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PARALLEL PROGRAMMING ON GENERAL  
BLOCK MIN MAX CRITERION

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A Thesis  
Presented to the  
Faculty of  
California State University,  
San Bernardino

---

In Partial Fulfillment  
of the Requirements for the Degree  
Master of Science  
in  
Computer Science

---

by  
ChuanChe Lee  
September 2006

PARALLEL PROGRAMMING ON GENERAL  
BLOCK MIN MAX CRITERION

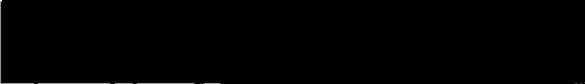
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by  
ChuanChe Lee  
September 2006

Approved by:

  
\_\_\_\_\_  
Dr. Keith Schubert, Chair, Computer Science

  
\_\_\_\_\_  
Dr. Ernesto Gomez

  
\_\_\_\_\_  
Dr. Richard Botting

Aug 9, 2006  
Date

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## ABSTRACT

General Block Min Max Criterion (GBMM) is a pre-2D-chopped robust estimation method designed by Dr. Schubert. It may be applied on image clarification, pollution detection ... etc. This thesis tries to parallelize GBMM method not only to speedup it, but also to see whether a pre-chopped algorithm is suitable to be implemented in checker-board method or not.

## ACKNOWLEDGMENTS

The support of God is gratefully acknowledged. Trust in the LORD with all your heart, and lean not on your own understanding; In all your ways acknowledge Him, And He shall direct your paths. Do not be wise in your own eyes; Fear the LORD and depart from evil. (Proverbs 3:5-7, NRSV)

I would first thank Dr. Keith Schubert, my advisor, who has encouraged me through my studies at California State University, San Bernardino. He explained to me in detail his dissertation so that I could start my master's thesis. He has also helped me to solve problems involving the machines I have used to run my thesis program. He has given me insights about how to design my thesis. I am grateful to Dr. Schubert for all these and many other helps that I have received from him.

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algorithm. He explained to me in detail the structure of a thesis proposal so that I could start writing my thesis.

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## DEDICATION

To my dear parents who have supported me both mentally and financially.



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## CHAPTER ONE

### BACKGROUND

#### 1.1 Introduction

The content of Chapter One presents an overview of the thesis. The contexts of the problem are discussed followed by the purpose, significance of the thesis, and assumptions. Next, the limitations that apply to the thesis are reviewed. Finally, definitions of terms are presented.

#### 1.2 Purpose of the Thesis

The purpose of the thesis is to develop a parallel implementation of the General Block Min Max Criterion (GBMM) which is designed by Dr. Keith Schubert. [7] GBMM is a robust estimation<sup>1</sup> method which tries to solve  $Ax = b$  where  $A$  is a matrix,  $b$  and  $x$  are vectors, especially when  $A$  is ill-conditioned<sup>2</sup>. This thesis not only tries to parallelize GBMM so that it will be performed more

---

<sup>1</sup> Robust estimation is "an estimation technique which is insensitive to small departures from the idealized assumptions which have been used to optimize the algorithm." [11]

<sup>2</sup> A matrix is ill-conditioned if the condition number ( $\kappa(A) = \|A^{-1}\| \cdot \|A\|$ ) is large. The condition number is a measurement of whether a problem is good to digital computation. The condition number "gives a bound on how inaccurate the solution  $x$  will be after approximate solution. Note that this is before the effects of round-off error are taken into account."

rapidly, but also tries to see whether a pre block-chopped algorithm may better fit the checker board decomposition<sup>3</sup> method or not.

### 1.3 Context of the Problem

The context of the problem is to address whether the block decomposed structure can match the checker board decomposition which is a widely used parallel method. Matrix multiplication is notoriously time consuming, but is widely used in many fields both in research and industry, such as physics, chemistry, pollution detection, image clarification.

### 1.4 Significance of the Thesis

The significance of the thesis is, at least, twofold. First of all, robust estimation and identification is important in many ways as listed in previous sections. But it usually takes time to calculate. The speedup is an endless desire and a necessity, especially in scientific usage. If we wish to clarify a video instantly for driving in fog, the speed is definitely important in that situation. Parallel computing is a good method to speedup.

---

<sup>3</sup> Checker board decomposition is a widely used method in parallel implication to get better speedup.

Secondly, whether the structure of an algorithm is an important issue to parallel or not? As a pre-block-chopped algorithm, GBMM is a good example to examine.

### 1.5 Assumptions

Although GBMM does not have the following assumptions, this thesis adds some assumptions listed below:

1. The matrix  $A$  is chopped into equal size.
2. The number of processes used is a perfect square number, say, 1, 4, 9, 16 ...  $n^2$  ..., etc.
3. All the number of partitions,  $q$  and  $p$ , and matrix size,  $h$  and  $w$ , are multiple of  $n$ , the square root of the number of processes used.
4. Assume none of the  $\psi_i$  in equation (6) listed in section 2.2 is zero.

### 1.6 Limitations

During the development of the thesis, a number of limitations were noted. These limitations are presented here.

This parallel implementation is based on Cannon's Algorithm which will be briefly introduced in 2.2; therefore, the number of processes should be a perfect



square number. This is the reason why this thesis must have that assumption.

### 1.7 Definition of Terms

The following terms are defined as they apply to the thesis.

CPO - Communication Parallel Overhead.

DM - Diagonal Matrix.

Focused process - The process which is doing more work than the other processes. Usually, process 0 is the focused process, but not always so.

GBMM - General Block Min Max. GBMM is a robust method proposed by Dr. Schubert.

MPI - The Message Passing Interface. MPI is a library specification for message-passing, proposed as a standard by a broadly based committee of vendors, implementers, and users.

RCPO - Redundant Calculations Parallel Overhead.

### 1.8 Organization of the Thesis

This thesis is divided into five chapters. Chapter One provides an introduction to the context of the problem, purpose of the thesis, significance of the thesis, limitations, and definitions of terms. Chapter Two is a review of relevant literature. Chapter Three

documents the methodology used in this thesis. Chapter Four presents the results from the research. Chapter Five gives the conclusion of the thesis. Finally, the references for the thesis are listed.

CHAPTER TWO  
LITERATURE REVIEW

2.1 Introduction

Chapter Two presents discussion of the relevant literature. Section 2.2 describes the GBMM method. Section 2.3 illustrates Cannon's Algorithm. Section 2.4 gives an introduction to the Householder QR decomposition. Section 2.5 mentions parallel QR decomposition. And a brief summary is presented in section 2.6.

2.2 The General Block Min Max Criterion

General Block Min Max Criterion (GBMM) is a robust method provided by Dr. Schubert. This section describes general ideas and equations that are used in this thesis.

The general (block) perturbation min max problem is stated as

$$\frac{1}{2} \left\| \begin{bmatrix} A_{1,1} + E_{1,1} & \cdots & A_{1,p} + E_{1,p} \\ \vdots & \ddots & \vdots \\ A_{q,1} + E_{q,1} & \cdots & A_{q,p} + E_{q,p} \end{bmatrix} \begin{bmatrix} x_1 \\ \vdots \\ x_p \end{bmatrix} - \begin{bmatrix} b_1 + E_{b,1} \\ \vdots \\ b_q + E_{b,q} \end{bmatrix} \right\|^2 \quad \dots\dots\dots (1)$$

where

A is the coefficient of  $Ax = b$ , where A belongs to

$\mathfrak{S}^{m \times n}$  and  $b$  belongs to  $\mathfrak{S}^m$ .

$q$  and  $p$  are block partition numbers of A on column and row, respectively.

$E$  is the errors in  $A$ .

$E_b$  is the errors in  $b$

The equations used in this thesis are listed below:

$$M_i = \|A_{i,*}x - b_i\| \quad \dots\dots (2)$$

$$\zeta_{i,j} = \frac{\eta_{i,j}\|x_j\|}{M_i} \quad \dots\dots (3)$$

$$\varphi_i = 1 + \sum_{j=1}^p \zeta_{i,j} + \frac{\eta_{b,i}}{M_i} \quad \dots\dots (4)$$

$$\Phi = \text{diag}(\varphi_1 I, \dots, \varphi_q I) \quad \dots\dots (5)$$

$$\Psi_j = \sum_{i=1}^q \frac{\eta_{i,j}^2 \varphi_i}{\zeta_{i,j}} \quad \dots\dots (6)$$

$$\Psi = \text{diag}(\Psi_1 I, \dots, \Psi_p I) \quad \dots\dots (7)$$

where

$\eta_{i,j} = \|\bar{E}_{i,j}\|$  and  $\eta_{b,i} = \|\bar{E}_{b,i}\|$  are the amount of uncertainty in the matrix  $A$  and vector  $b$ , respectively.

$I$  is the identity matrix.

Dr. Schubert provides a recursive method for GBMM. It has two recursive formulas:

$$x_i = \Psi^{-1} A^T \Phi (b - Ax_{i-1}) \quad \text{for big } \Psi \dots (8)$$

$$x_i = (A^T \Phi A)^{-1} (A^T \Phi b - \Psi x_{i-1}) \quad \text{for small } \Psi \dots (9)$$

where  $A^T$  is the transpose of  $A$  and  $\Psi^{-1}$  is the inverse of  $\Psi$ .

The Stopping condition is suggested as

$$\frac{\|x_i - x_{i-1}\|}{\|x_i\|} \leq \delta \quad \text{for } \delta \text{ between } 10^{-4} \text{ and } 10^{-8} \quad (10)$$

### 2.3 Cannon's Algorithm

This thesis uses Cannon's Algorithm to calculate the matrix multiplication. The standard Cannon's Algorithm requires the number of processes to be a perfect square number,  $n^2$ . The processes are arranged in a 2-D mesh. Each process contains an equal partition of the matrix  $A$  and  $B$  as well. (See Figure 1) The number of iterations that the algorithm requires in order to complete the whole calculation is the square root of the number of processes,  $\sqrt{n^2} = n$ . Before all the iterations, both  $A$  and  $B$  need an initial shift to start the calculation. (See Figure 2) After each iteration, all of the processes need to transfer their own portion of  $A$  to their left processes, and the leftmost processes needs to send its own portion of  $A$  to the rightmost processes. Not only  $A$  but also  $B$  requires shifts as well. The difference is that  $B$  needs an up shift. (See Figure 3) After all the iterations, both  $A$  and  $B$  need a final shift to restore all the partitions of  $A$  and  $B$  to the arrangement that existed before Cannon's Algorithm began.

In each iteration, each process does a serial matrix multiplication on the sub matrix the process has now. The sum of all the iterations in a process is the answer of the sub matrix that each process is responsible for.

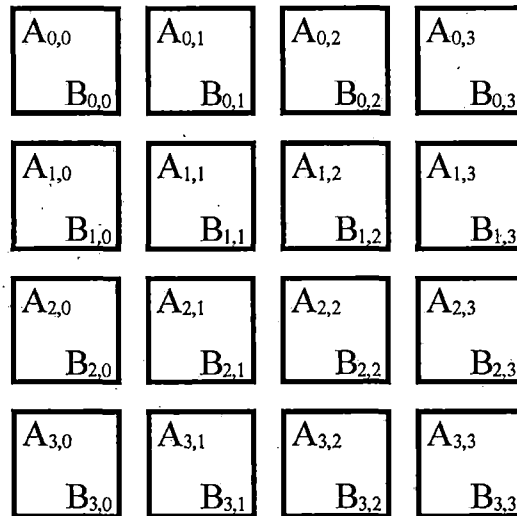


Figure 1. Initial Distribution of Blocks among  $16 = 4^2$  Processes

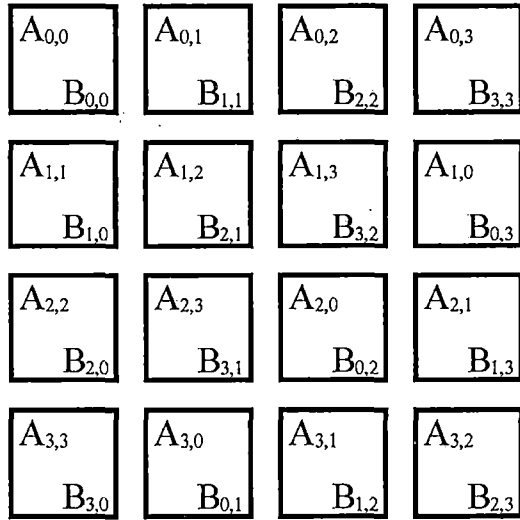


Figure 2. Initial Shift of Cannon's Algorithm so that Each Process Contains  $A_{i,k}$  and  $B_{k,j}$  which are what Matrix Multiplication Requires

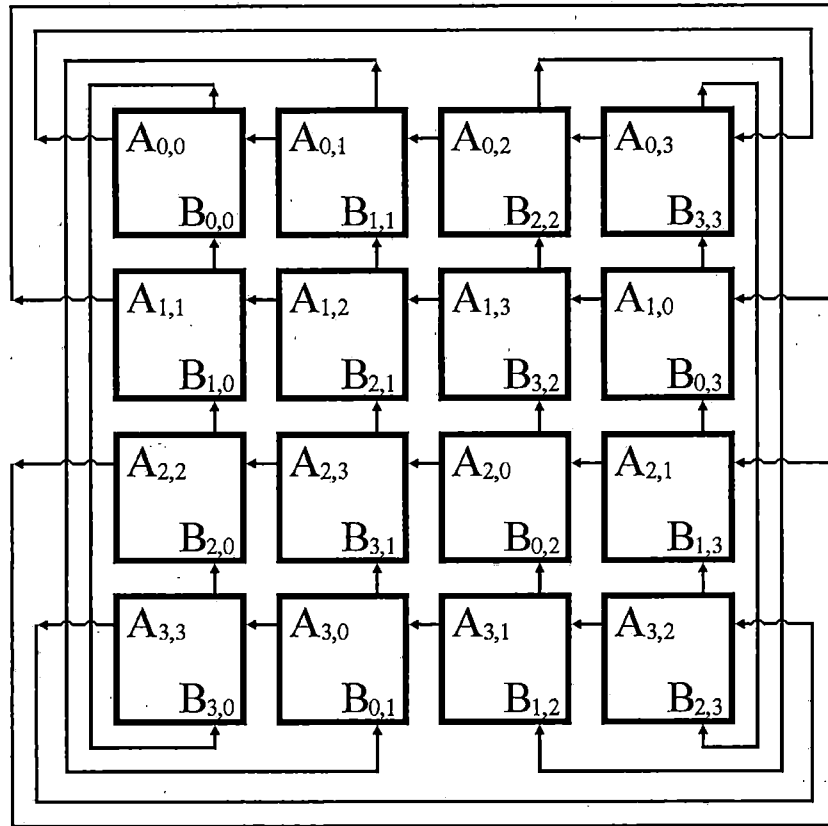


Figure 3. The Way Cannon's Matrix Multiplication Algorithm Shifts. In  $C = A * B$ , Sub-Matrix A needs a Left Shift While Sub-Matrix B Needs an Up Shift

#### 2.4 The Householder QR Decomposition

This thesis uses QR Decomposition instead of matrix inversion to calculate the matrix inverse<sup>4</sup> in equation (9)<sup>5</sup>. The result obtained through the use of QR

<sup>4</sup> Dr. Schubert uses Singular Value Decomposition (SVD) to compute the matrix inverse. SVD is more stable than QR but, of course, more complicated than QR.

<sup>5</sup> In the case of the diagonal matrix,  $\Psi$ , the inverse matrix of  $\Psi$ ,  $\Psi^{-1}$ , can easily be calculated by inverting all the diagonal cells. Therefore, equation (8) needs neither inverse nor QR.



factorization is more stable than the one obtained from the inverse.

QR decomposition forms an orthogonal projector of  $A$  on  $Q$ , so that  $A = QR$  where  $Q$  is an orthogonal matrix and  $R$  is an upper triangular matrix (UTM).

The idea to use QR instead of the inverse is due to the fact that if

$$A = QR,$$

then

$$Ax = b,$$

which becomes

$$QRx = b.$$

From the above, we can easily obtain

$$Rx = Q^{-1}b.$$

Because the only operator of  $x$  is the UTM  $R$ , it is very easy to solve for  $x$ .

This thesis use Householder QR Factorization to compute the QR decomposition. The implementation of the Householder QR Factorization Algorithm in this thesis can be written as the following formulas, which closely resemble those used by Math Lab:

for  $k = 1$  to  $n$

$$x = A_{k:m,k} \dots \dots \dots (11)$$

$$v_k = \text{sign}(x_1) \|x\|_2 e_1 + x \quad \dots\dots\dots (12)$$

$$v_k = v_k / \|v_k\|_2 \quad \dots\dots\dots (13)$$

$$A_{k:m,k:n} = A_{k:m,k:n} - 2v_k (v_k^* A_{k:m,k:n}) \quad \dots\dots\dots (14)$$

And the  $Q^{-1}b$  is obtained by the following formulas:

for  $k = 1$  to  $n$

$$b_{k:m} = b_{k:m} - 2v_k (v_k^* b_{k:m}) \quad \dots\dots\dots (15)$$

## 2.5 Parallel QR

There are some parallel QR algorithms like [2], [4] [5] or [9]. This thesis applies none of them. Nor does this thesis use Givens rotation which is more easily parallelized than Householder transformation. It just parallelize Householder QR algorithm according to equation (11) through (14) naively.

## 2.6 Summary

The literature important to the thesis was presented in this chapter. For a full version, please refer to the bibliography.

## CHAPTER THREE

### METHODOLOGY

#### 3.1 Introduction

Chapter Three documents the methodologies used in this thesis. The test code uses many speedup methods. The methods listed here are directly related to the parallel programming.

This chapter introduces methods mainly by the order of modules. Section 3.2 states reduce parallel overhead. Section 3.3 mentions general methods used in this thesis. Section 3.4 talks about speedup method used in Cannon's Algorithm. Section 3.5 discusses other matrix multiplication used. Section 3.6 states how the transpose is designed. Section 3.7 describes the Householder QR Decomposition. Section 3.8 documents the implementation of solving linear equation by QR decomposition. Section 3.9 explains how the main GBMM subroutine goes. And finally, the main test program is described in Section 3.10.

#### 3.2 Reduce Parallel Overhead

Parallel overheads hinder the parallel speedup from achieving the ideal value. The ideal speedup is just the number of processors used. These include extra calculation for parallel, communications between processes,

synchronizing the processes, etc. This thesis deals with two kinds of parallel overheads only: redundant calculations parallel overhead (RCPO) and communication parallel overhead (CPO).

### 3.2.1 Reduce Redundant Calculation Parallel Overhead

Redundant calculations parallel overhead are some calculations required in parallel program but not needed in serial programs. For example, getting the number of process used, knowing the ranking of this process, calculation of which portion of data this process is using, etc.

In this thesis, some of these calculations include the calculation of a process's 2-D coordinates and ranking, vertical ranking, horizontal ranking and local block size. It uses global variables so that they are calculated one time only in most cases.

### 3.2.2 Reduce Communication Parallel Overhead

Communication parallel overhead refers to the time spent on communications between processes which are totally unnecessary in serial programs.

There are many ways to reduce the CPO. In addition to the checker-board decomposition, this thesis groups

information that need to communicate together to reduce the latency.

Another method used in this thesis to reduce CPO is the application of Cannon's algorithm. See section 3.4 for details.

### 3.3 General Methods

Some RCPO is not "calculations." It maybe a simple if-statement, especially if the if-statement is in a loop, it may cause detectable timing. This section states how this thesis deals with this kind of problem.

#### 3.3.1 Delete Unnecessary If

Sometimes only the focused process has the correct answer. For example, at the end of a subroutine, we may need to write something like

```
if (id==y)      return  $\alpha$ ;6
else           return  $\beta$ ;
```

Because only the `id==y` has the correct answer,  $\alpha$ , letting all processes return  $\alpha$  saves an if-statement on the process whose rank is `y` which is the focused process so that the parallel overhead will be reduced a tiny bit.

---

<sup>6</sup> Unless explained, the programs or partial codes listed in this document are C style.

For example, when calculating the 2-norm in a subroutine, each process calculates the sum of the square of each cell of the sub matrix it owns, and then does a sum reduction to the focused process. The focused process does a square root of the total sum, and then returns the answer, which is the 2-norm. The standard way to code on the last return should be

```
return id==y ? garbage : sqrt(norm);
```

The focused process can not start calculating the square root until the last partial squared sum has been received which is a short time later than the last message had been sent. Therefore, though this will cause all unfocused processes in the same communication group an extra square root calculation, but will save the focused process an if-statement. Hence reduce the parallel overhead on focused process a tiny bit.

### 3.3.2 Loop Unrolling for Parallel Overhead

Loop unrolling is frequently used to speedup serial program. It expands loops in some ways to allow instruction rescheduling, better register usage, or reduce overhead instructions so that the speedup is achieved.

[12]

Usually, when a program is parallelized, some extra if-statement will be used which is a parallel overhead. If

this happened in a loop, it usually can be reduced by loop unrolling. An example used in this research will be stated in 3.4.

### 3.4 About Cannon's Algorithm

As briefly noted in 2.3, Cannon's Algorithm needs to shift both  $A$  and  $B$  on each iteration. The  $B$  in GBMM is a const matrix, see equation (9). Keeping all the square root of the number of process,  $n$ , portions of  $B^7$  required for each process in each process will reduce the time needed for communication, hence save  $n$  times of the communication of one over  $n^2$  portion of  $B$ . Though it wastes a little bit more than  $n$  times of RAM in each process, it speedups dramatically.

The way this thesis uses the advantage of constant matrix  $B$  in Cannon's Algorithm is as follows. The whole matrix  $B$  is cut into  $n$  columns and scattered to all processes from process 0. A three dimensional array,  $***A$ , is used to hold the  $n$  portions the process requires. Not only the content of the  $***A$  is all the value it needs, but also the order of the content is prearranged to what it will be used in Cannon's Algorithm. That is, the  $A[0]$

---

<sup>7</sup> This will reduce the scalability of this algorithm.

in each process contains the portion for the first iteration of Cannon's multiplication this process requires,  $A[1]$  the second, ...  $A[n-1]$  contains the last one required in Cannon's Algorithm.

The preorder treatment for the initial shift in Cannon's algorithm is done by exchanging the pointer  $*A$ , not by switch the content of  $***A$  so that the parallel overhead will be reduced. The preordered treatment helps each process to use just the  $A[i]$  to compute in the  $i^{\text{th}}$  iteration of Cannon's Algorithm. The processes need not to consider which sub 2-D array to use in this iteration. Not only no communication is performed for  $B$ , but also no tedious computation is executed.

The way the memory is allocated in  $***A$  is the same as  $C$  arranged 3-D array to get better locality in each sub 2-D array,  $**a$ , which is what really used in our algorithm.

About the serial multiplication part of Cannon's Algorithm, this thesis use both naively  $O(n^3)$  standard matrix multiplication method and  $O(n^{\log_2 7}) \approx O(n^{2.80735})$  Strassen's Algorithm to implement it. [10]



### 3.5 Multiplication

Many kinds of matrix multiplication are used in this thesis, not just the matrix multiplication mentioned in the previous section. Matrix diagonal-matrix (DM) multiplication, DM matrix multiplication, row-vector matrix multiplication row-vector column-vector multiplication and matrix column-vector multiplication are also used.

Among them, only the matrix column-vector multiplication, DM matrix multiplication and matrix DM multiplication are implemented in ways that parallel speedup may easily be detected.

During calculations, sub-matrices and sub-vectors are distributed among processes. We do not need to gather them to a focused process and redistributed them. This is especially the case when, if we are lucky, the distributed answers are distributed in the way the following calculation needs -- there will be no CPO in this case.

#### 3.5.1 Row-Vector Matrix Multiplication

Let whole 2-D mesh processes contain corresponding sub matrix. Let each row of processes contain a full set of the row vector as figure 4 for matrix DM multiplication. After calculation, each row of processes has a set of the answer.

### 3.5.2 Diagonal-Matrix Multiplication

A DM is a matrix with the property that the values of the entries that are not on the diagonal are zero. Therefore, we can use an one-Dimensional array to store the value of whole DM.

The sequence the DM matrix and matrix DM multiplication is implemented as follows. Let whole 2-D mesh processes contain corresponding sub matrix. Let each row of processes contain a full set of the diagonal of the DM as figure 4 for matrix DM multiplication. Let each column of processes contain a full set of the diagonal of the DM as figure 5 for DM matrix multiplication. Thus, each process contains all the values it needs to calculate the matrix DM or DM matrix multiplication of its own portion.

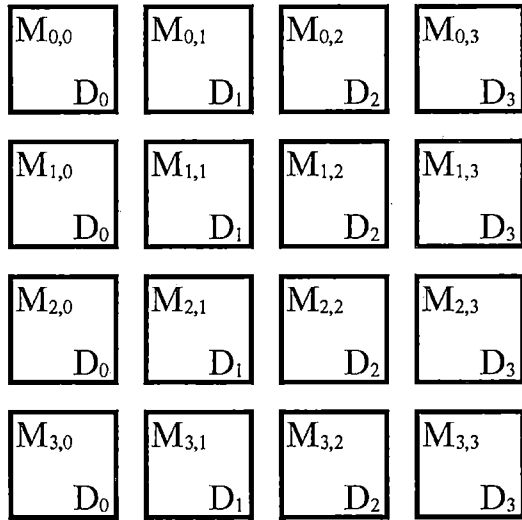


Figure 4. The Portion that Each Process Contains to Perform the Matrix Diagonal-Matrix Multiplication

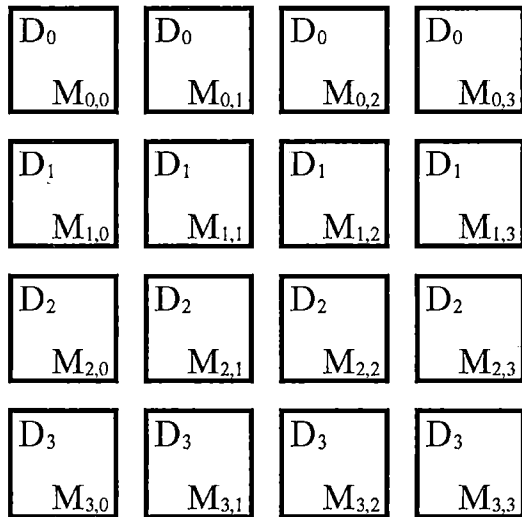


Figure 5. The Portion that Each Process Contains to Perform the Diagonal-Matrix Matrix Multiplication

Thus, there will be no CPO if the DM was stored as the multiplication demanded before the multiplication begins.

### 3.6 The Transpose

Both the vector and matrix may need to be transposed. The vector or matrix may be in focused process before the transpose is required or the vector or matrix has been scattered in processes already. Though this will have four different situations, the thesis used only two of them: vector transpose when the vector has been scattered and matrix transpose when the matrix is in the focused process only.

#### 3.6.1 The Vector Transpose

In this thesis, all vectors are stored as one-dimensional array. It depends on the function to interpret whether it is a column vector, row vector, or, even the diagonal of a DM.

Before entering the subroutine, all vectors had been row wise or column wise scattered among processes already. In the subroutine, calculate local size first, and then allocate memory for transposed vector. If the process is on the diagonal of the process 2-D mesh, copy the original values to the memory prepared for transposed vector.

Otherwise, calculate the rank of the destination process, send to and receive from the destination process the vector. Return the pointer points to the transposed vector.

### 3.6.2 The Matrix Transpose

The only one transpose happens in this thesis is at the beginning of the GBMM subroutine where the deblur matrix is stored in the focused process before been scattered and transposed.

In the matrix transpose subroutine, calculate local size first, and then allocate memories for both communication buffer and transposed sub matrix. The focused process calculates the rank of each process, gather corresponding sub matrix to a continuous RAM, scatters the corresponding part of the sub matrix to correct processes.

Note that only the content of the sub matrix, `**A`, are transferred. The index of the `**A`, `*A`, are calculated at the time the memory is allocated because both the sent and the received sub matrices are of the same arrangement and the same size. Thus, eliminate the unnecessary communication which is a redundant CPO.

The order to scatter the matrix is from the largest rank to the smallest rank, the focused one. This will save

a memory block on the focused process and save the time to copy from transfer buffer to the working buffer.

Each process begins transposing its own sub matrix after it has received the values it required. Then, free up the transfer buffer.

### 3.7 The Householder QR Decomposition

In the Householder QR decomposition subroutine, it calculates local size first, and then allocates memories for  $r$ ,  $R$ ,  $v$ , and  $V$ , where  $V$  is the matrix that collects the reflection vectors  $(RV)$ ,  $v$ . The final step of the initial work is copy  $A$  into  $R$ . Because  $x$  is useless after equation (12) and is almost the same as  $v$  except for the first element, there is no  $x$  exist in RAM. The  $v$  totally handles all the functions  $x$  need.

In implementing the loop of the Householder QR decomposition, it calculates the local size of  $k:m$  and  $k:n$  (see equation (11)), gets the rank,  $id\_now$ , of the process which contains the current  $k$ , place the if-statement which judges the process coordinates outside the loop of partial-squared-sum calculations to reduce the RCPO in loop, send the answer to the focused process, and sums the answer up to get the squared sum,  $n2$ , of the vector. The process whose rank is  $id\_now$  calculates the square-root of

$n_2$  to get the 2-norm of  $x$ . Change the value of the first element of  $v$  according to the equation (12).

About the equation (13), calculate the 2-norm of  $v$  through change of  $n_2$ , broadcast the 2-norm of  $v$  to those who are in the same column of the focused process, the one whose rank is  $id\_now$ , in the process 2-D mesh. Then the processes that contain the useful part of  $v$  normalize  $v$ .

Now start dealing with the equation (14). Broadcast the useful part of  $v$  horizontally so that the distribution of  $v$  matches the condition that the row-vector matrix multiplication needs. If the process contains useful part of  $v$ , make a pointer array,  $*s$ , in which each element points to a special address of  $A$  so that  $**s$  is just the sub matrix that equation (14) requires. Multiply row vector  $v$  and the sub matrix,  $**s$ . Otherwise, make an array that all the elements value are zero which represent the answer of zero vector times a sub matrix. Do a sum-reduction in the processes that are in the same column of the focused process. Broadcast the result,  $v'$ , to processes that are in the same column of the focused process. Separate this column of processes into four groups according to the position that the process relates to the focused one so that there is no RCPO in the loop

when doing the final part of equation (14),  $A_{km, kn}$   
 $= A_{km, kn} - 2v_k(v')$ . Copy the answer to the V matrix which  
 consists of the v. Free up memories, set the return  
 pointer points to V.

### 3.8 The Solving for x by QR

Consider the linear equation  $Ax = b$ , where A is a  
 matrix and b and x are vectors. The solution can be found  
 by QR factorization of A, if A is not singular, as  
 following:

$$A x = b$$

$$QR x = b$$

$$R x = Q^{-1}b$$

Then, solve for x through the last equation by  
 back-substitution because R is a UTM (see section 2.4).  
 And the  $Q^{-1}b$  can be obtained by the equation (15) listed  
 in section 2.4.

The parallel implementation of the equation (15) is  
 preceded by calculation of local matrix size. Then, copy  
 vector b to a temporary vector, qb, call QR decomposition  
 function to get V and R, where V is the matrix that  
 collects the reflection vectors (RV), v.

In the main part of the equation (15), starts a loop  
 from zero to number of processes used -1, n-1, as the



index for columns of 2-D process mesh. Then, if the processes contain the value of the RVs, send the whole sub V matrix to the processes in the first column in corresponding row. Start a loop from zero to the width of the local matrix minus one. Separate the processes in the first column into three groups according to what it contains about v: no valid v, partial v, or full v to calculate the partial  $2(v_k^* b_{k:m})$ . Call MPI\_Allreduce to get the sum of the partial  $2(v_k^* b_{k:m})$ , the true  $2(v_k^* b_{k:m})$ . Calculate the  $b_{k:m} = b_{k:m} - v_k(2v_k^* b_{k:m})$ . Broadcast the qb horizontally to match the parallel back-substitution requires.

The sequence of the back-substitution is listed below. The pretreatment includes calculating the local matrix size, allocating memories, making a copy of vector b so that the b will remain unchanged after this calculation and calculating the last equation  $a_{m,n} x_n = b_m$ .

For the loop part, the outer loop runs from n-1 down to zero while the inner loop runs from local width minus one, w1, down to one. The two nested loops form the whole range of the width of the original matrix. Vertically broadcast the  $x_m$  which has been pre-calculated in the pretreatment or previous iteration. Let all the processes on the same column of focused process calculate their own

part of

$x_{n-1} = [(b_m) - a_{*,n}x_n] / a_{*,n-1}$ . After the inner loop, broadcast the  $x_{\text{lowest\_one}}$  vertically as the pre-calculated  $x_n$  of the next iteration of the outer loop. If the focused process is not in the first column of process 2-D mesh, send the  $x$  to the process left to itself.

At the end of this function, free up the memory which stores the copy of vector  $b$ , return the calculated  $x$ .

### 3.9 The General Block Min Max

The main GBMM routine implements the equations (2) to (10) listed in section 2.2 to get the answer. It sets all the local global variables<sup>8</sup> first to reduce the RCPL. Then, it distributes the deblur matrix,  $A$ , to each process as Cannon Algorithm's matrix  $B$  and shift it as mentioned in section 3.4. The routine transpose it to each process, then, scatters the vector  $b$ ,  $\eta_b$ , and the matrix  $\eta$  in checker-board style. Set all  $x_i$  to 1 as the seed of the first iteration. Set the pointer to  $b$  transpose points to  $b$  by the fact that  $b$  transpose equals to  $b$  in process 0, the focused one. In other process, allocate memory for transposed vector of  $b$  for processes in the first column.

---

<sup>8</sup> The global variables are set in the same `gbmm.c` file only to preserve some data security.

Calculate the transposed coordinate and rank. Except for the focused one, all the processes in the first row send its own  $b$  to the corresponding processes in the first column.

In the iteration part, the routine broadcasts  $x$  vertically if this is not the first iteration. Then it calculates  $Ax$ , calculates the equation (2), (3),  $\Phi$  and  $\Psi$ . It frees up the memories used by equations (3) and (2). It transposes  $\Phi$  to be horizontally distributed so that the distribution fits the requirement that the matrix  $DM$  multiplication requires. It frees up the memory used by  $\Phi$ . It calculate the  $A^T\Phi$ . It frees up the memory used by the horizontal version of  $\Phi$ . Then it calculates the norm of  $\Psi$ . It broadcasts the value horizontally so that each process has the norm of  $\Psi$ . The threshold to determine to use equation (8) or (9) is set to be 100.

In the implementation of equation (8), the big  $\Psi$  version, the code starts with calculating the inverse of the  $\psi^9$ . Transpose the distribution of  $\Psi$  among processes from horizontally to vertically<sup>10</sup>. Then calculate the  $\Psi^{-1}A^T\Phi$ . Transpose  $Ax$  from the first column to the first row.

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<sup>9</sup> See footnote e on section 2.4.

<sup>10</sup> There is no need to transpose if the processes are on the diagonal, of course.

Let the processes in the first row calculate  $b - Ax$  and store it in  $Ax$ . Broadcast it vertically. Finally, use the matrix column-vector multiplication subroutine to calculate the new  $x$ ,  $\Psi^{-1} A^T \Phi (b - Ax)$ .

In the implementation of equation (9), the small  $\Psi$  version, the code begins with calculating the  $A^T \Phi b$  through matrix column-vector multiplication subroutine. Then the processes in first row calculate  $\Psi x$ . Transpose the value of  $\Psi x$  from stored in the first row of processes to the first column ones. Let the first column processes calculate the  $A^T \Phi b - \Psi x$  and store them in the same address of those who store  $A^T \Phi b$ . Let all processes calculate  $A^T \Phi A$ . Use QR subroutine to solve for  $x$  in equation (9),  $x = (A^T \Phi A)^{-1} (A^T \Phi b - \Psi x_{i-1})$ . Free up  $A^T \Phi b$ .

No matter the norm of  $\Psi$  is big or small, now start dealing with the final parts: free up memories used in all processes. The processes in the first row copy new  $x$ , calculate equation (10), the  $\frac{\|x_i - x_{i-1}\|}{\|x_i\|} \leq \delta$ , and free up the unused memories and set pointer of  $x$  to new one. The process 0 broadcasts the  $\delta$  to all processes, increases the iteration counter. Finally, all processes check the condition of whether the next iteration is needed by check the  $\delta$  and iteration counter.

After all iterations, free up all the memories used. Perform a gather action. Finally, free up the memory used by  $x$ .

### 3.10 The Main Test Program

The main test program is written as follows. It reads in the  $\eta$  and the  $\eta_b$  files. The 2-D numbers of partitions are written in the  $\eta$  file. The program generates a random matrix as an original "image" / vectors sources. Then, generates a random square matrix as the blur matrix. Blur the "image" by the blur matrix. The uncertainty bound of the blur matrix is bound by 20% of the maximum of each partition. Transpose the "image" so that the original column vectors are continuously stored in memory, that is, it is now row vectors which, in C, is stored continuously. Finally, it starts to deblur the vectors one by one and sets the time stamp just before and after the calling of the GBMM subroutine.

## CHAPTER FOUR

### RESULTS

#### 4.1 Introduction

Included in Chapter Four was a presentation of the results of the thesis. Section 4.2 states the hardware and software used. Section 4.3 lists the numerical result. Section 4.4 analysis the result. Finally, the summary of the research is stated.

#### 4.2 Machine Used

Raven is the machine that this thesis has used to run the programs. It is a cluster computer composed of thirteen Compaq ProLiant DL360 G2 computers. The ProLiant DL360 G2 has dual Intel® Pentium® III 1.40GHz on board, L1 cache is 128KB, L2 cache is 512KB on-die. Each computer has 512 MB of 133MHz SDRAM 2:1 interleaved. Two Compaq NC 7780 Gigabit Ethernet NICs Embedded 10/100/1000 which are optimized for best latency, but only one of them is connected to the router. [14] The router used is D-Link DGS-3224TG, which is a 20-port managed layer 2 Gigabit Ethernet switching hub. The operation system used is Red Hat Linux 3.4.20-8smp with gcc version 3.2.2-5. MPI 1.2 is used as the interface.

### 4.3 Numerical Result

This thesis is tested on Raven uses one, four, nine, and sixteen processors. The 2-D partition number,  $q$  and  $p$ , are always the same, namely, twelve and twelve, throughout the test listed in this document. The heights of the "image" used to test are multiple of 60 from 180 through 1380. The widths of the "image" used to test are all the same, namely, twelve. The  $\delta$  in equation (10) in section 2.2 is set to be  $10^{-30}$  to cause a virtual infinite loop so that the number of iteration can be controlled. The serial part of the Cannon's Algorithm is implemented in two different ways: the standard matrix multiplication and Strassen's Algorithm.

#### 4.3.1 Standard Matrix Multiplication

The number of "images" used is ten if the image height,  $h$ , is smaller than 660. It is six if  $h$  is 660, 720 or 780. It is five if  $h$  is 840, 900, 960 or 1080. It is four if  $h$  is 1020 or 1200. It is three if  $h$  is 1140 or 1260. It is two if  $h$  is 1320 or 1380. The result of the time needed and the corresponding graph are listed below.

Table 1. Time Needed for Ten GBMM Iterations for Vector Size from 180 through 1380 for 1, 4, 9 and 16 Processors

Proc. Size	1	4	9	16
180	0.532	4.760	4.095	6.015
240	2.153	7.242	6.431	6.812
300	5.658	9.483	8.172	8.526
360	12.374	11.220	10.425	10.325
420	22.357	14.229	12.602	12.271
480	37.283	17.794	14.773	14.149
540	56.412	29.470	17.133	16.280
600	77.887	36.044	19.777	18.303
660	105.033	55.879	22.973	21.012
720	137.464	66.949	28.255	24.308
780	177.919	93.987	35.999	29.239
840	223.167	110.904	48.308	34.469
900	277.959	145.708	62.328	41.158
960	571.489	178.777	83.245	45.703
1020	409.968	214.258	97.979	61.006
1080	489.306	257.634	119.555	73.932
1140	573.724	297.162	142.294	92.600
1200	682.590	351.683	173.309	97.441
1260	785.533	398.219	198.378	132.042
1320	893.648	463.022	230.760	147.963
1380	1020.838	520.903	267.046	173.182



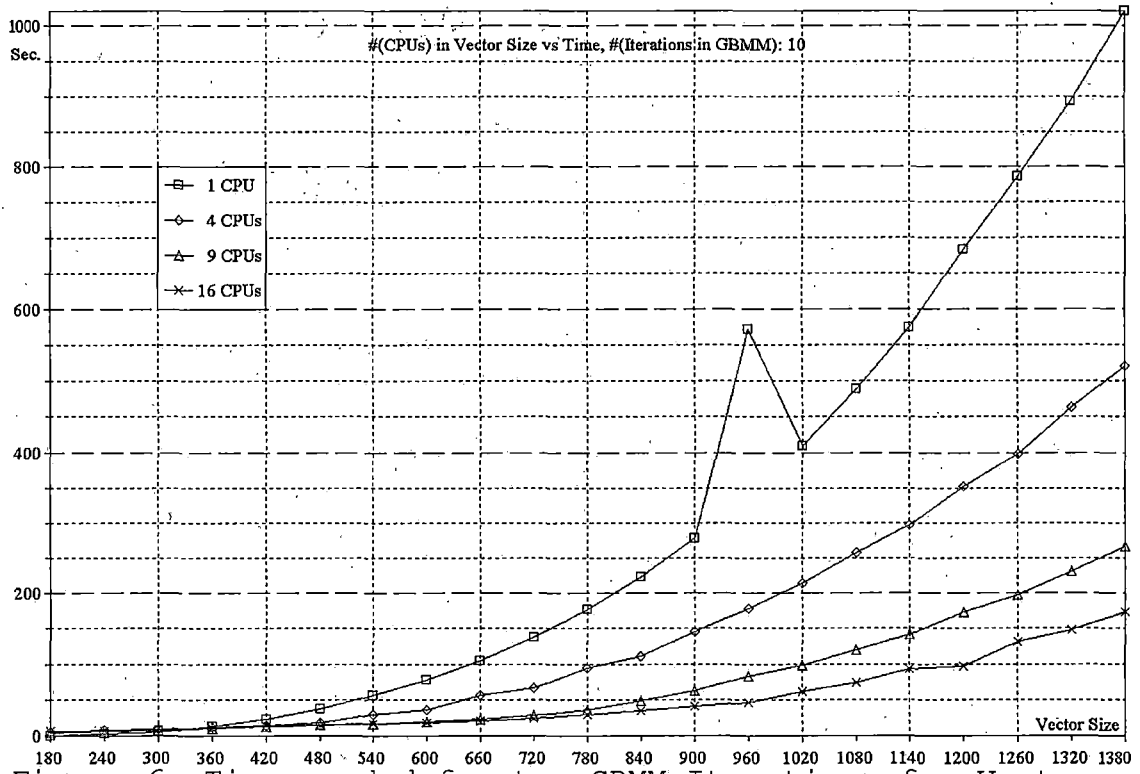


Figure 6. Time needed for ten GBMM Iterations for Vector Size from 180 through 1380 for 1, 4, 9 and 16 Processors

According to the time recorded, the speedup, which is the ratio between the sequential execution time and the parallel execution time is calculated, listed and plotted below.

Table 2. Speedup on 4, 9, 16 Processors for Vector Size from 180 through 1380

Size \ Proc.	4	9	16
180	0.112	0.130	0.088
240	0.297	0.335	0.316
300	0.597	0.692	0.664
360	1.103	1.187	1.199
420	1.571	1.774	1.822
480	2.095	2.524	2.635
540	1.914	3.293	3.465
600	2.161	3.938	4.255
660	1.880	4.572	4.999
720	2.053	4.865	5.655
780	1.893	4.942	6.085
840	2.012	4.620	6.474
900	1.908	4.460	6.753
960	3.197	6.865	12.504
1020	1.913	4.184	6.720
1080	1.899	4.093	6.618
1140	1.931	4.032	6.196
1200	1.941	3.939	7.005
1260	1.973	3.960	5.949
1320	1.930	3.873	6.040
1380	1.960	3.823	5.895

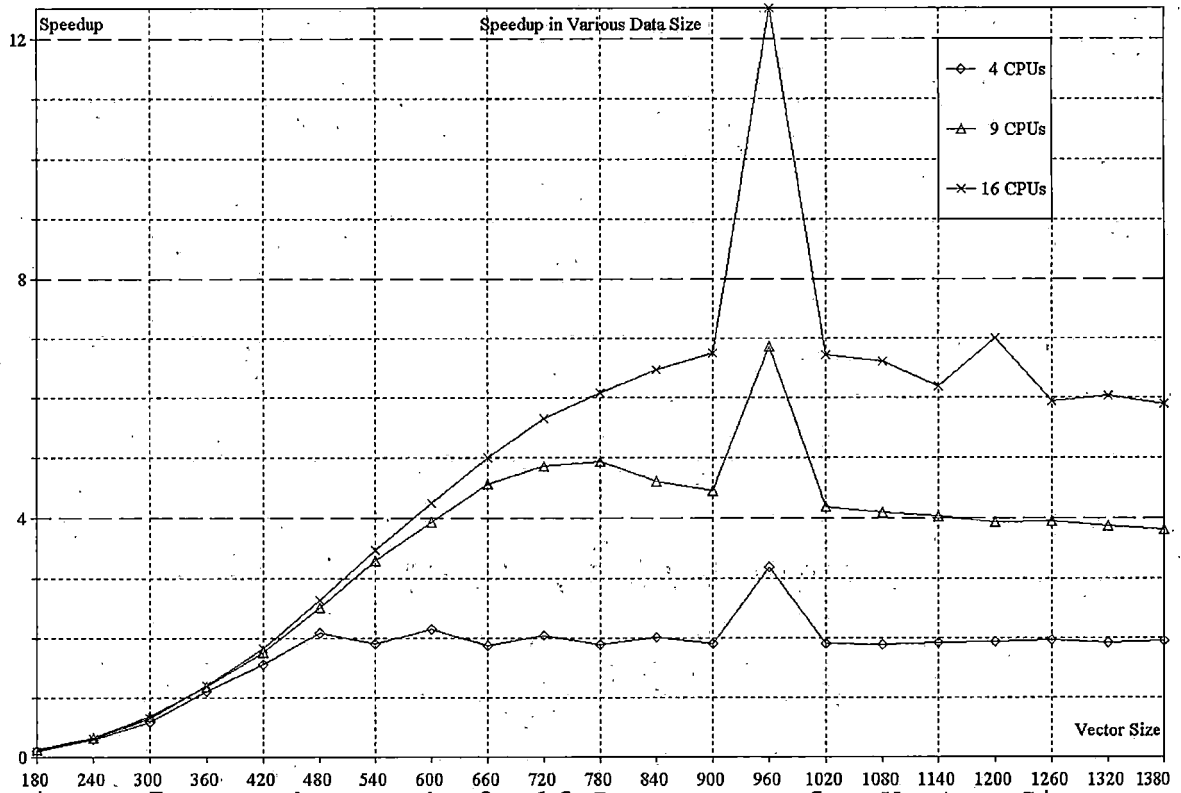


Figure 7. Speedup on 4, 9, 16 Processors for Vector Size

from 180 through 1380

#### 4.3.2 Strassen's Algorithm

The number of "images" used is all the same, namely, two, in testing the speedup if the serial part of Cannon's Algorithm is implemented in Strassen's Algorithm. The result of the time needed and the corresponding graph are listed below.

Table 3. Time Needed for ten GBMM Iterations for Vector Size from 180 through 1380 for 1, 4, 9 and 16 Processors

Size \ Proc	1	4	9	16
180	0.532	4.606	4.000	5.959
240	1.358	7.298	6.440	6.776
300	3.267	9.394	8.257	8.444
360	6.722	10.993	10.376	10.306
420	11.834	13.047	12.712	12.260
480	19.712	15.305	16.838	14.142
540	28.973	20.062	16.876	16.373
600	42.901	26.185	18.956	18.303
660	57.960	36.535	21.293	20.717
720	76.145	45.340	24.477	24.114
780	97.243	60.519	29.637	27.665
840	122.503	73.044	38.079	31.230
900	167.043	93.323	47.200	35.660
960	229.045	124.835	61.374	39.901
1020	242.863	137.547	71.824	49.590
1080	266.533	161.112	88.637	57.717
1140	362.473	193.199	102.805	70.793
1200	391.721	226.431	127.123	96.325
1260	449.664	258.130	141.275	97.704
1320	506.156	297.431	163.541	108.862
1380	582.519	335.688	187.471	128.020

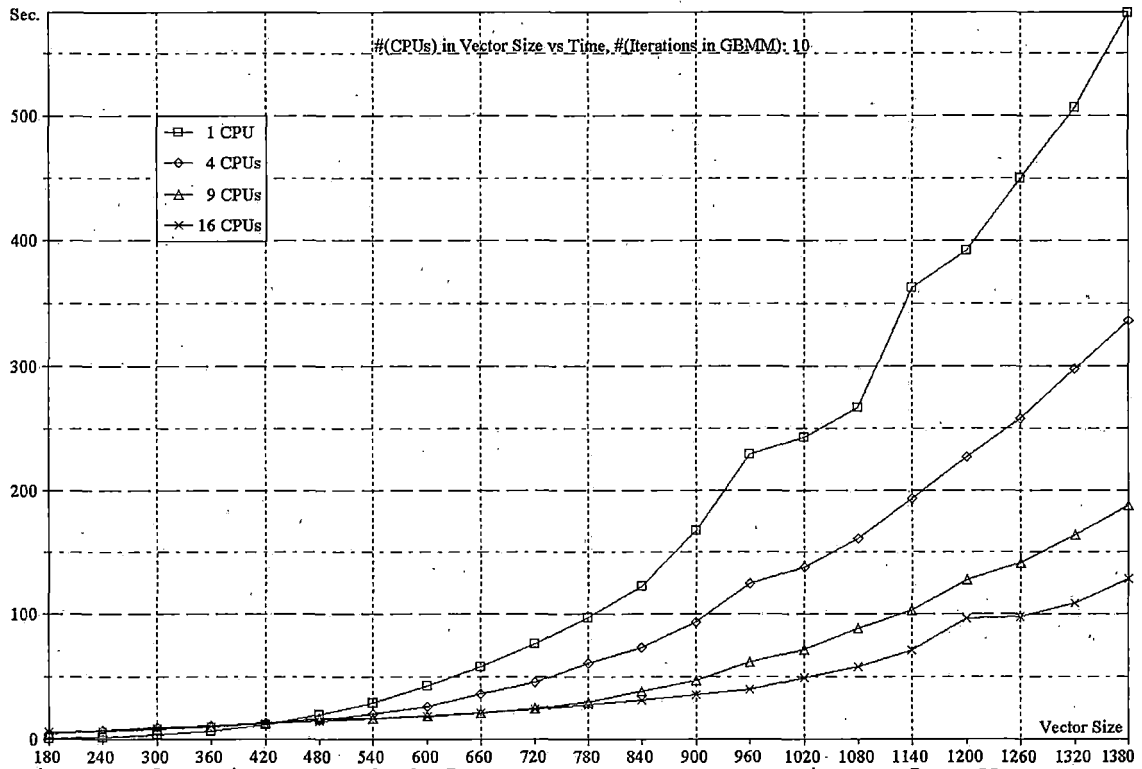


Figure 8. Time Needed for Ten GBMM Iterations for Vector Size from 180 through 1380 for 1, 4, 9 and 16 Processors

According to the time recorded, the speedup is calculated, listed and plotted below.

Table 4. Speedup on 4, 9, 16 Processors for Vector Size from 180 through 1380

Size \ Proc.	4	9	16
180	0.115	0.133	0.089
240	0.186	0.211	0.200
300	0.348	0.396	0.387
360	0.611	0.648	0.652
420	0.907	0.931	0.965
480	1.288	1.171	1.394
540	1.444	1.717	1.770
600	1.638	2.263	2.344
660	1.586	2.722	2.798
720	1.679	3.111	3.158
780	1.607	3.281	3.515
840	1.677	3.217	3.923
900	1.790	3.539	4.684
960	1.835	3.732	5.740
1020	1.766	3.381	4.897
1080	1.654	3.007	4.618
1140	1.876	3.526	5.120
1200	1.730	3.081	4.067
1260	1.742	3.183	4.602
1320	1.702	3.095	4.650
1380	1.735	3.107	4.550

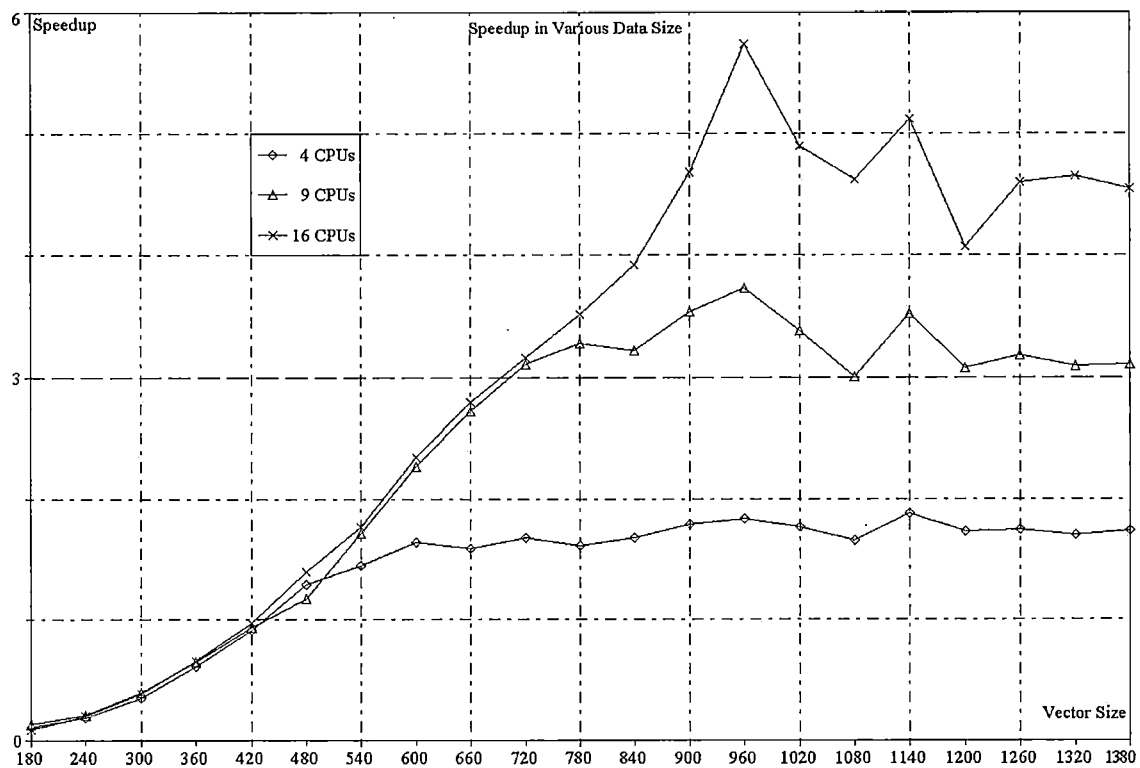


Figure 9. Speedup on 4, 9, 16 Processors for Vector Size

from 180 through 1380

#### 4.4 Result Analysis

##### 4.4.1 Small Image Clarification

The parallel speedup effect begins when the vector size is larger than 350 and 450 when using standard and Strassen's Algorithm, respectively which are both larger than the NTSC VCD image size, 320 \* 240. This gives a hint that unless a parallel speedup algorithm whose speedup threshold is apparently smaller than, say, 280 appears, it is useless trying to use parallel method to get better speedup on application of small images.

#### 4.4.2 Speedup

The speedup "looks" good on both algorithms when vector size is smaller than, say, 750. According to Amdahl effect which says that "for a fixed number of processors, speedup is usually an increasing function of the problem size," the curve should not bend down or stay around 2.0, 4.5 and 6.5 on 4, 9 and 16 processors respectively for a standard algorithm and around 1.7, 3.2 and 4.2 for Strassen's Algorithm on 4, 9 and 16 processors respectively. The reason for that may be that the Ethernet cards on the Raven are optimized for latency but the algorithms used in this thesis are all designed for optimized on bandwidth.

#### 4.4.3 Pre Block-Chopped Algorithm

The implementation of equations (5) and (7) does not use the fact that the value in  $\Phi$  and  $\Psi$  are not totally different. Instead of having different values of the number of the height and width of the deblur matrix, they have only the number of the partitions,  $q$  and  $p$ , different values, respectively. Making use of that fact to implement the equations (5) and (7), especially the equations (8) and (9) where DM multiplication is dealt with, in parallel may get a little bit speedup.



But by simply benchmark each step of GBMM, the ratio of the time spent on the final step of equation (9), the solving  $x = \Omega^{-1} \beta$ , to the time spent on the whole GBMM is huge. It ranges from 0.29 to 0.46 on serial version. It ranges from 0.58 to 0.96 (the average is 0.664) on four processes test. On nine and sixteen processes test, it ranges from 0.64 to 0.91 (average 0.732) and 0.65 to 0.91 (average 0.781), respectively. (See Table 5) This shows that the final step of equation (9) is the bottle neck of the speedup in this implementation of GBMM, especially the more processes is used, the more the average of the ratio is.

The fact that more than half of the time is spent on solving  $x = \Omega^{-1} \beta$ , especially the more processes is used, the more the average of the ratio is, tells us that unless there exist an parallel algorithm which can make good use of the pre-chopped characteristic to solve  $x = \Omega^{-1} \beta$ , or there exist an parallel algorithm that can fast and accurate to solve  $x = \Omega^{-1} \beta$ , the pre-chopped nature in GBMM does not lead to easily parallel speedup through checker-broad decomposition method.

Table 5. Simply Test the Time Spend on Whole GBMM (Time W) and on the Last Step of Equation (9) (Time 9) on 1, 4, 9, and 16 Processes. The Ratio of the Time W to the Time 9 is Calculated and Listed Right to the Elements Recording that Test

CPU Size	1			4			9			16		
	Time W	Time 9	Ratio	Time W	Time 9	Ratio	Time T	Time 9	Ratio	Time W	Time 9	Ratio
180	0.023	0.05	0.46	0.363	0.38	0.96	0.280	0.37	0.76	0.476	0.53	0.90
240	0.067	0.23	0.29	0.586	0.62	0.95	0.499	0.56	0.89	0.463	0.53	0.87
300	0.182	0.56	0.32	0.741	0.83	0.89	0.463	0.51	0.91	0.768	0.87	0.88
360	0.450	1.26	0.36	1.059	1.20	0.88	0.811	0.89	0.91	0.949	1.08	0.88
420	0.856	2.25	0.38	1.249	1.59	0.79	1.022	1.20	0.85	1.071	1.24	0.86
480	1.494	3.74	0.40	1.437	1.87	0.77	1.204	1.38	0.87	1.335	1.53	0.87
540	2.248	5.60	0.40	1.778	2.88	0.62	1.365	1.61	0.85	1.548	1.71	0.91
600	3.241	7.81	0.41	2.514	3.88	0.65	1.557	1.90	0.82	1.732	1.96	0.88
660	4.453	10.54	0.42	3.333	5.85	0.57	1.796	2.34	0.77	1.887	2.21	0.85
720	5.925	13.79	0.43	4.252	7.09	0.60	1.994	2.76	0.72	1.967	2.40	0.82
840	9.811	22.39	0.44	6.779	11.55	0.59	3.356	5.09	0.66	2.842	3.55	0.80
900	12.314	27.76	0.44	8.732	15.02	0.58	4.081	6.27	0.65	2.982	4.10	0.73
960	19.089	57.36	0.33	10.597	18.17	0.58	5.541	8.44	0.66	3.360	4.53	0.74
1020	18.845	41.34	0.46	12.819	21.97	0.58	6.505	10.15	0.64	4.158	6.12	0.68
1080	22.267	48.99	0.45	14.766	25.87	0.57	7.834	12.25	0.64	5.262	7.59	0.69
1140	26.346	57.73	0.46	17.372	30.05	0.58	9.164	14.45	0.63	6.478	9.63	0.67
1200	31.098	68.47	0.45	20.155	35.19	0.57	10.917	17.24	0.63	7.093	10.17	0.70
1260	35.922	78.48	0.46	23.227	40.31	0.58	12.889	20.32	0.63	9.054	13.57	0.67
1320	41.142	90.28	0.46	26.742	46.73	0.57	15.007	23.72	0.63	9.973	15.34	0.65
1380	46.442	102.46	0.45	30.203	52.51	0.58	17.290	27.38	0.63	11.868	17.98	0.66
Average	0.413			0.664			0.732			0.781		

#### 4.5 Summary

Neither deblur small images nor the advantage of the pre-chopped structure of GBMM can be achieved by the parallel methods used in this research.

## CHAPTER FIVE

### CONCLUSION

#### 5.1 Introduction

Chapter Five presents the conclusion of the thesis. Lastly, the Chapter concludes with a summary

#### 5.2 Known Problems That Hinder the Parallel Speedup

There are some known problems that hinder the parallel speedup. Section 5.2.1 describes problems in the implementation of QR decomposition. Section 5.2.2 states the memory allocation problem. Section 5.2.3 suggests using better MPI functions.

##### 5.2.1 Problems about Implement QR

As described in section 4.4.3, the final step of the equation (9), the solving  $x = \Omega^{-1} \beta$ , is the bottle neck of the parallel speedup in this implementation of GBMM. Therefore, if we want to improve instead of re-design the algorithms used in this research, it is the QR and solve-through-QR that one should first put the effort to.

In the implementation of QR decomposition, there are many chances that only part of the processes in the same column as the focused process need to have the value from the focused one. For example, the upper part of the

process may not need to be involved in the communication when  $k$  is larger than the height of the matrix over the square root of the number of process,  $n$ . The program broadcasts the value to all processes in the same column by using standard broadcast function, `MPI_Bcast`, in stead of designing a suitable and fast algorithm to send messages only to the ones that need the value in all the implementation similar to that.

Of course, one may re-design these two algorithms, QR and solve through QR, through better parallel QR algorithm such as Given's rotation. This should get better parallel speedup.

### 5.2.2 The Memory Allocation

There are too many memory allocations and frees used in this implementation. Calculate the total memory needed in the beginning of GBMM subroutine and allocate it one time at the beginning of the GBMM main subroutine, calculate all the pointers point to different and suitable address should both speedup the serial version and reduce some parallel overhead. Hence, the parallel speedup should be a little bit more than this version.

### 5.2.3 Using Better MPI Functions

MPI has more than four sets of send / receive functions: standard (`MPI_Send`), nonblocking (`MPI_Isend`),

synchronous (MPI\_Issend) and user-specified buffer (MPI\_Bsend). For most of the algorithms used in this research are suitable to use specified send / receive functions such as user-specified function or synchronous function. The MPI send / receive functions used in this research are all basic ones: MPI\_Send and MPI\_Recv. For example, using user-specified buffering may reduce time for copying the content.

#### 5.2.4 Adjust the Threshold

Though equation (8), the big  $\Psi$  version, is rarely used in practice, the test code sets threshold to be 100, which is found to be somewhat too large. The result is that none of the more than 8000 test samples<sup>11</sup> run on equation (8). They all run on equation (9).

Equation (8) is faster than Equation (9). It does not need to calculate QR decomposition. The inversion of the diagonal cells can be fully parallelized so that its parallel speedup is more than Equation (9). Therefore, the average parallel speedup of GBMM should be a little bit higher.

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<sup>11</sup> About 3000 of the test samples are done during the program test. They are not listed in chapter 4.

### 5.3 Further Study

There are many ways to do further studies. For accuracy, use singular value decomposition (SVD) instead of QR to solve the problem. For speed, try to use even find faster parallel speedup method to solve  $x = A^{-1} b$ . For matching the design, use parallel computer whose Ethernet cards are tuned for bandwidth and retest this algorithm.

The reason for the outlying point on the one process version at size 960 is still unknown. It had been run many times during more than two months on three different Pentium-based computers. It seems to be something related to the problem about matrix multiplication. It was found that the more the matrix size is related to power of two, the slower it seems to be. The experiments show that the average Megaflops is around 180 on the test machine, but it drops to around 40 when size is 256, 384, 448, 512, 576, 640, 704, 768, 832, 896, 960, 1024 or 1088. It drops to around 120 when size is 320, 448, 544, or 608. It drops down to around 90 when size is 800, 864. (See Figure 10)

960 is the only test size of GBMM in this research that hits on one of the slow point. So it shows a big outlying point there.

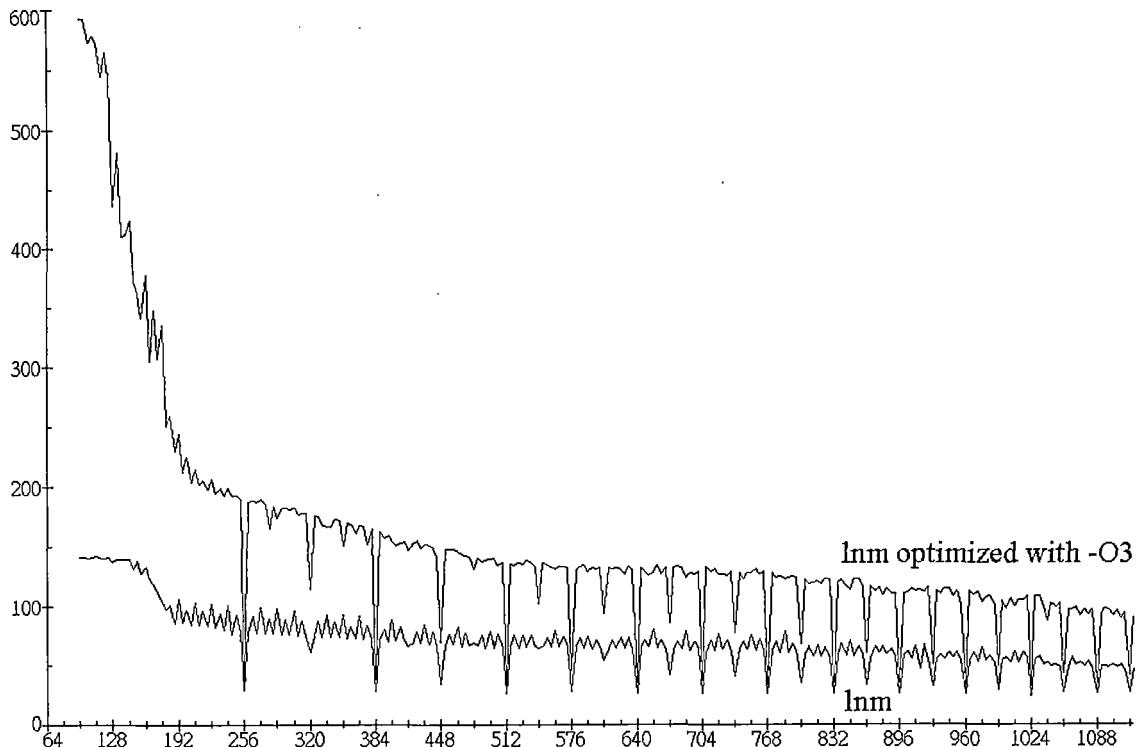


Figure 10. A Strange Phenomenon about the Megaflops Drop

on Matrix Multiplication. The Unit on x Axis is the Size of Matrix, on y is the Megaflops. No Matter the Code is Compiled with Linux gcc -O3 Option or Not, It Drops

One more thing can be suggested here for further research. In fact, about 150 of the more than 8000 samples (less than 1.875%) take long run time on four, nine, or sixteen processes for unknown reason. Twelve of them are around six times long and others are about twice as long. They are all grouped in "images", which means that it should be related to the deblur matrix. But by inspecting the code, all the if-statement are related to process rank, none of them are related to matrix or vector value.



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