems prove difficult to micromachine using planar IC processes. The high aspect ratio micromachining method such as LIGA is required to build the three-dimensional structure of magnet and solenoid. Magnetostatic micromotor was shown in Fig.10. Electrostatic actuator dominates in the development of actuators in microworld because of its simpler and more compatible with IC fabrication.

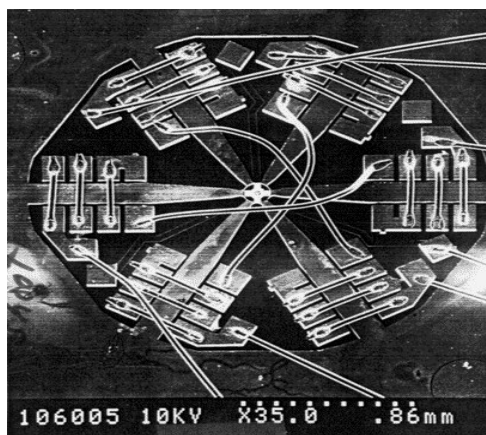


Figure 10. Magnetostatic micromotor. (Courtesy of UW Madison)

Another form of microactuation is based on the piezoelectric effect [5]. This material exhibits deformation of crystal when voltage is applied. Therefore, piezoelectric films can be used to provide actuation in a variety of applications such as valves, pumps, and positioning devices. Typical piezoelectric thin films now used in microactuator technology are zinc oxide (ZnO), lead zirconate titanate (PZT), and polyvinylidene fluoride. Of these materials, PZT has the largest piezoelectric coefficient. Thermal actuator uses bimorph structure that there is thermal coefficient of expansion mismatch between two layers of materials to generate force or motion. The bimorph structure can provide deformations in the lateral or normal to the plane of substrate. In general, thermal microactuators have a slow response time (on the order of tens of milliseconds) and high power consumption (on the order of tens of milliwatts). Electrostatic microactuators can be much faster (with response time measured in microseconds), and consume far less power but less force or motion generated.

4.2 Microsensor

Microsensors are component that converts one form of energy into another and provides a usable energy output in response to a specific measurable input. Due to the micro-scale size of microsensors, less invasive, high accurate/sensitive, and low cost/weight sensor can be achieved. The smart sensor fabricated by IC processes can integrate with CMOS electronic circuits on the chip to handle, switch, or amplify the signal. Several kinds of microsensors are successful in the market such as pressure sensor, flow sensor, thermal sensor, gas/chemical sensor, accelerometer, and immunosensor. The commercially available integrated accelerometer for automotive air bag system developed by Analog Devices was shown in Fig.11.

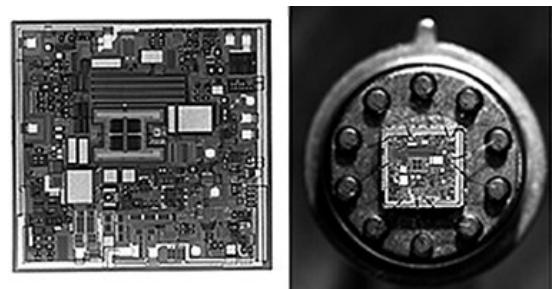


Figure 11. Integrated accelerometer and packaged device. (Courtesy of Analog Devices)

5. MEMS for Optical Applications

Micro-Opto-Electro-Mechanical System (MOEMS) is a specific field of MEMS that includes the knowledge in fields of optoelectronics and optics to create the micro-optical components and systems. Some micro-optical components recently fabricated at University of Colorado, Boulder, Colorado have been described and demonstrated as follow [6].

5.1 Piston micromirrors

One of the most useful MOEM components is the electrostatically actuated piston mirror. This device takes advantage of the planar nature of the surface micromachining process and the ease to form parallel plate capacitor structures by sacrificial layers releasing. The segmented or membrane deformable micromirrors have been fabricated. The upper plate of the structure can be metallized to create a moving mirror. The lower plate was used as an underlying addressable electrode. When a voltage is applied between the two plates, an attractive electrostatic force is developed and balanced by the restoring mechanical force of the flexures that suspend the mirror over electrode. The phase of incoming light modulated by mirror deflection can be controlled by applied voltage between two electrodes. Fig.12 shows one element of micromirror array.

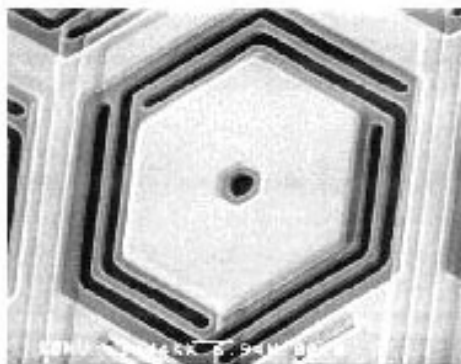
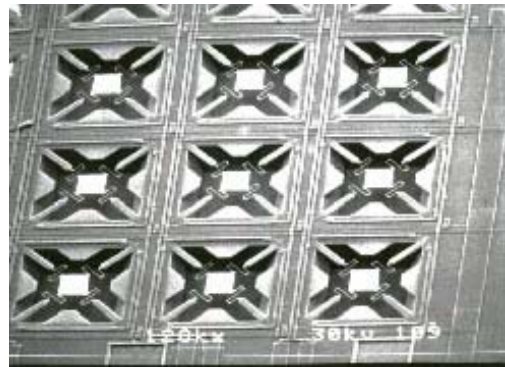


Figure 12. Element of segmented deformable micromirror

Bulk micromachining process is another way to fabricate micromirror array that micromirror and CMOS circuit can be integrated on the same chip. Thermal bimorph actuator was used instead of electrostatic actuator to actuate the mirror in vertical direction. The larger deflection stroke can be achieved with trade off in lower modulated frequency. The bulk micromachining micromirror array was shown in Fig.13. Applications of deformable micromirror array include active aberration correction for atmosphere's turbulence

compensation or free space optical communication systems. The schematic diagram of wavefront compensation for aberration correction was shown in Fig.14. The incoming wavefront was phase-modulated by up/down movement of micromirror



element.

Figure 13. Micromirror array fabricated by bulk micromachining

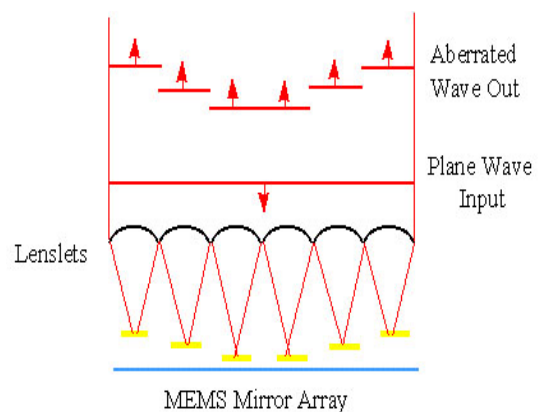
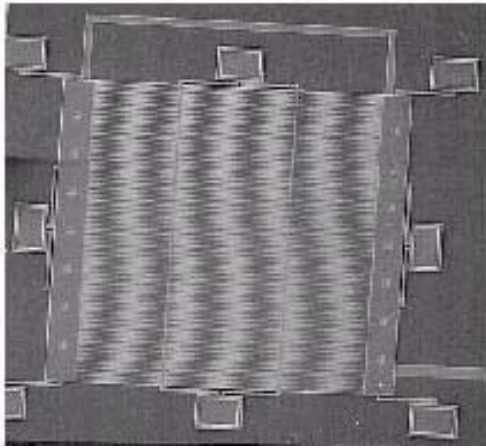


Figure 14. Aberration correction

5.2 Gratings

Optical grating is another optical element that can be easily fabricated in surface micromachined polysilicon. The optical grating is an optical element that serves to periodically modulated the phase or the amplitude of the incident wave. The grating consists of repetitive arrays of polysilicon line suspended over substrate by flexure which individual line was electrostatically moved perpendicular to the plane of substrate to diffract light of a particular wavelength at a designed angle. The electrostatic grating, shown in Fig.15, has an active area of $500\ \mu\text{m} \times 500\ \mu\text{m}$ with $2\ \mu\text{m}$ lines spaced $4\ \mu\text{m}$ center-to-center. The array of grating line is moved perpendicular to the plane of the substrate to change the phase relationship between

light reflected off the grating lines and substrate. This grating is designed to be able to modulated optical intensity by shifting power from the zero



diffracted order to the $\pm 1^{\text{st}}$ diffracted orders.

Figure 15. Micro-optical grating

5.3 Fresnel Lenses

Since surface micromachining uses materials with uniform layer thickness, it is not possible to design curved refracting lenses: however, Fresnel lenses can be fabricated easily. Fresnel lens consists of an array of polysilicon circular rings increasing in width and spacing toward the center. An example of a 7 order Fresnel lens is shown in Fig.16. The plate is 200 μm tall and locks into place. The slider attached at the left lifts the plate. The bottom of lens plate is hinged so it can be flipped up into the light path. The Fresnel lens on substrate can be used to collimate laser light from laser diode. The schematic diagram of microhinge is shown in Fig.17

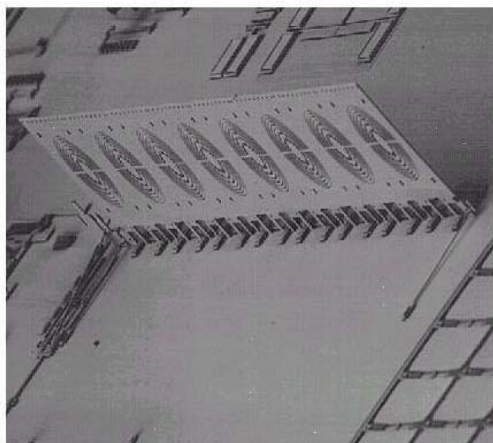


Figure 16. Micro-Fresnel lenses.

5.4 Optical Scanner

Optical scanner is another optical component successfully demonstrated for commercial market. The scanner consists of hinged mirror plates connected to thermal actuator arrays, which can move 10 μm laterally on substrate. The lateral thermal actuator consists of a narrower polysilicon hot arm connected to a wider polysilicon cold arm.

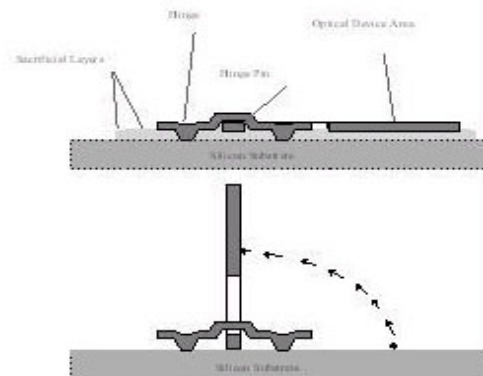


Figure 17. Schematic diagram of micro-hinge for flip-up structure

When the current is applied to them, the higher current density in the hot arm causes it to heat and expand more than the cold arm. This causes the actuator tip to move laterally in an arcing motion towards the cold arm side as shown in Fig.18. Typical dimensions of thermal actuator are: 'hot' arm 2.5 μm wide, 240 μm long; 'cold' arm 16 μm wide, 200 μm long and gap between both arms 2 μm wide.

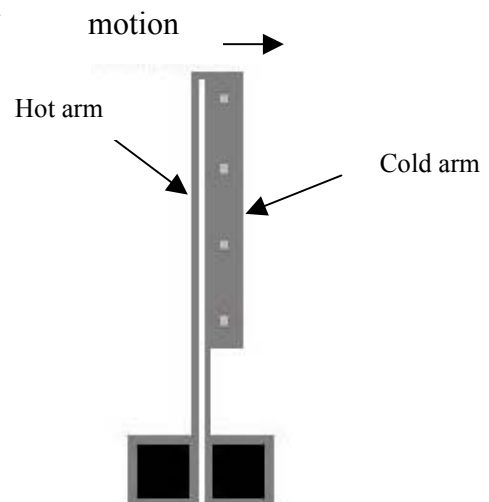


Figure 18. Thermal actuator (Heatuator).

The coated gold mirror surface is 75 μm square (for reference, the diameter of human hair is about 70-80 μm). An etch hole has been cut in the center of

the mirror to ensure that the mirror is completely released during the sacrificial oxide etch. The mirror is connected to the substrate with two substrate hinge, and to the actuator array with a self-locking tether. The lock and key mechanism consists of a key hole in the bottom of the mirror plate with a wide opening at the top and narrow opening at the bottom. The tether end is tapered into a triangular shape which slightly overhangs the bottom of the keyhole. Below the triangular tip, slots are cut into both sides of tether, corresponding to the size of the narrow bottom of the keyhole. As a hinged plate is rotated off the substrate, the tether slide into the keyhole. The actuator array is used to set the angle of the mirror plate for beam steering, or it could be used to move continuously, to create a scanning mirror with a large scan angle. The 15.7° maximum deflection angle is observed [6]. Micro-optical scanner for bar code scanning or display projection was shown in Fig.19.

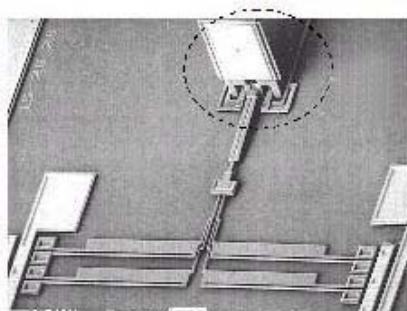
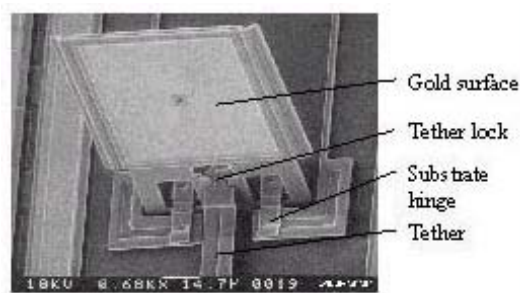


Figure 19. Micro-optical scanner

Rotate mirror plate is another mechanism for scanning the optical beam. Fig.20 shows a flip-up mirror attached to rotary stepper motor, which is driven by an array of thermal actuator. The $200\ \mu\text{m}$ sector gear on the base allows the 180° of positioning. Mirror is $185\ \mu\text{m}$ wide and $200\ \mu\text{m}$ tall.

5.5 Corner Cube Retroreflector

So far only single device have been described; however, more complex systems can be developed. One of the most interesting optical components is a

corner-cube retroreflector (CCR). A CCR has three mutually hinged, stand-up gold plated mirrors. One hinged mirror is positioned and modulated with a thermal actuator array, in the same manner as the scanning mirror. The other hinged mirror is held by a slotted locking plates to fix the position of mirror.

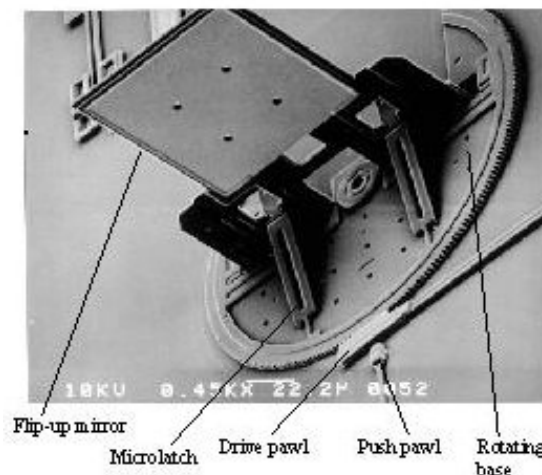


Figure 20. 180 degree scanning mirror

As shown in Fig.21, CCR system has a static gold mirror on the substrate and two perpendicular, mirrored walls. This mirror arrangement will reflect light back in the direction of its incoming path, and is commonly used in roadside reflectors. The CCR can be used for line-in-sight optical communication

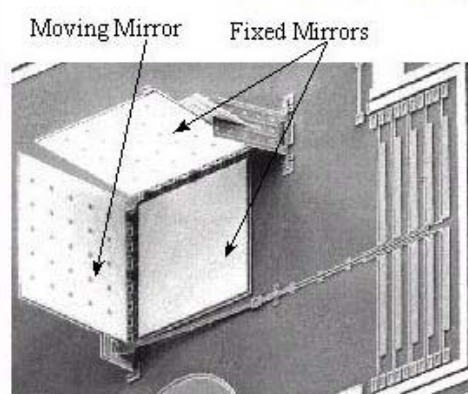


Figure 21. Micro-corner cube retroreflector

The previously described optical components can be combined to form a micro optical bench as shown in Fig.22. A vertical cavity surface emitting laser (VCSEL) is used as a laser light source. The laser beam is emitted perpendicular to the substrate and reflected by 135° mirror. The beam is

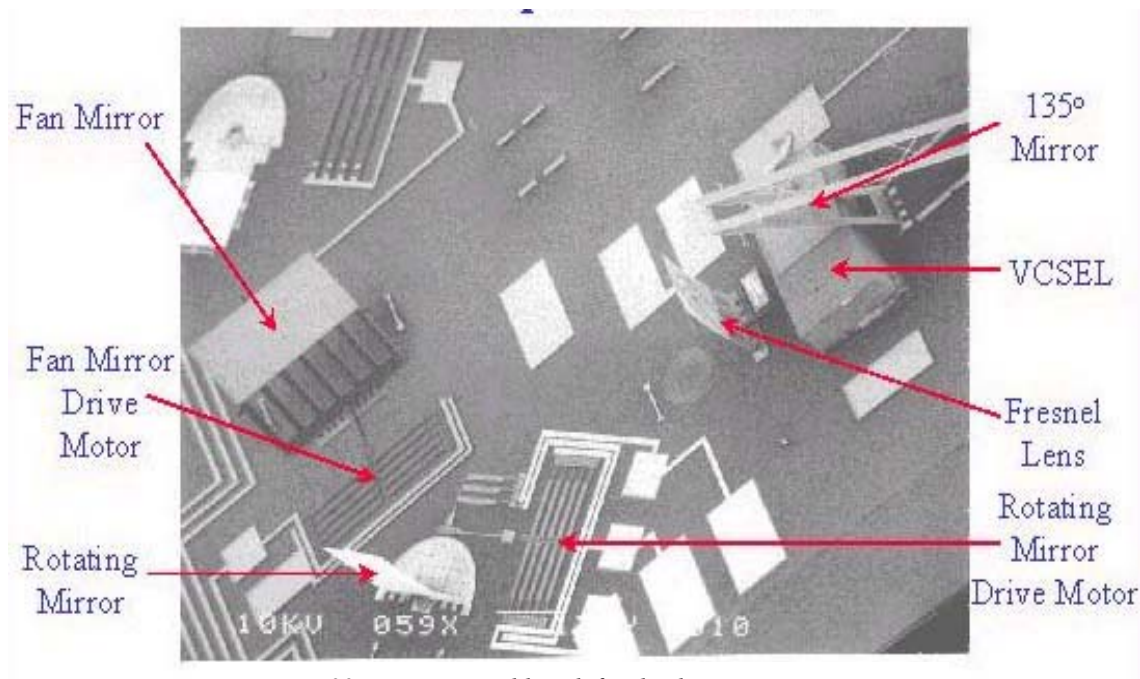


Figure 22. Micro-optical bench for display projection system

collimated by Fresnel lens and scanned in two dimensions by rotating micromirror and fan mirror. This micro optical system is proposed as low cost laser scanner or bar code scanner [7].

6. Conclusion

MEMS proves to be a promising technology for future sensors and actuators. Trend to decrease size, enhance performance, and lower the cost of transducer in market is made possibly by the success of MEMS technology. Fabrication technique has to be developed further to support the increasing MEMS industry. MEMS has merged several fields of knowledge to create a micro-scale device by using today available IC fabrication technology. Discussions of MEMS technology, fabrication tool, MEMSCAD tool, and MEMS applications for sensor and actuator concentrated on micro-optics applications have been presented in this paper.

Acknowledgement

Thank you M. A. Michalick for nice MEMS pictures and V. Thiantamrong for typing and Thai translation.

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ไวรัสคอมพิวเตอร์

นาย สัญญา คล่องในวัย

หน่วยปฏิบัติการวิจัยและพัฒนาเทคโนโลยีคอมพิวเตอร์และระบบอัตโนมัติ

ศูนย์เทคโนโลยีอิเล็กทรอนิกส์และคอมพิวเตอร์แห่งชาติ

สำนักงานพัฒนาวิทยาศาสตร์และเทคโนโลยีแห่งชาติ

กระทรวงวิทยาศาสตร์ เทคโนโลยีและสิ่งแวดล้อม

ABSTRACT – In the past, computer viruses have created a huge damage to the computer systems over the world. The objective of the new viruses is to destroy the system and cause the effects to the societies and economics. Virus's development and concepts of writing it has trended to be more powerful and cause more damage everyday. This paper presents information about computer viruses in the detail of techniques and concepts of the way they work, objective of the attack, trend, producing techniques, protection methods, and the future technology.

KEY WORDS – Computer Virus, Virus Technique

บทคัดย่อ – ระยะเวลาที่ผ่านมาไวรัสคอมพิวเตอร์ ได้สร้างความเสียหายแก่ระบบคอมพิวเตอร์ทั่วโลกเป็นอย่างมาก เป้าหมายการสร้างคอมพิวเตอร์ที่เกิดจากไวรัสคอมพิวเตอร์ชนิดใหม่ๆ ในปัจจุบัน ได้สร้างผลกระทบต่อดังกล่าวและเศรษฐกิจในทุกๆด้าน การพัฒนาการของไวรัสโดยเทคนิคแบบใหม่ แนวคิดในการเขียนโปรแกรมมีแนวโน้มสู่ความรุนแรง และสร้างความเสียหายในวงกว้างมากขึ้น บทความนี้เป็นการนำเสนอข้อมูลเกี่ยวกับไวรัสคอมพิวเตอร์ แนวคิดเทคนิคการทำงาน เป้าหมายการโจมตี แนวโน้มของการเกิดไวรัสเทคนิค, แนวคิดใหม่ในการสร้างไวรัสคอมพิวเตอร์, การป้องกันไวรัส และเทคโนโลยีในอนาคต

คำสำคัญ – ไวรัสคอมพิวเตอร์, เทคนิคไวรัส

1. บทนำ

ไวรัสคอมพิวเตอร์เป็นโปรแกรมสำหรับทำงานบนระบบคอมพิวเตอร์ประเภทหนึ่งมีการทำงานเหมือนกับโปรแกรมประยุกต์โดยทั่วไป แต่วัตถุประสงค์ในการทำงานของไวรัสคอมพิวเตอร์เป็นไปในทางลบมากกว่าการสร้างสรรค์ มีรูปแบบการทำงานเฉพาะตัวการแพร่กระจาย, การฟักตัว, การทำลายที่คล้ายคลึงกับการทำงานของเชื้อไวรัส แนวคิดของโปรแกรมเชิงทำลายในยุคแรกเกิดขึ้นบนระบบยูนิกซ์ ซึ่งมีการพัฒนามาจากการเขียนโปรแกรมสคริปต์บนยูนิกซ์เพื่อความสะดวกในการทำงาน เช่น การเขียนเชลล์สคริปต์ให้มีการลบไฟล์ที่ไม่ต้องการเมื่อถึงกำหนดเวลา, วันที่ ที่ตั้งไว้ โดยโปรแกรมพวกนี้ยังไม่นับว่าเป็น “ไวรัส” เพราะยังไม่มี การแพร่กระจาย แต่ต่อมาได้พัฒนา กลายมาเป็นไวรัสที่

ใช้วันในการทำงาน (Date Trigger) หรือการล้นรอบ ทำสำเนาเชลล์ควบคุมการเซต uid, การทำสำเนาไฟล์ บัญชีรายชื่อผู้ใช้ระบบ และรหัสผ่าน วิธีที่ใช้คือการวาง หลุมพราง การใช้โปรแกรมพวก Trojan ทำสำเนาไฟล์ ไปยังไดเรกทอรีที่สามารถเข้าถึงโดยทั่วไป เช่น การเพิ่มคำสั่ง suid ลงในไฟล์ “.login” ดังตัวอย่าง “cp/bin/sh/tmp/gotu ; chmod 4777 /tmp/gotu สำเนาของข้อมูลสร้างขึ้นจะถูกเก็บที่ไดเรกทอรี /tmp (ไฟล์หรือข้อมูลต่างๆ จะเข้าถึงได้โดยผู้เป็นเจ้าของไฟล์และการตรวจสอบ uid ที่ถูกต้องเท่านั้น) นอกจากนี้ยังมีโปรแกรมประเภทหนอน (Worm) ซึ่งฝังตัวเองภายในระบบพยายามทำลายระบบรักษาความปลอดภัยของระบบปฏิบัติการ โปรแกรมหนอน เริ่มมีการแพร่กระจายตัวเองซึ่งเป็นจุดเริ่มต้นของไวรัสหนอน และ

เริ่มมีการใช้คำว่าไวรัสคอมพิวเตอร์ ในปี 1988 ไวรัสได้แพร่กระจายบนระบบเน็ตเวิร์คแต่การทำลายไม่รุนแรงมากนักเนื่องจากขณะนั้นระบบเน็ตเวิร์คถูกใช้ในวงจำกัด จากนั้นการพัฒนาของไวรัสก็เปลี่ยนจากการทำงานบนระบบยูนิคซ์ ซึ่งมีหลายตระกูล มาเป็นไวรัสที่ทำงานบนระบบดอส และโค้ดแบบ X86 ซึ่งมีการใช้งานอย่างกว้างขวาง การเพิ่มจำนวนของไวรัสคอมพิวเตอร์ในปัจจุบันมีอัตราที่ ในแต่ละปีจะมีไวรัสที่ถูกค้นพบประมาณ 1,000 ตัวต่อปี หรือกล่าวได้ว่ามีไวรัสคอมพิวเตอร์เกิดขึ้นวันละ 2 – 3 ตัว ^[1] การศึกษาทำความเข้าใจเกี่ยวกับไวรัส เป็นสิ่งจำเป็นเพื่อนำมาใช้ในการควบคุมการแพร่กระจาย การปกป้องข้อมูลและระบบไม่ให้ถูกทำลายจากไวรัสคอมพิวเตอร์

2. ไวรัสคอมพิวเตอร์

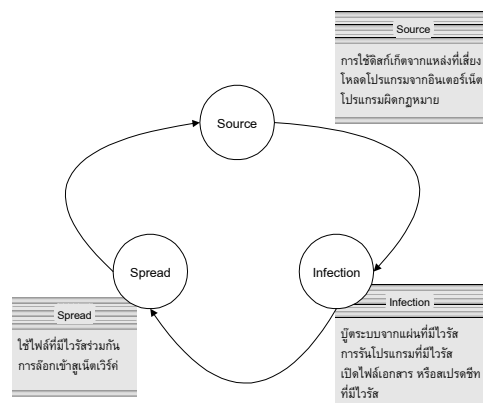
ไวรัสคอมพิวเตอร์ สามารถแพร่กระจายไปกับโปรแกรมไฟล์, แฟ้มข้อมูลเอกสาร, สเปรดชีต, ไฟล์ระบบปฏิบัติการ, แผ่นดิสก์ข้อมูล, การแลกเปลี่ยนข้อมูลโดยแผ่นดิสก์เกิด, การบู๊ตระบบจากแผ่นดิสก์เกิดที่ไม่ปลอดภัย, การแนบไฟล์ต่างๆ ไปกับจดหมายอิเล็กทรอนิกส์ ไวรัสจะทำงานตามรหัสของโปรแกรมที่บรรจุเอาไว้เพื่อสร้างความเสียหายแก่ข้อมูล หรือโปรแกรมระบบ ไวรัสคอมพิวเตอร์จะไม่สามารถทำลายระบบฮาร์ดแวร์ เช่น โพรเซสเซอร์ จอภาพ หรือคีย์บอร์ดได้ แต่ไวรัสสามารถควบคุม หรือก่อกวนการทำงานของระบบฮาร์ดแวร์ ทำให้ระบบไม่สามารถทำงานได้ตามปกติเช่น การเข้าทำลายข้อมูลของ BIOS ที่ใช้ FLASH BIOS [ไวรัสเซอร์โนบิล, Win CIH] ทำให้ไม่สามารถบูตระบบได้ หรือไวรัสบางตัวจะเข้าควบคุมการทำงานของการ์ดแสดงผล ทำให้ภาพที่ปรากฏบนจอหายไป ไม่แสดงตัวอักษร มีตัวอักษรที่อยู่บรรทัดบนของจอตกลงมาขณะใช้งาน หรือกำหนดค่าที่ผิดพลาดให้แก่ตัวควบคุมบังคับให้ลำโพงเกิดกริ่งเป็นจุดได้ นอกจากนี้ยังมีไวรัสที่สร้างขึ้นเพื่อความสนุกสนานมีเสียงดนตรีขณะที่ไวรัสทำงาน เช่น ไวรัส ลาวดวงเดือนที่

เคยระบาดในเมืองไทยช่วงหนึ่ง หรือไวรัสหลอกลงที่เป็นจดหมายเวียนต่างๆ (Hoax Virus) ซึ่งได้สร้างความตื่นตระหนก และการก่อกวนมากกว่าการมุ่งเน้นทำลายระบบเป็นต้น

2.1 วงจรชีวิตของไวรัสคอมพิวเตอร์

การทำงานของไวรัสคอมพิวเตอร์ มีรูปแบบเฉพาะที่แตกต่างจากโปรแกรมโดยทั่วไป ซึ่งลักษณะหรือพฤติกรรมที่แสดงออกนั้นทำให้สามารถศึกษาถึงวงจรชีวิตและการทำงานในแต่ละช่วงของการทำงานของไวรัส

วงจรชีวิตของไวรัสคอมพิวเตอร์แบ่งออกได้เป็น 3 ช่วงคือ แหล่งที่มาของไวรัส (Source) ช่วงการติดเชื้อ (Infection) และช่วงการแพร่กระจาย (Spread) แหล่งที่มาของไวรัสจะมาได้จากสื่อต่างๆ โดยในช่วงการติดเชื้อนี้เป็นช่วงที่เครื่องคอมพิวเตอร์มีไวรัส จากนั้นไวรัสก็พร้อมที่จะแพร่กระจายต่อไป



รูปที่ 1. แสดงวงจรชีวิตของไวรัสคอมพิวเตอร์

2.2 เทคโนโลยีของไวรัสคอมพิวเตอร์

เทคนิคต่างๆ ถูกนำมาใช้ในการพัฒนาขีดความสามารถของไวรัสเพื่อให้สามารถหลบหลีกการตรวจสอบและค้นหา โดยเทคนิคเหล่านี้มีการเปลี่ยนแปลงไปในทางที่ซับซ้อนมากขึ้นตามประเภทการทำลาย

2.2.1 Stealth เป็นเทคนิคที่ออกแบบให้โปรแกรมสามารถป้องกันตัวเองจากการค้นหา หรือกำจัดได้ โดยทั่วไปจะใช้วิธีขัดขวาง (Interrupt) การทำงานของกระบวนการอ่านของระบบดิสก์โดยเมื่อไฟล์ที่ไม่มีไวรัสถูกอ่านขึ้นมา มันจะถูกแทรกรหัสของไวรัสเข้าไป

(Read Stealth Virus) นอกจากนี้ไวรัสที่ทำการเปลี่ยนแปลงขนาดของไฟล์ข้อมูล, ไตเรกทอรีของข้อมูล (Size Stealth Virus) เมื่อไวรัสทำงานจะทำการแทรกรหัสระหว่างการอ่านข้อมูล เช่น ไวรัสมีขนาดข้อมูล 1,024 ไบต์ และไฟล์ข้อมูลเดิมมีขนาด 4,096 ไบต์ ขนาดของไฟล์จะเป็น $(1,024 + 4,096)$ 5,120 ไบต์ ซึ่งขนาดของไฟล์ถูกเปลี่ยนแปลง และจะถูกตรวจพบได้ ไวรัสจะขัดขวางการทำงานของระบบของไตเรกทอรี โดยการอ่านค่าขนาดไฟล์ที่เป็น 5,120 ไบต์ขึ้นมา และลบออกด้วยขนาดของตัวเอง และจะส่งผลที่ได้ไปยังระบบเพื่อแสดงผลอีกครั้ง

2.2.2 Polymorphic อาศัยการเปลี่ยนแปลงรูปแบบของไวรัส มีการแบ่งรหัสของตัวไวรัสเป็นส่วนย่อยแทรกอยู่ระหว่างแฟ้มข้อมูล เมื่อแฟ้มข้อมูลทำงานรหัสไวรัสจะถูกนำไปรวมกันในหน่วยความจำ การใช้การเข้ารหัสและการถอดรหัสก่อนการทำงานด้วยคีย์เฉพาะ ทำให้ยากต่อการตรวจสอบจากรหัสลายเซ็นไวรัส (รหัสลายเซ็นไวรัส *Virus Signature* เป็นรหัสเฉพาะของไวรัสที่ผู้เขียนโปรแกรมป้องกันไวรัสได้ทำการถอดรหัสออกมา ซึ่งไวรัสแต่ละตัวก็จะมีรูปแบบของข้อมูลที่แตกต่างกัน) โดยพื้นฐานของไวรัสประเภทนี้มาจากโครงสร้างของ TPE (Trident Polymorphic Engine) และ MtE (Mutation Engine) ซึ่งมีรายงานการค้นพบในยุโรปช่วงปี 1992^[2]

2.2.3 Multipartite การทำงานหลากหลายรูปแบบในตัวเองสามารถแพร่กระจายทางไฟล์ปกติ และสามารถแพร่กระจายในส่วนของ Boot Record ของระบบดิสก์ได้ เมื่อไฟล์ข้อมูลเอกสารที่ติดไวรัสประเภทนี้ ถูกอ่านขึ้นมาทำงาน ไวรัสก็จะทำงานโดยการคัดลอกตัวเองเข้าไปบันทึกหรือเขียนทับข้อมูลในส่วนของระบบ Boot Record เมื่อมีการบูตระบบครั้งต่อไป ไฟล์ทุกไฟล์ที่ถูกเรียกใช้งานก็จะติดไวรัส

2.2.4 Companion Virus เทคนิคนี้ถูกคิดค้นขึ้นมาโดยอาศัยช่องว่างในการทำงานของระบบปฏิบัติการ และการทำงานตามเงื่อนไขที่ถูกต้องของระบบปฏิบัติการในการทำลายระบบและแพร่กระจาย การทำตัวเสมือนหนึ่งเป็นโปรแกรมปกติของระบบถูกนำมาใช้ โดยอาศัย

หลักการในการรันโปรแกรมแบบลำดับ ถ้าชื่อไฟล์เหมือนกัน ไฟล์ที่มีนามสกุลเป็น .COM จะทำงานก่อน ไฟล์ที่มีนามสกุลเป็น .EXE เสมอ เมื่อไฟล์ CHKDSK.EXE ติดไวรัส ไวรัสจะทำการสร้างไฟล์ใหม่ในชื่อ CHKDSK.COM ซึ่งเป็นโปรแกรมไวรัส เมื่อเราเรียกไฟล์ CHKDSK มาทำงานในครั้งต่อไปไฟล์ CHKDSK.COM ซึ่งเป็นไวรัสจะทำงานก่อน

2.2.5 Malicious Programs เทคนิคเป็นเทคนิคที่เกิดขึ้นในช่วงหลังๆ จากที่มีการใช้โปรแกรมภาษาจาวา และ Active X ซึ่งเป็นภาษาที่นิยมใช้กับอินเทอร์เน็ต โดยอาศัยช่องว่างของตัวรักษาความปลอดภัยภายในโปรแกรม Browser, E-mail, โปรแกรมที่ใช้การสื่อสารพูดคุยผ่านเน็ตเวิร์ค โดยไวรัสจะเข้าควบคุมระบบจากระยะไกล หรือการขโมยข้อมูลรหัสผ่านเข้าสู่ระบบจากเครื่องเป้าหมายส่งคืนไปยังผู้ที่เข้าโจมตีระบบ ลักษณะเหล่านี้มักจะเป็นโปรแกรมประเภทหลุมพราง (Trojan Horse) เป้าหมายจะไม่ได้เน้นการทำลายไฟล์หรือข้อมูล แต่มีจุดประสงค์ในการเข้ายึดครองระบบ

2.3 ประเภทของไวรัสคอมพิวเตอร์

ไวรัสคอมพิวเตอร์ที่มีอยู่ในปัจจุบันสามารถจัดประเภทต่างๆ ได้ 3 ประเภทใหญ่คือ

2.3.1 โปรแกรมไฟล์ไวรัส (Program Viruses) เป็นไวรัสที่ทำงานและแพร่กระจายกับไฟล์ต่างๆ ไป ปกติจะเป็นไฟล์ที่มีนามสกุลเป็น .COM, .EXE นอกจากนี้ในปัจจุบันยังสามารถทำงานได้กับไฟล์ของระบบในลักษณะต่างๆ เช่น .SYS, .DLL, .OVL และ .SCR ไวรัสแฟ้มข้อมูลยังเป็นไวรัสที่เฉพาะเจาะจงสำหรับแต่ละระบบปฏิบัติการอีกด้วย เช่น DOS, WINDOWS, UNIX ฯลฯ

2.3.2 บูตไวรัส (Boot Viruses) เป็นไวรัสที่ไม่ทำงานกับไฟล์ข้อมูล แต่จะทำงานในพื้นที่เฉพาะของแผ่นดิสก์เกิด และฮาร์ดดิสก์ สามารถแพร่กระจายจากเครื่องหนึ่งไปยังอีกเครื่องหนึ่งผ่านทางดิสก์เกิด ไวรัสประเภทนี้มีการแพร่กระจาย และทำงานได้ดีกว่าไวรัสประเภทแรก

บูตไวรัสจะแฝงตัวเองในพื้นที่ที่ เรียกว่า Boot Sector ของระบบดิสก์ ซึ่งทุกครั้งที่มีการบูตระบบข้อมูลที่เก็บอยู่ในส่วนนี้จะถูกอ่านไปเก็บไว้ในหน่วยความจำเสมอ และไวรัสที่แฝงอยู่ก็จะทำงานด้วยเช่นกัน บูตไวรัสสามารถทำงานได้กับระบบไฟล์ของ DOS, Windows 3.X, Windows9X, Windows NT, หรือ Novell Netware นอกจากนี้การกำจัดไวรัสประเภทนี้อาจทำให้ระบบไม่สามารถบูตระบบกลับมาทำงานได้อีกด้วย

2.3.3 ไวรัสมาโคร (Macro Viruses) ไวรัสประเภทใหม่นี้ สามารถติดไปกับไฟล์ต่างๆ ที่มีความสามารถในการใช้งานมาโครได้ เช่น เอกสารไมโครซอฟท์เวิร์ด มีความสามารถในการสร้างเทมเพลตได้ มาโครไวรัสจะแฝงตัวเข้ากับเทมเพลต ไวรัสนิพนธ์นี้สามารถกระจายผ่านการดาวน์โหลดข้อมูลบนอินเทอร์เน็ต การแชร์ข้อมูล และการแนบเอกสารไปกับ E-Mail

เมื่อไวรัสคอมพิวเตอร์ทั้ง 3 ประเภทถูกสร้างขึ้นมาจะมีการนำเอาเทคนิคต่างๆ ที่ได้กล่าวไว้ตอนต้นมาผสมผสานเข้าไป ทำให้ไวรัสในปัจจุบันมีลักษณะเด่นหลายรูปแบบในตัวเอง ใช้เทคนิคหลายแบบในแต่ละส่วนของโค้ดไวรัส ทำให้ยากแก่การตรวจสอบและทำลาย

3. ก้าวต่อไปของไวรัสคอมพิวเตอร์

ไวรัสคอมพิวเตอร์ จัดเป็นรูปแบบหนึ่งของการคุกคามข้อมูล และความปลอดภัยของระบบ ในปัจจุบันนี้เทคโนโลยีของไวรัสมีการพัฒนารูปแบบที่แตกต่างมากเมื่อไวรัสตัวหนึ่งประสบความสำเร็จในการทำลายระบบไวรัสตัวนั้นก็จะกลายมาเป็นแม่แบบ ของไวรัสรุ่นต่อไปและพัฒนาความรุนแรงเพิ่มขึ้นทำให้เกิดปัญหาของไวรัสมากยิ่งขึ้น และวิธีการที่จะนำเสนอต่อไปนี้จะถูกใช้มากขึ้นในอนาคต

3.1 เครื่องมือสำหรับการพัฒนาไวรัส (Virus Authoring Tools) วิธีการนี้ถูกนำมาช่วยในการสร้างไวรัสอย่างแพร่หลายในปัจจุบัน เครื่องมือเหล่านี้มีลักษณะเป็นโปรแกรมช่วยสร้างที่ง่ายต่อการใช้งาน มีส่วนเชื่อมต่อกับผู้ใช้ (User Interface) แบบง่ายๆ ผู้สร้างไม่จำเป็นต้องรู้เรื่องระบบคอมพิวเตอร์มากนัก

เพียงทำตามคำแนะนำก็สามารถสร้างไวรัสขึ้นมาได้ โดยตัวโปรแกรมจะมีโครงสร้างหลัก (Engine) ที่ใช้เทคนิค Polymorphic Virus โดยภายในอาจมีโครงสร้างแบบ MIE หรือ TPE ไวรัส นอกจากนี้ยังเปิดโอกาสให้ผู้สร้างใส่รหัสโปรแกรม และนำโปรแกรมต้นแบบ (Source Program) มาดัดแปลงเพิ่มเติมได้ เครื่องมือที่ช่วยในการพัฒนาไวรัสลักษณะนี้ทำให้จำนวนไวรัสเพิ่มมากขึ้น แต่ไวรัสที่สร้างโดยวิธีนี้มักจะถูกตรวจพบได้ง่ายๆ เพราะรูปแบบการทำงานไม่ซับซ้อนมาก อย่างไรก็ตามหากผู้พัฒนาที่มีความรู้เกี่ยวกับระบบ จะสามารถดัดแปลงให้ตรวจจับยากขึ้น และการทำลายสูงขึ้นด้วยเครื่องมือเหล่านี้สามารถหาได้ง่ายจากระบบอินเทอร์เน็ตในปัจจุบัน และยังเป็นที่ยอดนิยมในหมู่นักเรียน นักศึกษาบางกลุ่ม นอกจากนี้ยังมีการแจกจ่ายและแลกเปลี่ยนไวรัสกันระหว่างกลุ่ม

3.2 การโจมตีระบบป้องกัน เป้าหมายของการโจมตีของไวรัสคอมพิวเตอร์ในปัจจุบันได้เปลี่ยนแปลงรูปแบบต่างไปจากเดิมที่มุ่งการสร้างความเสียหายต่อไฟล์ข้อมูล และไฟล์ระบบ ซึ่งจะทำให้ถูกตรวจจับจากระบบป้องกันได้โดยง่าย เนื่องจากเทคโนโลยีการป้องกันไวรัสในปัจจุบันมักมีการตรวจจับพฤติกรรมของไวรัสในแบบเดิมได้ดี ปัจจุบันไวรัสจะยกเลิกการทำงานของตัวป้องกันไวรัสก่อนแล้วจึงเริ่มทำงานการโจมตีไฟล์ และแพร่กระจาย

3.3 ไวรัสบนเครือข่าย ไวรัสบนระบบเครือข่ายเป็นอีกรูปแบบหนึ่งของการแพร่กระจาย สามารถแพร่กระจายผ่านการสื่อสารข้อมูลภายในเครือข่ายทั้งภายใน และภายนอก รวมทั้งการดาวน์โหลดข้อมูลโปรแกรมจากสถานที่ต่างๆ และการสนทนาบนระบบเครือข่าย โดยทั่วไปไวรัสมักจะมีลักษณะเป็นหลุมพราง (Trojan Horse) โดยค้นหาข้อมูลที่สำคัญจากเครื่องเป้าหมายเพื่อเป็นประตูนำไปสู่การเข้าโจมตีระบบ หรือการควบคุมระบบในภายหลัง [การเจาะระบบจากนักเจาะระบบ Hacker และการโจมตีจากเครือข่ายระยะไกลแบบ Command – Bomber]

3.4 Multi - Platform เนื่องจากเทคนิคการพัฒนาแบบของโปรแกรมที่ไม่ยึดติดกับระบบในปัจจุบันที่นิยม

กันอย่างแพร่หลาย เพราะมีความยืดหยุ่นในการทำงานสูง แต่จุดนี้ทำให้ผู้พัฒนาไวรัส อาศัยช่องว่างการทำงานของระบบมาพัฒนาโปรแกรมไวรัสในลักษณะที่ไม่ขึ้นกับระบบออกมา ซึ่งอาศัยเทคนิคการเขียนโปรแกรมโดยใช้ java และ Active X มากขึ้น

3.5 Hardware - Level จากแนวคิดแบบเก่าที่ว่า “ไวรัสคอมพิวเตอร์เป็นโปรแกรม (ซอฟต์แวร์) ชนิดหนึ่งที่ทำหน้าที่ทำงานบนระบบคอมพิวเตอร์ จะไม่สามารถสร้างความเสียหายต่อระบบฮาร์ดแวร์ได้” ได้ถูกท้าทายโดยไวรัสชนิดใหม่ๆ ที่พัฒนาขึ้นมาโดยไม่ได้มุ่งเน้นการทำลายข้อมูลอย่างเดียว แต่เปลี่ยนเป็นการมุ่งเน้นการทำลายข้อมูลถาวรในระดับฮาร์ดแวร์ การเข้าควบคุมในระดับฮาร์ดแวร์จะทำให้การทำลายสูงขึ้น การเข้าไปแก้ไขข้อมูลที่สำคัญของระบบใน CMOS หรือการทำลายข้อมูล BIOS ของระบบที่ใช้เทคโนโลยี Flash BIOS การเพิ่มความสามารถของไวรัสในการเข้าโจมตีจุดอ่อนของระบบแบบนี้ก่อให้เกิดความเสียหายในระดับที่รุนแรง (ไวรัสเซอร์โนบิล CIH มีความสามารถดังกล่าว)

3.6 ไวรัสที่พัฒนาโดยภาษาระดับสูง ไวรัสในปัจจุบันไม่ได้มีการพัฒนามาจากภาษาภาษาระดับล่างที่เป็นแอสเซมบลี (Assembly Language) แต่เพียงอย่างเดียว แต่ยังมีมีการนำเอาภาษาระดับสูงมาใช้มากขึ้น ทำให้ความง่ายในการพัฒนามีมากขึ้น นอกจากนี้การนำเอาความสามารถของภาษาระดับสูงมาใช้เพิ่มความสามารถให้กับไวรัส การที่ไวรัสสามารถยกระดับความสามารถของตัวเอง ผ่านการสื่อสารทางอินเทอร์เน็ต เมื่อตัวไวรัสตรวจพบว่ามี การ Up – Date Code และฟังก์ชันใหม่ๆ ได้ โดยเทคนิคนี้เป็นการเลียนแบบการทำงานของโปรแกรมป้องกันไวรัสในการ Up – Date ฐานข้อมูลไวรัส และรหัสใหม่ๆ ของไวรัส (Virus Signature)

4. เทคนิคในการตรวจจับไวรัส

เทคนิคในการตรวจจับ และวิเคราะห์การทำงานของไวรัสคอมพิวเตอร์ที่นิยมใช้กันอย่างแพร่หลายในโปรแกรมสำหรับป้องกันไวรัสที่สำคัญและจะกล่าวถึงในบทความนี้ 2 วิธีคือ

4.1 วิธีการวิเคราะห์พฤติกรรม เทคนิคนี้ใช้วิธีการวิเคราะห์การทำงานของโปรแกรมต่างๆ ที่ถูกโหลดขึ้นมาทำงาน โดยโปรแกรมป้องกันไวรัสจะทำหน้าที่ตรวจจับพฤติกรรมการทำงานต่างๆ ที่เป็นรูปแบบเฉพาะของไวรัส เช่น ตรวจสอบการพยายามฝังตัวของโปรแกรมลงในหน่วยความจำ (Memory Resident Program) การตรวจจับโปรแกรมที่พยายามจะเข้าแก้ไขข้อมูลในส่วนของบูตเรคคอร์ดของฮาร์ดดิสก์ ซึ่งเมื่อตรวจจับพฤติกรรมที่เข้าข่ายที่ระบุได้ว่าเป็นไวรัส โปรแกรมป้องกันก็จะแจ้งเตือน

4.2 วิธีการเปรียบเทียบข้อมูลในระดับไบนารี เทคนิคนี้เป็นเทคนิคที่ใช้เปรียบเทียบข้อมูลของไฟล์หรือโปรแกรมในระดับไบนารี โดยจะนำเอาข้อมูลไวรัสจากฐานข้อมูลที่เก็บรหัสลายเซ็นของไวรัสมาทำการเปรียบเทียบกับชุดของข้อมูลในไฟล์ต่างๆ ซึ่งวิธีการนี้จะต้องอาศัยการ Up-date ฐานข้อมูลรหัสลายเซ็นไวรัสอย่างสม่ำเสมอเพื่อที่จะทำให้โปรแกรมป้องกันไวรัสสามารถรู้จักไวรัสชนิดใหม่ๆ และวิธีการนี้จะใช้ไม่ได้ผลกับไวรัสที่เป็น Stealth และ Polymorphic นอกจากนี้วิธีการนี้จะทำได้ช้า

เทคนิคที่กล่าวข้างต้นเป็นเทคนิคพื้นฐานในการตรวจสอบและวิเคราะห์การทำงานของโปรแกรมต้องสงสัย เทคนิคแบบผสมผสานจึงถูกนำมาใช้มากขึ้น นอกจากนี้ผู้พัฒนาโปรแกรมป้องกันไวรัสแต่ละราย ก็จะมีเทคนิคพิเศษเฉพาะตัวในการเพิ่มประสิทธิภาพในการค้นหาไวรัส ความเร็วในการทำงานของโปรแกรม การกำจัดไวรัส และการค้นคืนข้อมูลที่เกิดความเสียหายจากไวรัส และการทำสำเนาข้อมูลที่สำคัญของระบบเก็บสำรองไว้ใช้ในกรณีฉุกเฉิน เป็นต้น

5. ผลกระทบต่อสังคม

ไวรัสคอมพิวเตอร์ ได้ก่อให้เกิดปัญหาและความเสียหายต่อสังคมทั้งทางด้านเศรษฐกิจ และทางด้านจริยธรรม ความเสียหายที่เกิดจากนักพัฒนาโปรแกรมที่มีความสามารถสูงแต่ขาดความรับผิดชอบต่อสังคม จากข่าวการทำลายระบบของ ไวรัสที่ผ่านมามีมูลค่าความเสียหายต่อธุรกิจโดยรวมสูง เช่น ไวรัสเซอร์โนบิลได้

สร้างความเสียหายต่อระบบคอมพิวเตอร์เฉพาะในเอเชียมากกว่า 100,000 เครื่อง ไวรัสเมริสสา ได้สร้างความเสียหายในอเมริกามากกว่า 200,000 เครื่อง ^[4]

นอกจากความเสียหายที่เกิดขึ้นแล้ว เหตุการณ์ลักษณะนี้ ก็มี部分是แรงกระตุ้นให้แก่ผู้ที่มีแนวคิด และนักพัฒนาไวรัสรุ่นใหม่ ๆ เกิดตามมาอีกอย่างหลีกเลี่ยงไม่ได้ แนวทางการป้องกันดูจะเป็นทางออกอย่างหนึ่งในการป้องกันความเสียหายที่เกิดจากการคุกคามโดยไวรัสคอมพิวเตอร์ นักพัฒนาระบบความปลอดภัย และนักวางแผนไอที จะต้องลงทุนในส่วนรักษาความปลอดภัยเป็นมูลค่าที่สูงขึ้นและการทุ่มงบประมาณในการพัฒนา การวิจัย แม้ว่าระบบป้องกันจะมีการพัฒนาไปมากขึ้นแต่นักพัฒนาก็พยายามพัฒนาไวรัสเพื่อที่จะผ่านแนวป้องกันให้ได้เช่นกัน

ในบางประเทศมีการแจ้งข้อมูลความเสียหายที่เกิดจากไวรัสคอมพิวเตอร์ ลักษณะการทำลาย และการฝ่าเข้าสู่แนวป้องกัน ต่อหน่วยงานที่ดูแลด้านความปลอดภัยของระบบคอมพิวเตอร์โดยรวม เพื่อใช้เป็นบทเรียนกับหน่วยงานอื่น สำหรับบางประเทศทำในสิ่งที่ตรงกันข้าม คือ การปกปิดข้อมูลที่เกิดขึ้น เพื่อเหตุผลที่ต้องการรักษาชื่อเสียง ของหน่วยงาน หรือผู้รับผิดชอบดูแลระบบความปลอดภัย ทำให้การสร้างความรู้ความเข้าใจ และการแบ่งปันประสบการณ์เกี่ยวกับไวรัส และพฤติกรรม การแพร่ระบาดต่างๆ ทำได้น้อยลง ส่งผลให้ การแก้ไข และป้องกันทำได้ยากยิ่งขึ้น

6. บทสรุป

จากข้อมูลที่น่าเสนอข้างต้น ไวรัสคอมพิวเตอร์เกิดขึ้นมาจากการพัฒนาเทคนิคในการเขียนโปรแกรมเพื่อการทำงานในลักษณะของการทำลาย สร้างความเสียหาย แต่เทคโนโลยีบางส่วนของไวรัส เป็นเทคนิคที่มีประโยชน์สามารถนำไปพัฒนาโปรแกรมทั่วไปให้มีความสามารถในการพึ่งตัวเองในหน่วยความจำ การป้องกันการลบ เป็นต้น นอกจากนี้จุดที่ไวรัสคอมพิวเตอร์ใช้ เพื่ออาศัยเป็นช่องทางเข้าสู่การโจมตีระบบคือการอาศัยผู้ใช้เป็นพาหะ หากผู้ใช้คอมพิวเตอร์ทุกคนมีวินัยที่ดีในการใช้เครื่องคอมพิวเตอร์ และมีวินัย

ที่ดีในการทำงานกับระบบ แล้วไวรัสคอมพิวเตอร์ก็ไม่สามารถสร้างความเสียหายต่อผู้ใช้ สังคม และเศรษฐกิจ

ทางหนึ่งในการสร้างวินัยที่ดีในการใช้ระบบคอมพิวเตอร์ คือการปรับเปลี่ยนพฤติกรรมที่เสี่ยงต่อการนำเอาไวรัสคอมพิวเตอร์เข้าสู่ระบบ เช่น การเสริมสร้างความรู้ความเข้าใจเกี่ยวกับการทำงานของไวรัส การฝึกอบรมการใช้งานระบบพื้นฐานการฝึกนิสัยที่ดีในการใช้งานแผ่นดิสก์เก็ต หรือไฟล์ต่างๆ ที่นำมาจากที่อื่น ที่แนบมากับจดหมายอิเล็กทรอนิกส์ หรือการดาวน์โหลดจากอินเทอร์เน็ต ควรทำการสแกนตรวจหาไวรัสก่อนการใช้งานทุกครั้ง การหมั่น Up-date เพิ่มความสามารถของโปรแกรมป้องกันไวรัสตามคำแนะนำของโปรแกรม สิ่งเหล่านี้จะเป็นเกราะป้องกันไวรัสคอมพิวเตอร์เข้าสู่คุกคามระบบคอมพิวเตอร์ได้

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Parallel K-means Clustering Algorithm on NOWs

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ABSTRACT — Despite its simplicity and its linear time, a serial K-means algorithm's time complexity remains expensive when it is applied to a problem of large size of multidimensional vectors. In this paper we show an improvement by a factor of $O(K/2)$, where K is the number of desired clusters, by applying theories of parallel computing to the algorithm. In addition to time improvement, the parallel version of K-means algorithm also enables the algorithm to run on larger collective memory of multiple machines when the memory of a single machine is insufficient to solve a problem. We show that a problem size can be scaled up to $O(K)$ times a problem size on a single machine.

KEY WORDS -- Clustering algorithms, K-means algorithms, Parallel Algorithms, Computational Geometry, Data Mining

บทคัดย่อ -- ถึงแม้ว่าอัลกอริทึมเคมีนจะง่ายและทำงานในเวลาเชิงเส้น แต่เมื่อใช้ในการแก้ปัญหาเวกเตอร์แบบหลายมิติขนาดใหญ่ก็จะใช้เวลาในการทำงานที่มากและซับซ้อน ในบทความนี้ได้มีการนำเสนอวิธีการปรับปรุงอัลกอริทึมเคมีนโดยการนำการคำนวณแบบขนานเข้ามาช่วย ผลที่ได้แสดงให้เห็นว่าได้ผลดีขึ้นด้วยปัจจัย $O(K/2)$ โดยที่ K คือจำนวนกลุ่มที่ต้องการ นอกจากนี้อัลกอริทึมเคมีนรุ่นที่ใช้การคำนวณแบบขนานยังสามารถทำงานในเครื่องหลายๆ เครื่องที่มีหน่วยความจำแบบสะสมได้ขนาดใหญ่ เมื่อหน่วยความจำของเครื่องใดเครื่องหนึ่งไม่เพียงพอต่อการแก้ปัญหาอีกด้วย ผลการทดลองแสดงให้เห็นว่าขนาดของปัญหาสามารถเพิ่มขึ้นในขนาด $O(K)$ เท่าของขนาดปัญหาบนเครื่องเดียว

คำสำคัญ -- อัลกอริทึมแบบกลุ่ม อัลกอริทึมเคมีน อัลกอริทึมแบบขนาน เราคาดคิดเชิงคำนวณ เหมือนข้อมูล

1. Introduction

Clustering is the grouping of similar objects and a clustering of a set is a partition of its elements that is chosen to minimize some measure of dissimilarity [1]. Clustering algorithms are often useful in applications in various fields such as visualization, pattern recognition, learning theory, and computer graphics. A classical vector quantization problem is usually solved as a gradient-descent problem. However, in practice a more convenient computing scheme is batch computation, usually named the K-means algorithm [2].

Given a set S of N D -dimension vectors without any prior knowledge about this set, the serial K-means clustering algorithm forms K disjoint nonempty subsets $\{C_1, C_2, C_3, \dots, C_K\}$ of vectors

such that each vector v_{ij} , $1 \leq i \leq K$, $1 \leq j \leq |C_i|$ has the closest distance (i.e., Euclidean distance) to means \bar{X}_i , $1 \leq i \leq K$ [1] (See figure 1 for an example of K-means categorization of 25 points for $K = 4$). The algorithm achieves this result by minimizing a square-error function E such that

$$E = \sum_{i=1, K} \sum_{v \in C_i} \| \bar{X}_i - v \|^2$$

A K-means algorithm is measured by two criteria: intra-cluster criterion and inter-cluster criterion. An intra-cluster criterion (i.e., the inner summation) represents how good the cluster C_i is. Typical intra-cluster criteria are the diameter, radius, variance, variance multiplied by $|C_i|$, variance multiplied by $|C_i|^2$ of point set $|C_i|$, a Euclidean distance, and a square-error criterion. In this paper we use a square-error function as our criterion because 1) our purpose is to parallelize K-means algorithm and 2) the square-error criterion, defined above, is

the most commonly used and a good measure of the within-cluster variation across all the partitions [5]. For more information about other criteria, we suggest the paper [1] by Mary Inaba, Naoki Katoh, and Hiroshi Imai. The inter-cluster criterion (i.e., the outer summation) is defined as the total cost of the K clusters. Generally, the inter-cluster criteria are $\max\{\text{intra}(C_1), \text{intra}(C_2), \dots, \text{intra}(C_K)\}$ and $\sum_{i=1, K} \text{intra}(C_i)$ where $\text{intra}(C_i)$ is an intra-cluster criterion of C_i . In this paper we use the latter criterion. By minimizing each intra-cluster criterion locally (i.e., moving only vectors that reduce the error function to a new appropriate cluster), we expect that the algorithm will globally yield an optimal inter-cluster criterion. The K-means clustering algorithm is then to find a K clustering that minimizes the inter-cluster criterion or the error function.

Serial K-means Algorithm

1. Randomly select $|S|/K$ members of the set S to form K -subsets
2. While Error E is not stable:
3. Compute a means \bar{X}_i , $1 \leq i \leq K$ for each of the K subsets.
4. Compute distance $d(i, j)$, $1 \leq i \leq K$, $1 \leq j \leq N$ of each vector such that $d(i, j) = \| \bar{X}_i - v_j \|$
5. Choose vector members of the new K subsets according to their closest distance to \bar{X}_i , $1 \leq i \leq K$.
6. End

The serial K-means algorithm has time complexity $O(R_s KN)$ where K is the number of desired clusters and R_s is the number of iterations [3].

2. Proposed Algorithm

In this section we present some related works, motivations, materials, our parallel K-means algorithm, and complexity analysis.

2.1 Related Works and Motivations

In [4] authors present a clustering using a coarse-grained parallel genetic algorithm to obtain an optimal minimum squared-error partitions and use a distributed algorithm to improve the total execution time. Their algorithm is based on a SIMD model. In [7] authors present an optimal adaptive K-means algorithm with dynamic adjustment of learning rate to induce a near-optimal clustering solution in a situation where the pattern ensemble is not available. In [8] authors define the notion of a well-separated pair decomposition of points in d -dimensional space and develop efficient sequential and parallel algorithms for computing such a decomposition. The authors then present a

decomposition of multidimensional point sets and its applications to k -Nearest-Neighbors and n -body potential fields. Their parallel algorithm is based on a CREW PRAM model. These are some papers related to parallel clustering and K-means algorithms that are known to us.

Many applications for clustering algorithms, particularly applications in data mining, usually require the algorithms to work on massive data sets with an acceptable speed. For instance, in [6] NASA launches satellites for studying the earth's ecosystems. The Earth Observing System (EOS) is capable of generating about a terabyte of data per day. These terabytes of data will then be used to identify anomalies on earth by a visualization program. A grouping of such data sets could be done by clustering algorithms. However, when a data set is large, processing time and space requirement by the serial algorithms have become a serious concern. To our knowledge, no parallel non-heuristic K-means clustering algorithm has been developed on a message-passing model of a network of workstations (NOWs). We are interested in developing K-means algorithm because it is simple and widely used in practice. In addition, we are also motivated by an advantage of wide availability and relatively inexpensive costs of parallel computing on a network of workstations. Our contributions in this paper are then 1) to significantly reduce time complexity of the serial K-means algorithm by data parallelism and 2) to eliminate a limitation of memory requirement on a single machine when data sets are massively large.

2.2 Materials and Parallel K-means Algorithm

We use a network of homogeneous workstations with Ethernet network and use message-passing for communication between processors. In an Ethernet network, all communications consist of packets transmitted on a shared serial bus available to all processors [9]. Message-Passing Interface (MPI) is used as a library routine in C programming language for communication between processes. The following is a description of the parallel K-means clustering algorithm. A master-slave single program multiple data approach (SPMD) is used.

Let T_{startup} be a constant time needed in sending a blank message and let T_{data} be a constant time needed to send one data element (i.e., 4 bytes of integer). Note that in practice these two time constants may vary from one system to another.

Master Process

1. Randomly form K equal subsets of set S
2. Send each subset to each of the K slaves
3. Receive K resulting subsets from K slaves.

Complexity

$$K(T_{\text{startup}} + N/KT_{\text{data}})$$

$$T_{\text{comm1}} = K(T_{\text{startup}} + N/KT_{\text{data}})$$

Phase 2: After each slave process receives a subset from master process, it computes its mean \bar{X}_{myrank} from subset P. This step takes

$$T_{\text{comp1}} = |P|$$

Phase 3: In this phase each slave broadcasts its own mean to every other slave. Thus,

$$T_{\text{comm2}} = T_{\text{startup}} + T_{\text{data}}$$

Phase 4: Each slave computes Euclidean distance of each vector in subset P and computes vector members of the new K subsets. This phase takes

$$T_{\text{comp2}} = 2K|P|$$

Phase 5: In this phase each slave broadcasts K subsets to every other slave. Thus,

$$T_{\text{comm3}} = T_{\text{startup}} + |P|T_{\text{data}}$$

Phase 6: Each slave forms the new subset P. Hence,

$$T_{\text{comp3}} = |P|$$

Phase 7: Each slave sends its subset P to master. Hence,

$$T_{\text{comm4}} = T_{\text{startup}} + |P|T_{\text{data}}$$

Let R_p be the number of iterations of the while loop at step 2, TCM be total communication time, and TCP be total computation time. The total time complexity can then be computed.

$$\text{Total time} = \text{TCM} + \text{TCP}$$

$$\begin{aligned} \text{TCM} &= T_{\text{comm1}} + T_{\text{comm2}} + T_{\text{comm3}} + T_{\text{comm4}} \\ &= K(T_{\text{startup}} + N/KT_{\text{data}}) + R_p(2T_{\text{startup}} + (|P|+1)T_{\text{data}}) + T_{\text{startup}} + |P|T_{\text{data}} \\ &= (2R_p + K + 1)T_{\text{startup}} + (N + R_p(|P|+1) + |P|)T_{\text{data}} \\ &= O(N + R_p|P|) \end{aligned}$$

$$\begin{aligned} \text{TCP} &= T_{\text{comp1}} + T_{\text{comp2}} + T_{\text{comp3}} \\ &= R_p(2|P| + 2K|P|) = O(2R_pK|P|) \end{aligned}$$

$$\begin{aligned} \text{Total time} &= O(N + R_p|P|) + O(2R_pK|P|) \\ &= O(2R_pK|P|) \end{aligned}$$

Given a uniformly distributed data set of N vectors, each slave process on one machine requires space of $O(N/K)$. Hence, the parallel K-means algorithm has total space complexity $O(N)$.

Slave Process

1. Receive a vector subset P from master process
2. While Error E is not stable:
3. Compute a mean \bar{X}_{myrank} of the subset P $|P|$
4. Broadcast the mean \bar{X}_{myrank} to every other slaves $T_{\text{startup}} + T_{\text{data}}$
5. Compute distance $d(i,j)$, $1 \leq i \leq K, 1 \leq j \leq |P|$ of each vector in P such that $d(i,j) = \|\bar{X}_i - v_j\|$ $K|P|$
6. Choose vector members of the new K subsets according to their closest distance to $\bar{X}_i, 1 \leq i \leq K$ $K|P|$
7. Broadcast K subsets computed in step 6 to every other slaves $T_{\text{startup}} + |P|T_{\text{data}}$
8. Form the new subset P by collecting vectors that belong to \bar{X}_{myrank} that were sent from other slaves in step 7 $|P|$
9. End
10. Send the subset P to master process $T_{\text{startup}} + |P|T_{\text{data}}$

It is worth noting that broadcasting in this algorithm does not undermine the overall performance. In fact, broadcasting is intentionally used in order to improve the performance of the algorithm because broadcasting only requires one setup time for each broadcast while a pair of send() and receive() requires one setup time each time the message is sent from one process to another. Since the setup time for each message passing in MPI is large, broadcasting helps alleviate this problem significantly while achieving the same effect as send() and receive().

2.3 Time/Space Complexity Analysis

We analyze the algorithm into communication steps and computation steps. Let T_{comm} be the time complexity of communication and T_{comp} be the time complexity of computation. There are 4 communication phases and 3 computation phases in the algorithm. Each phase can be described as follows.

Phase 1: Master process sends K equal subsets to K slaves. Thus,

3. Experimental Results

Both versions of K-means algorithms are run with $K = 4$ and $D = 2$. All experimental input data are uniformly distributed random vectors. Execution times, the number of iterations, and speedup are measured as follows:

N D=2	Iter. Serial	Iter. Para	Exec. Sec. Serial	Exec. Sec. Para	Speedup
100K	35	34	127	268	-
200K	22	22	174	328	-
300K	32	31	351	648	-
400K	31	31	472	859	-
500K	27	28	543	1044	-
600K	26	26	946	1749	-
700K	29	31	3683	3322	1.11
800K	36	36	6871	5923	1.16
900K	28	28	13146	6248	2.10
1000K	-	25	-	8216	-

From the table, we observe that there is no speedup from $N = 100,000$ to $N = 600,000$ because communication time is much greater than computation time. (The MPI library seems to require a lot of time for initialization and cleanup stages. In addition, a MPI broadcast is a simulation on a single bus.) However, from $N = 700,000$ to $N = 900,000$, the computation time starts to dominate the communication time, resulting in substantial speedup. The parallel version also allows one to use larger problem sizes because data are distributed to several machines. In the experiment the serial version could not continue when $N = 1,000,000$ because a single machine did not have sufficient memory to meet computational requirement. The parallel version is expected to gain more speedup as N increases and computation time starts to dominate communication time. However, due to our limited memory space, we can show experimental results of N as large as 1,000,000 vectors (See figure 2).

4. Conclusion

Time complexity of the serial K-means algorithm is $O(R_sKN)$ whereas time complexity of the parallel K-means algorithm is $O(2R_pK|P|)$. Since R_s and R_p are inherently equivalent and $N \gg |P|$, $O(2R_pK|P|)$ is asymptotically better than $O(R_sKN)$.

Suppose N is sufficiently large and data is uniformly distributed. $|P|$ would be close to N/K . We can measure performance of the parallel K-means algorithm against the performance of the

serial algorithm by using speedup $S(K)$, where K is the number of processors:

$$\begin{aligned}
 S(K) &= \frac{\text{Execution time of single processor}}{\text{Execution time of } K \text{ processors}} \\
 &= \frac{O(R_sKN)}{O(2R_pK|P|)} = \frac{O(R_sK^2|P|)}{O(2R_pK|P|)} \\
 &= O(K/2)
 \end{aligned}$$

The experiment confirms that when N is sufficiently large, speedup gain is $O(K/2)$ as predicted.

In a system with P processors a possible maximum speedup is P . In our parallel algorithm the number of processors P is essentially equal to K . Let T be the efficiency defined as

$$T = (\text{speedup gain}/\text{maximum speedup})100\%$$

Thus, efficiency of parallel K-means algorithm

$$T = (K/2)/K \times 100\% = 50\%$$

We can conclude that our parallel K-means algorithm achieves 50% efficiency of time complexity. 50% is relatively efficient and cost effective if we consider that the system used in this paper is an Ethernet-based message-passing system and that the K-means clustering algorithm operates globally by nature. In terms of space complexity, the parallel K-means algorithm has the same total complexity $O(N)$ as the complexity of the serial version. However, the parallel version allows one to use larger problem sizes because of its distributive nature. The parallel algorithm can scale a problem size up to $O(K)$ times the size of the problem on a single machine.

5. Future Work

The speedup of the proposed algorithm may be improved even more significantly if we reduce communication time by grouping two or more subsets together on one machine. However, this will likely affect scalability of the algorithm. In addition, our algorithm needs to use exactly K machines to operate. Future work could be making the algorithm more flexible by allowing it to adapt itself into any number of machines. In [9] the authors work on overlapping connectivity Ethernet. Their configuration can be expected to reduce even more communication time of our algorithm significantly without having impacts on scalability. Besides, because most clustering applications tend to apply to a massive size of data

sets, we are interested in finding a method to partition a data set by K-means algorithm in such a way that we can temporarily ignore some resulting partitions in order to work on a few chosen specific partitions without sacrificing clustering quality. A motivation is to save some significant working space and we believe, by means of doing so, we can find a way to add a new portion of a data set into the existing partitions without having to rerun the K-means algorithm from the start. Some partially-related work has already been studied in [8]. A by-product of this study is a domain decomposition for possibly applying Divide-and-Conquer strategies to parallelize the algorithm for better speedup.

6. Acknowledgements

We would like to thank the Department of Electrical Engineering and Computer Science at Tufts University for allowing us to use computer facilities in our experiment.

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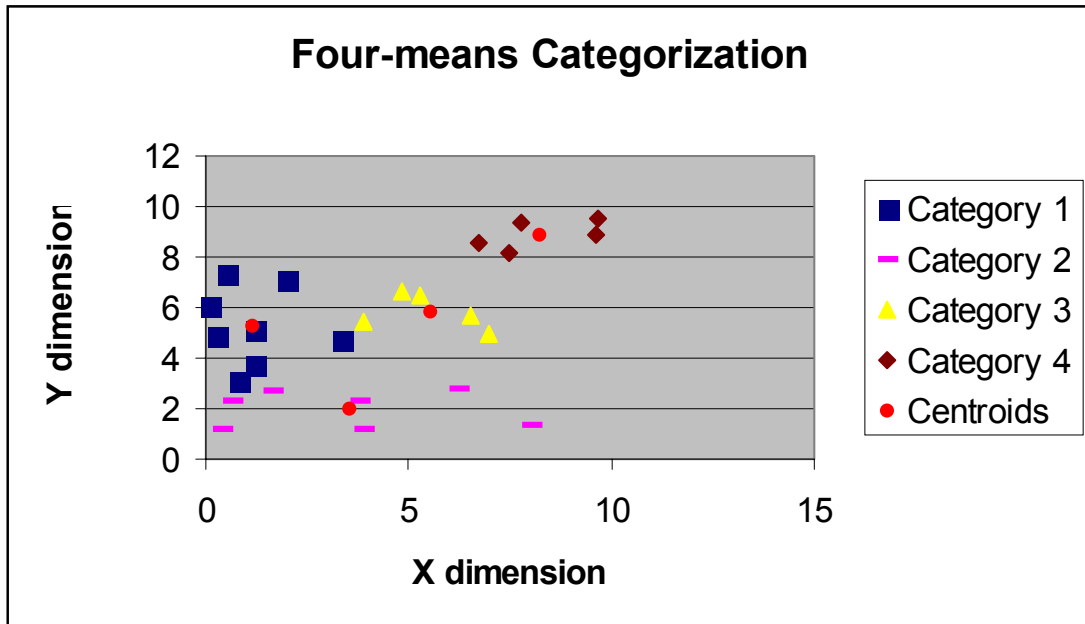


Figure 1. Two-dimensional data are clustered into 4 categories by running K-means algorithm on the data. Each color represents each category. The centroids are the representatives of each category.

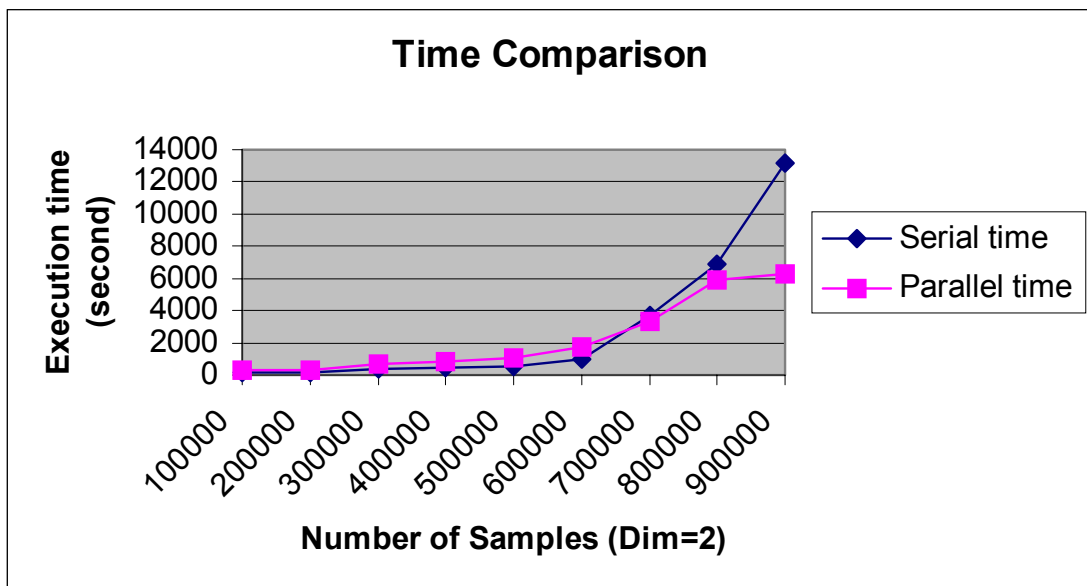


Figure 2. The running time of parallel and serial K-means algorithms are shown in the graph. It can be seen that the parallel time is less than the serial time when the number of samples is greater than 700,000 and it is about twice less than the serial time when the number of samples is 900,000.

Text-dependent Speaker Identification Using Neural Network On Distinctive Thai Tone Marks*

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ABSTRACT-- This paper presents a neural network based text-dependent speaker identification system for Thai language. Linear Prediction Coefficients (LPC) are extracted from speech signal and formed feature vectors. These features are fed into multilayer perceptron (MLP) neural network with backpropagation learning algorithm for training and identification processes. Five Thai tone marks are considered very closely in choosing the sentences in order to achieve the best speaker identification accuracy. Five speaking texts with each Thai tone and a mixed tone text are comparatively experimented. Average identification rate on 9 speakers achieves above 95% when using mixed tone text, and poor results occur with middle and low tone texts, which usually cause vagueness or unclear voices.

KEY WORDS -- Text-dependent speaker identification, Linear prediction coefficients, Neural networks, Thai tone.

บทคัดย่อ-- บทความฉบับนี้นำเสนอระบบระบุผู้พูดสำหรับภาษาไทยแบบกำหนดคำพูด โดยใช้โครงข่ายประสาทเทียมเป็นระบบในการจดจำ ในขั้นตอนสัญญาณเสียงจะถูกนำมาผ่านกระบวนการสกัดค่าลักษณะสำคัญ ซึ่งคือค่าสัมประสิทธิ์การประมาณพหุระเชิงเส้น (Linear Prediction Coefficients) และใช้เป็นอินพุตสำหรับโครงข่ายประสาทเทียมประเภทเพอเซปตรอนหลายชั้น (Multilayer Perceptron) โดยใช้กระบวนการเรียนรู้แบบแพร่กระจายกลับหลัง (Backpropagation) จุดมุ่งหมายของการทดลองเพื่อพิจารณาผลกระทบของการใช้เสียงวรรณยุกต์ที่แตกต่างกันต่อการระบุผู้พูดจึงกำหนดให้ใช้ประโยคในการพูด 6 ประโยค 5 ประโยคแรกแต่ละประโยคมีเสียงวรรณยุกต์เดียวจาก 5 ระดับเสียงวรรณยุกต์ในภาษาไทย ส่วนประโยคสุดท้ายมีทั้ง 5 เสียงวรรณยุกต์ผสมกัน การทดลองเปรียบเทียบการพูดประโยคแต่ละประโยคเพื่อระบุผู้พูดจำนวน 9 คน ปรากฏว่าเมื่อใช้ประโยคที่มีเสียงวรรณยุกต์ผสมจะได้ผลการระบุผู้พูดสูงที่สุดซึ่งได้ผลมากกว่า 95 เปอร์เซ็นต์ และผลการระบุผู้พูดต่ำที่สุดเมื่อใช้ประโยคที่มีเสียงวรรณยุกต์เอกซึ่งเป็นเสียงที่ต่ำและไม่ชัดเจน

คำสำคัญ -- การระบุผู้พูดแบบขึ้นกับกำหนดคำพูด, ค่าสัมประสิทธิ์การประมาณพหุระเชิงเส้น, โครงข่ายประสาทเทียม, วรรณยุกต์ไทย

1. Introduction

Speaker recognition can be separated into two groups [1,5]; speaker verification which has main task in verifying speaking person, and speaker identification which tries to answer who is speaking. Speaking text dependency is an important limitation of these systems. On text-dependent system, the first essential procedure is to select some speaking texts that can cover speaker's characteristics as much as possible for the recognition

process. This task is language dependent requiring some comprehensive researches.

Thai language consists of 44 consonants, 18 vowels, 10 Thai digits, and 5 tonal levels or tone marks. Tone marks, different from intonation, can be added in Thai words and caused different meaning. This characteristic of Thai language is experimented carefully to consider its effect. Thai tone mark is an outstanding feature like tone marks in Mandarin or Korean. Five Thai tonal levels can be classified into dynamic and static tones. Dynamic

*This article is a reprint of the article appeared in the Proceedings of IEEE-INNS International Joint Conference on Neural Network, July, 1999.

tones, rising and falling tones, have a great change of fundamental frequency with respect to duration, while the static tones, low, middle, and high tones, are quite stable. Figure 1 [6] illustrates a graph of fundamental frequency of each tone plotting with average time duration.

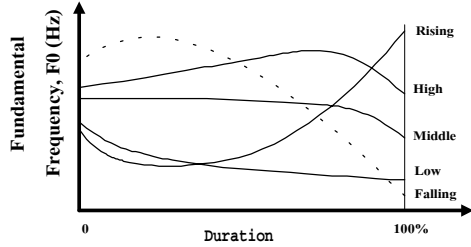


Figure 1. Fundamental frequency curve with respect to speech duration for each Thai tone.

Speaker identification system can conclusively be modeled as shown in Figure 2 [2]. Features are some quantities, which are extracted from preprocessed speech and can be used to represent the whole speech signal. Two sets of features consisted of spectral and prosodic features are proposed in many researches. Many works have concluded that the spectral based features such as Linear Prediction Coefficients (LPC), Cepstral coefficients, and their derivatives, have more efficient than prosodic-based features like fundamental frequency, formant frequency, and speech energy [3-5]. Main reasons are easiness in extraction and their consistency over several variations. Also, there are many recognition system proposed for speaker recognition such as a well-known nonlinear time-aligned techniques called Dynamic Time Warping (DTW) [1,4], Vector Quantization (VQ) [12], Artificial Neural Network (ANN) [10], and statistical Hidden Markov Model (HMM) [1,5]. What technique should be used depends on some factors in the implemented system.

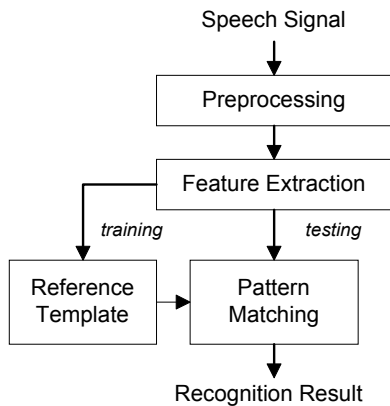


Figure 2. Speaker recognition model

In this paper, time duration of speaking voices is normalized via a time normalization technique. Hence, equal number of features, LPC is extracted from equal time-duration speech and can suitably form the input of backpropagation neural network, which has an essential limitation on number of input but has a strength of nonlinear mapping or recognizing [8].

2. Proposed Speaker Identification System

In the proposed system, digital speech signal is passed through a preprocessing procedure, which performs energy-based endpoint detection and time normalization. LPC features are then extracted from preprocessed speech and the input vectors have passed through the backpropagation learning algorithm with multilayered perceptron network for both training and evaluation processes. Figure 3 shows overall model of the proposed system.

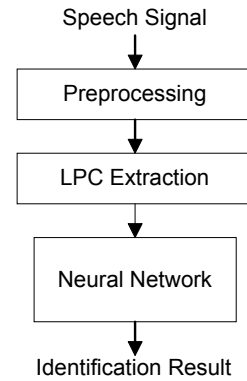


Figure 3. Overall proposed speaker identification model

2.1 Linear Prediction Coefficient (LPC)

A well-known speech coding strategy is to assume that each speech sample can be estimated from linear combination of p-previous speech samples as described in the following equation.

$$\hat{X}(n) \approx \sum_{k=1}^p a_k X(n-k) \quad (1)$$

where $X(n)$ is a speech sample n , a_k 's are p-order linear prediction coefficients (LPC), which can represent a speech signal. The way to find value of a_k is to minimize an error between an original speech sample and

an estimated speech signal as shown in equation 2 by differentiation with each a_k .

$$E_n = \sum_m \left[\bar{X}_n(m) - \sum_{k=1}^p a_k X_n(m-k) \right]^2 \quad (2)$$

Equation 2 forms an error of the whole speech frame instead an error of each sample. N denotes index of speech frame and m denotes index of speech sample within frame n. P equations derived from the differentiation of error equation are then solved to obtain the values of a_k by Levinson-Durbin algorithm [7].

2.2 Multilayer Perceptron (MLP) with Backpropagation Learning Algorithm

In this paper, we have chosen to use a backpropagation neural network [8,9,11] since it has been successfully applied to many pattern classification problems including speaker recognition [10] and our problem has been considered to be suitable with the supervised rule.

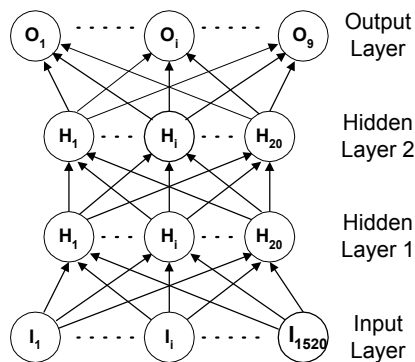


Figure 4. The structure of MLP

MLP neural network we used consists of four layers; one input layer, two hidden layers and one output layer. The structure of the backpropagation neural network is shown in Figure 4. The first layer has 1,520 input neurons (152 frames x 10 LPC-orders) which are fully connected to the first hidden layer. The two next hidden layers consist of 20 neurons per layer. The last layer is the output layer consisting of 9 neurons which one output neuron represented one speaker. All four layers are fully feed-forwarded.

3. Experimental Results

Our experiments were conducted on six sentences. Each sentence consists of five words. The first five sentences contain the same word in a tonal level of middle, low, falling, high and rising, respectively. The last sentence

contains one word from each tonal level. So the last sentence has five different tonal levels. All six sentences used in our experiments are shown in the Table 1.

In the experiment, we recorded in an office environment at 11.025 kHz sampling rate, 16 bit and single channel. The average lengths of each sentence are 2.5 second. The utterance is obtained from 9 local speakers (4 females and 5 males). Each speaker was asked to pronounce each sentence ten times per day for two days. Therefore, the total utterances are 180 utterances for each sentence. False starts, pauses, and background noise are manually controlled in this database. The data were randomly divided into two sets, with 135 utterances in the training set and 45 utterances in the test set.

- Training set consists of 8 and 7 times from the first and second day, respectively. Total is 135 utterances (15 x 9).
- Test set consists of 2 and 3 times from the first and second day, respectively. Total is 45 utterances (5 x 9).

Each utterance was pre-emphasized, time normalized, and performed the 10th order autocorrelation analysis. The results were used to find the LPC feature vector. The LPC analysis was performed for every 20-ms speech frame with 5-ms overlapping.

Table 1. Six sentences in our experiments.

No.	Sentences	Phonetics	Tone mark
1	ㄅ-ㄅ-ㄅ-ㄅ-ㄅ	/?e:0 ?e:0 ?e:0 ?e:0 ?e:0/	Middle
2	ㄅ-ㄅ-ㄅ-ㄅ-ㄅ	/?e:1 ?e:1 ?e:1 ?e:1 ?e:1/	Low
3	ㄅ-ㄅ-ㄅ-ㄅ-ㄅ	/?e:2 ?e:2 ?e:2 ?e:2 ?e:2/	Falling
4	ㄅ-ㄅ-ㄅ-ㄅ-ㄅ	/?e:3 ?e:3 ?e:3 ?e:3 ?e:3/	High
5	ㄅ-ㄅ-ㄅ-ㄅ-ㄅ	/?e:4 ?e:4 ?e:4 ?e:4 ?e:4/	Rising
6	ㄅ-ㄅ-ㄅ-ㄅ-ㄅ	/?e:0 ?e:1 ?e:2 ?e:3 ?e:4/	All 5 tones

Two experiments were conducted. The first one was performed by using backpropagation network on the training and testing sets. The neural network simulator used in our experiments is SNNS (Stuttgart Neural Network Simulator) [9]. The second experiment was conducted by applying the Euclidean distance on the mean of distances of 20 utterances of each speaker on each sentence.

The identification rates of all six training sentences by neural network are all approaching 100%. The identification rates in percentage on testing data between

the backpropagation network and the Euclidean distance are shown in Table 2. It is found that the ANN produces the best accuracy with a mixed five tone sentence at above 95% and give lowest average identification rate with sentence of middle tonal level at 68.89%. Meanwhile, the Euclidean distance gives the corresponding same result with ANN. The mixed tone sentence gives the best performance at 82% identification rate, while the worst result was obtained from sentence with middle tone mark at only 65%.

Table 2. Comparison of the identification rate between backpropagation network and Euclidean distance.

Sentence No.	Identification rate (%)	
	Neural Network	Euclidean Distance
1	68.89	65.00
2	77.78	69.00
3	88.89	74.00
4	82.22	73.00
5	86.67	80.00
6	95.56	82.00

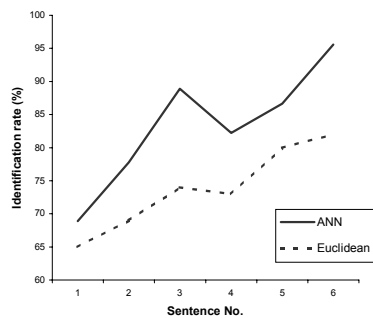


Figure 5. The comparison of the identification rates between ANN and Euclidean distance.

In Figure 5, the identification rates in percentage of ANN are better than ones of the Euclidean distance, but the best sentence of each technique are alike, while the sentence with middle tonal level gives the lowest identification rate in both techniques also. Therefore, the experimental results have shown that tonal levels of Thai tone marks are important to Thai speaker identification system. Furthermore, the sentence with several tone marks produces a better accuracy than a sentence with single tone mark with the same length of words.

Further experiment has performed with ten isolated Thai digits (0-9) on 20 speakers. Voices of each digit are

recorded 10 times per week for 4 weeks, 7 times are used for training and the rest are used for testing. Table 3 illustrates phonetic of Thai digits, their tonal levels, and identification results.

Table 3. Identification results using speaking text of isolated Thai digits

Thai digit	Phonetics	Tone mark	Identification rate (%)
0	/su:n4/	Rising	80.00
1	/nvng1/	Low	80.83
2	/s@:ng4/	Rising	82.08
3	/sa:m4/	Rising	82.08
4	/si:1/	Low	79.17
5	/ha:2/	Falling	84.58
6	/hok1/	Low	60.42
7	/cet1/	Low	78.33
8	/pa:t1/	Low	70.83
9	/kao:2/	Falling	84.17

Larger number of speakers, and also shorter speaking text duration may normally pull down the performance of identification system as shown in Table 3. However, the results still confirm our conclusion on tone effect. Falling tone such as digit "5" and "9", and rising tone such as digit "2" and "3", can give quite high identification rates, while for example; digit "4", "6", and "8" conduct poor results. Another interesting notice is the worst identification obtained by digit "6", which may be caused by not only a low tone digit, but also a very short utterance digit.

Future researches of Thai text-dependent speaker identification system will be deeply investigated on the suitable length of speaking text, Thai alphabets and vowels, and other preprocessing and identification techniques.

4. Conclusion

LPC speech feature and a neural network with backpropagation training algorithm are appropriate to use for a Thai text-dependent speaker identification system on distinctive Thai tone marks. The best average identification rate is over 95% on nine Thai native speakers with ANN. In the comparison between ANN and Euclidean distance as an identification engine, ANN shows a great powerful nonlinear recognition performance. To improve system capability, mixed tone speech in appropriate length of speech duration should be selected for speaking sentence since it can cover more

personal characteristics than using each tone in all utterances.

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รายนามผู้ประเมิน

รายนามผู้ประเมินบทความของวารสารวิชาการเนคเทค ปีที่ 1 ตั้งแต่ฉบับที่ 1 ถึงฉบับที่ 6 ขอขอบพระคุณผู้ประเมินทุกท่านที่กรุณาสละเวลาอันมีค่าประเมินบทความให้กับวารสารวิชาการเนคเทค

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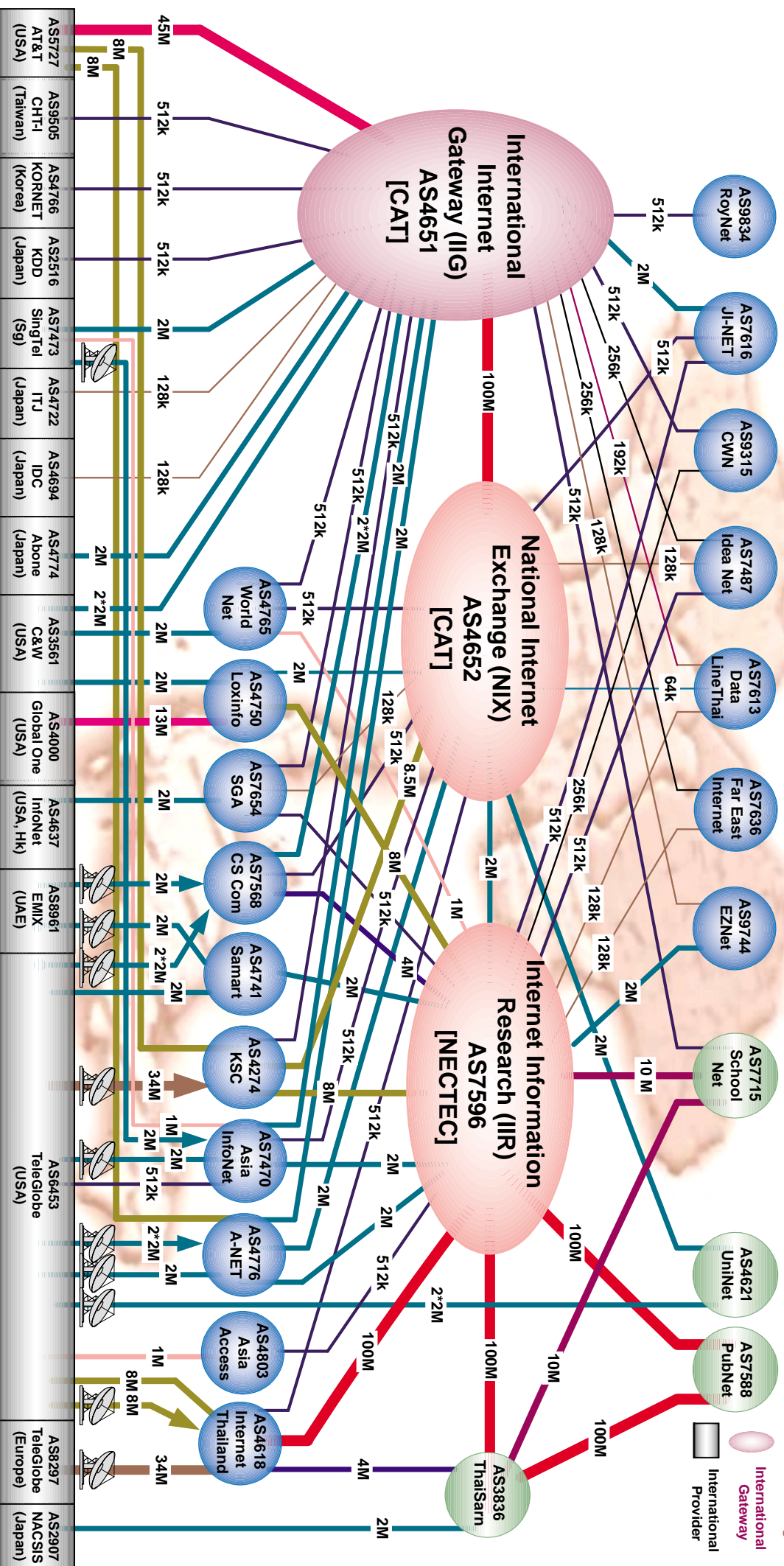


Chart Date: 2000-02-01

