Implementing a Canonical Correlation Analysis Algorithm Built-in System on an ARM-based Embedded System for Steady-State Visual Evoked Potential Applications.

Ting-Kuei, Hu
Department and Institution of Eletronics,
National Chiao Tung University,
Hsinchu, Taiwan

Tseng-Po, Yen
Department and Institution of Eletronics,
National Chiao Tung University,
Hsinchu, Taiwan

***Abstract*—Steady State visual Evoked Potential (SSVEP) is widely used in the rising need of Brain Computer Interface products. It can now be applied on broad users, not like the traditional BCI products. Canonical Correlation Analysis(CCA) can be used to conduct brain waves main frequencies, and it is more accurate than conventional Fourier transform. In this paper, a four channel CCA processor is introduced and verified on FPGA. The verified hardware will be design and packaged under AMBA disciplines, and an user interface and driver is also included to make it an easy-apply silicon IP for Arm-based embedded system.**

I. Introduction

Steady state visual evoked potentials are signals that are natural response to visual stimulations at specific frequencies. When the retina is excited by stimulus, the brain generates electrical activity at the same or harmonic frequency of the visual stimulus. However, raw brain signals are easily contaminate when measuring. Therefore, canonical correlation analysis is used to find out relationship between two multidimensional variables (raw brain wave signals and reference signals) which indicate the desire main frequencies. In this paper, a fusion of Fourier transform and CCA is used to analyze frequency components of brainwaves. Finally, the verified CCA algorithm implementation on hardware will be design and packaged under AMBA disciplines, which is the most common specification, the silicon IP could be re-use by other buildings followed AMBA specifications.

II. Methods

A. Frequency analysis based on CCA

We use CCA to find linear combinations which have maximum correlation with each other on two sets of variables (signals) x(t) and y(t). The first set of variables x(t), is the EEG signals recorded from visual part of participants' brain. Due to the efficiency matter which will be mentioned later, 4 channels were used to conduct an accurate solution. The second set of variables, y(t), is the set derived from the stimulus signals. Because every periodic signals can be decomposed into the Fourier series, the most significant terms from Fourier series are chosen to be our reference stimulus signals, which is:

$$x(t) = \begin{bmatrix} x_{1,1} & \cdots & x_{1,4} \\ \vdots & \ddots & \vdots \\ x_{128,1} & \cdots & x_{128,4} \end{bmatrix} \quad (1)$$

$$y(t) = \begin{bmatrix} \sin(2\pi ft) \\ \cos(2\pi ft) \end{bmatrix}, t = \frac{1}{s}, \frac{2}{s} \cdots \frac{\mathrm{T}}{\mathrm{s}} \quad (2)$$

The chosen frequencies are the same as the stimulus frequencies. We calculated those coefficients with all stimulus signals. The maximum ones would be the frequencies of the SSVEP.

B. CCA equation and some approximations

Due to the fact that the coefficients can be derived from the CCA equations below[2]:

$$R_{yy}^{-1} R_{yx} R_{xx}^{-1} R_{xy} - \rho^2 I = 0 \quad (3)$$

Where R_{xx} and R_{yy} are the covariance matrix of x and y respectively. We multiply the right-hand side with the matrix $R_{yy}^{-\frac{1}{2}}$ and, with proper arrangements, derives a new equation:

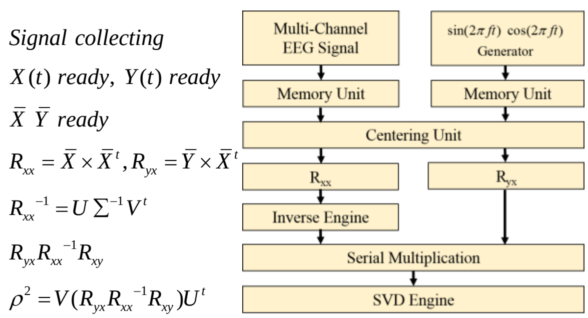
$$R_{yy}^{-\frac{1}{2}} R_{yx} R_{xx}^{-1} R_{xy} R_{yy}^{-\frac{1}{2}} - \rho^2 I = 0 \quad (4)$$

This new equation contains several advantages. First, the matrix of the serial multiplication of the five matrices would be a symmetric matrix. Second, due to the simulation result from Matlab, we find that the matrix $R_{yy}^{-\frac{1}{2}}$ can be approximated as a constant at any frequencies. Therefore we generalize this CCA algorithm to be a general symmetric eigenvalue problem.

III. HARDWARE STUCTUER AND IMPLEMENTATION

A. *Hardware design flow*

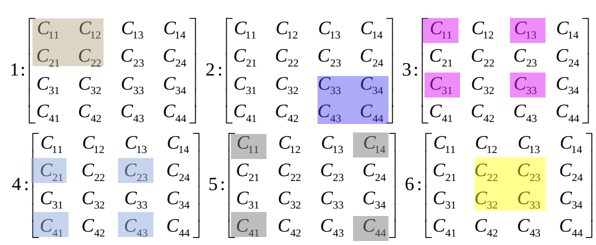
We aim to design an easy way for realizing our algorithm on hardware. Therefore, symmetry of matrices is one of the top concerns in order to reduce area needs under limited processing speed, design flow chart is as follows:



After entering memory units, the EEG signals undergoes a "centering" process to deduce further computation complexity and yields covariance matrices. In order to compute the covariance ρ , we are using its inverse matrix during singular value decomposition.

B. *Jacobi Singular value decomposition*

By Jacobi method, we know a 4x4 matrix can be separated in to four 2x2 matrices when computing. Also, we could approximate all off diagonal elements to zero by iterating. Every 2x2 matrices could be decomposed in to left rotation matrix and right rotation matrix. And because of the symmetry of our matrices, left angle and right angle would be the same. It is a useful property during hardware implementation.



$$\begin{bmatrix} \cos\theta_l & -\sin\theta_l \\ \sin\theta_l & \cos\theta_l \end{bmatrix} M \begin{bmatrix} \cos\theta_r & -\sin\theta_r \\ \sin\theta_r & \cos\theta_r \end{bmatrix} = \begin{bmatrix} \Psi_1 & 0 \\ 0 & \Psi_2 \end{bmatrix}$$

$$\begin{aligned} \theta_l + \theta_r &= \arctan([c+b]/[d-a]) \\ \theta_l - \theta_r &= \arctan([c-b]/[d+a]) \end{aligned} \quad \textit{for } M = \begin{bmatrix} a & b \\ c & d \end{bmatrix}$$

C. *Cordic algorithm.*

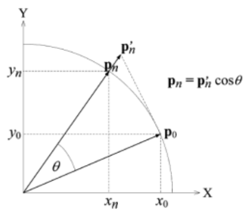
[3]Cordic algorithm can solve singular value decomposition problems. Singular value decomposition of a matrix **M** is given by:

$$M = U\Sigma V^T,$$

Where U and V are orthogonal matrices. Why do we use Cordic algorithm to compute the arctangent elements value is because only addition and displacement should be done to achieve the computation. This is also an useful property for hardware implementation. Below is a brief introduction of Cordic:

Coordinate transform of a point could be written as follows

$$\begin{pmatrix} x' \\ y' \end{pmatrix} = \begin{pmatrix} \cos(\theta) & \sin(\theta) \\ -\sin(\theta) & \cos(\theta) \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}$$



We could rotate the matrix by given different angle θ ,in a view of matrix, an all off diagnal elements being zero matrix could be done by rotation

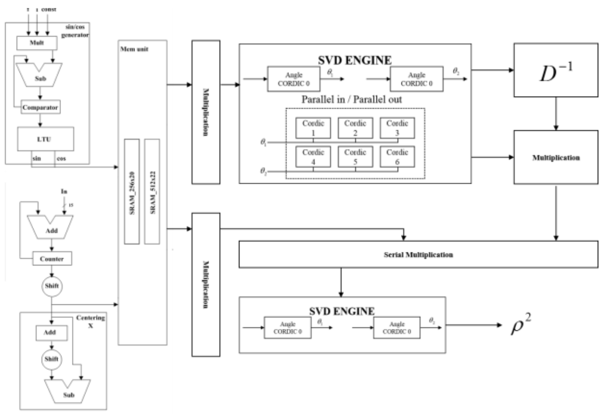
$$\begin{aligned} \begin{pmatrix} x' \\ y' \end{pmatrix} &= \begin{pmatrix} \cos\theta & \sin\theta \\ -\sin\theta & \cos\theta \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} \\ &= \cos\theta \begin{pmatrix} 1 & \tan\theta \\ -\tan\theta & 1 \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} \\ &= (1+\tan^2\theta)^{\frac{1}{2}} \begin{pmatrix} 1 & -\tan\theta \\ \tan\theta & 1 \end{pmatrix} \end{aligned}$$

After several steps, the last equation gaurantees that the floating points number calculation will be deduce in half, because we only have to do the calculation of angles. Moreover, by using specific angles, we could just move the decimal point instead of multiplication for computation,

tan	
tan(45)	1
tan(26.565051177078)	1/2
tan(14.0362434679265)	1/4
tan(7.1250163489018)	1/8
tan(3.57633437499735)	1/16
tan(1.78991060824607)	1/32
tan(0.8951737102111)	1/64
tan(0.4476141708606)	1/128
tan(0.2238105003685)	1/256

D. *Hardware implementation*

Two SRAM memory is used to save signals, and the covariance is processed by the eigenvalue engine. After reciprocating and multiplication with former matrices, an eigenvalue decomposition will be done again to get the desire square of covariance.

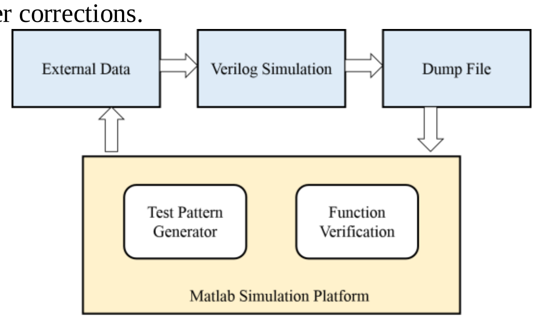


E. System design and implementation

IV. EXPERIMENT

A. Verification process

A firm verification process is needed to make sure the accuracy of CCA algorithm hardware implementation, thus, a reliable comparison is needed. We use Neuroscan to analyze a set of brain waves and process it by CCA on Matlab, then we could get a set of ideal value. We can now verify our numerical result from FPGA in comparison with those ideal result, and make further corrections.



B. Experiment flow

At the beginning, participants wore the Neruoscan cap, four channels on the visual part were used to sensor and record raw data. After checking signal fetching is in process, participants were asked to relax their eyes muscles for 20 seconds. Then they will be looking at the visual stimulus made by LEDs, we fetched 20 seconds of signal for every experiment set. Participants rest for five minutes between every set to reduce possible deviation cause by visual fatigue. Frequency of 9, 10, 11, 12, 13, 14 Hz stimulus were used under this experiment. At last, 6 set of signals were recorded per participant, which were used as patterns for verification after processing. The reason why we use LED as stimulus instead of monitor is because of the refresh rate of the monitor. Say, a monitor has a 60Hz refresh rate, it cannot work as an accurate 13 Hz visual stimulus.

V. RESULT

VI. DISCUSSION AND CONCLUSION

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