Abstract

The true costs of high performance computing are currently dominated by software. Addressing these costs requires shifting to high productivity languages such as Matlab. The development of MatlabMPI (www.ll.mit.edu/MatlabMPI) was an important first step that has brought parallel messaging capabilities to the Matlab environment, and is now widely used in the community. The ultimate goal is to move beyond basic messaging (and its inherent programming complexity) towards higher level parallel data structures and functions. The pMatlab Parallel Toolbox provides these capabilities, and allows any Matlab user to parallelize their program by simply changing a few characters in their program. The performance has been tested on both shared and distributed memory parallel computers (e.g. Sun, SGI, HP, IBM, Linux and MacOSX) on a variety of applications.

1 Introduction

MATLAB® is the dominant interpreted programming language for implementing numerical computations and is widely used for algorithm development, simulation, data reduction, testing and system evaluation. The popularity of Matlab is driven by the high productivity that is achieved by users because one line of Matlab code can typically replace ten lines of C or Fortran code. Many Matlab programs can benefit from faster execution on a parallel computer, but achieving this goal has been a significant challenge (see [2] for a review). MatlabMPI [3, 4, 5] has brought parallel messaging capabilities to hundreds of Matlab users and is being installed in several HPC centers.

The ultimate goal is to move beyond basic messaging (and its inherent programming complexity) towards higher level parallel data structures and functions. pMatlab achieves this by combining operator overloading (first demonstrated in Matlab®P) with parallel maps (first demonstrated in Lincoln’s Parallel Vector Library - PVL) to provide implicit data parallelism and task parallelism. In addition, pMatlab is built on top of MatlabMPI and is a “pure” Matlab implementation which runs anywhere Matlab runs, and on any heterogeneous combination of computers. pMatlab allows a Matlab user to parallelize their program by changing a few lines. For example, the following program is a parallel implementation of a classic “corner turn” type of calculation commonly used in signal processing.

```
pMATLAB_Init; Ncpus=comm_vars.comm_size; % Initialize
mapX = map([1 Ncpus/2],{},[1:Ncpus/2]) % Map X
mapY = map([Ncpus/2 1],{},[Ncpus/2+1:Ncpus]) % Map Y
X = complex(rand(N,M,mapX),rand(N,M,mapX)); % Create X
Y = complex(zeros(N,M,mapY)); % Create Y
coefs = ... % Local matrix of coefs.
weights = ... % Local matrix of weights.
Y(:, :) = conv2(coefs,X); % Parallel filter + corner turn.
Y(:, :) = weights*Y; % Parallel matrix multiply.
pMATLAB_Finalize; exit; % Finalize pMATLAB and exit.
```

The above example illustrates several powerful features of pMatlab: independence of computation and parallel mapping, “automatic” parallel computation, and data redistribution via operator overloading.

2 Performance Results

The vast majority of potential Matlab applications are “embarrassingly” parallel and require minimal performance out of the communication capabilities in pMatlab. These applications exploit coarse grain parallelism and communicate rarely. Figure 1 shows the speedup

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1MATLAB is a registered trademark of The Mathworks, Inc.

2This work is sponsored by the High Performance Computing Modernization Office, under Air Force Contract F19628-00-C-0002. Opinions, interpretations, conclusions and recommendations are those of the author and are not necessarily endorsed by the United States Government.
**Title:** Parallel Matlab: The Next Generation

**Performing Organization:** MIT Lincoln Laboratory, Lexington, MA 02420

**Abstract:** See also ADM001694, HPEC-6-Vol 1 ESC-TR-2003-081; High Performance Embedded Computing (HPEC) Workshop (7th), The original document contains color images.
obtained on a typical parallel clutter simulation. Never-
the-less, measuring the communication performance is
useful for determining which applications are most suit-
able for pMatlab. pMatlab has been run on several plat-
forms. It has been benchmarked and compared to the
performance of the underlying MatlabMPI upon which it
is built. These results indicate that the overhead of pMat-
lab is minimal (see Figure 2), the primary difference is
in the latency: 70 milliseconds for pMatlab compared to
35 milliseconds for MatlabMPI. Both pMatlab and Mat-
labMPI match the performance of native C MPI [1] for
very large messages.

These results indicate that it is possible to write effective parallel programs in Matlab with minimal modifica-
tions to the serial Matlab code. In addition, these capa-
bilities can be provided in a library that is written entirely
in Matlab. Ultimately, it is our goal to establish a unified
interface for parallel Matlab that a broad community sup-
ports. We are actively collaborating with Ohio State, UC
Santa Barbara and the MIT Laboratory for Computer Sci-
ence to provide a single Unified Parallel Matlab interface
that is supported by multiple underlying implementations
(e.g. pMatlab and Matlab*P).

References

[1] Message Passing Interface (MPI), http://www.mpi-
forum.org/


[3] J. Kepner, Parallel Programming with MatlabMPI,
HPEC 2001 Workshop


the Journal of Parallel and Distributed Computing,

Figure 1: Clutter Simulation Speedup. Parallel perform-
ance speedup of a radar clutter simulation on a cluster
of workstations.

Figure 2: pMatlab vs. MatlabMPI Bandwidth. Com-
munication performance on a “Ping Pong” benchmark as
a function of message size on a Linux cluster. pMat-
lab equals underlying MatlabMPI performance at large
message sizes. Primary difference is latency (70 vs. 35
milliseconds).
Parallel Matlab: The Next Generation

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This work is sponsored by the Department of Defense under Air Force Contract F19628-00-C-0002. Opinions, interpretations, conclusions, and recommendations are those of the author and are not necessarily endorsed by the United States Government.
Outline

- Introduction
- Motivation
- Challenges
- Approach
- Performance Results
- Future Work and Summary
Motivation: DoD Need

• Cost

  = 4 lines of DoD code

• DoD has a clear need to rapidly develop, test and deploy new techniques for analyzing sensor data
  – Most DoD algorithm development and simulations are done in Matlab
  – Sensor analysis systems are implemented in other languages
  – Transformation involves years of software development, testing and system integration

• MatlabMPI allows any Matlab program to become a high performance parallel program
Challenges: Why Has This Been Hard?

- **Productivity**
  - Most users will not touch any solution that requires other languages (even cmex)

- **Portability**
  - Most users will not use a solution that could potentially make their code non-portable in the future

- **Performance**
  - Most users want to do very simple parallelism
  - Most programs have long latencies (do not require low latency solutions)
Outline

• Introduction

• Approach
  • MatlabMPI messaging
  • pMatlab programming

• Performance Results

• Future Work and Summary
• Can build a parallel library with a few messaging primitives
  • MatlabMPI provides this messaging capability:
    
    \[
    \text{MPI\_Send}(\text{dest},\text{comm},\text{tag},X); \\
    X = \text{MPI\_Recv}(\text{source},\text{comm},\text{tag});
    \]

• Can build a application with a few parallel structures and functions
  • pMatlab provides parallel arrays and functions
    
    \[
    X = \text{ones}(n,\text{mapX}); \\
    Y = \text{zeros}(n,\text{mapY}); \\
    Y(:, :) = \text{fft}(X);
    \]
MatlabMPI functionality

- “Core Lite” Parallel computing requires eight capabilities
  - `MPI_Run` launches a Matlab script on multiple processors
  - `MPI_Comm_size` returns the number of processors
  - `MPI_Comm_rank` returns the id of each processor
  - `MPI_Send` sends Matlab variable(s) to another processor
  - `MPI_Recv` receives Matlab variable(s) from another processor
  - `MPI_Init` called at beginning of program
  - `MPI_Finalize` called at end of program

- Additional convenience functions
  - `MPI_Abort` kills all jobs
  - `MPI_Bcast` broadcasts a message
  - `MPI_Probe` returns a list of all incoming messages
  - `MPI_cc` passes program through Matlab compiler
  - `MatMPI_Delete_all` cleans up all files after a run
  - `MatMPI_Save_messages` toggles deletion of messages
  - `MatMPI_Comm_settings` user can set MatlabMPI internals
MatlabMPI: Point-to-point Communication

- Any messaging system can be implemented using file I/O
- File I/O provided by Matlab via load and save functions
  - Takes care of complicated buffer packing/unpacking problem
  - Allows basic functions to be implemented in ~250 lines of Matlab code

MPI_Send (dest, tag, comm, variable);
variable = MPI_Recv (source, tag, comm);

• Sender saves variable in Data file, then creates Lock file
• Receiver detects Lock file, then loads Data file

File I/O provided by Matlab via load and save functions
– Takes care of complicated buffer packing/unpacking problem
– Allows basic functions to be implemented in ~250 lines of Matlab code

• Sender saves variable in Data file, then creates Lock file
• Receiver detects Lock file, then loads Data file
Example: Basic Send and Receive

- Initialize
- Get processor ranks

```matlab
MPI_Init; % Initialize MPI.
comm = MPI_COMM_WORLD; % Create communicator.
comm_size = MPI_Comm_size(comm); % Get size.
my_rank = MPI_Comm_rank(comm); % Get rank.
source = 0; % Set source.
der = 1; % Set destination.
tag = 1; % Set message tag.
if(comm_size == 2) % Check size.
    if (my_rank == source) % If source.
        data = 1:10; % Create data.
        MPI_Send(dest,tag,comm,data); % Send data.
    end
    if (my_rank == dest) % If destination.
        data = MPI_Recv(source,tag,comm); % Receive data.
    end
end
MPI_Finalize; % Finalize Matlab MPI.
exit; % Exit Matlab
```

- Execute send
- Execute receive

- Finalize
- Exit

- Uses standard message passing techniques
- Will run anywhere Matlab runs
- Only requires a common file system
pMatlab Goals

- Allow a Matlab user to write parallel programs with the least possible modification to their existing matlab programs

- New parallel concepts should be intuitive to matlab users
  - parallel matrices and functions instead of message passing
  - Matlab*P interface

- Support the types of parallelism we see in our applications
  - data parallelism (distributed matrices)
  - task parallelism (distributed functions)
  - pipeline parallelism (conduits)

- Provide a single API that potentially a wide number of organizations could implement (e.g. Mathworks or others)
  - unified syntax on all platforms

- Provide a unified API that can be implemented in multiple ways,
  - Matlab*P implementation
  - Multimatlab
  - matlab-all-the-way-down implementation
  - unified hybrid implementation (desired)
Structure of pMatlab Programs

Initialize globals

\[ \text{pMATLAB\_Init;} \]

mapX = map([1 N/2],{},[1:N/2]);
mapY = map([N/2 1],{},[N/2+1:N]);
X = ones(n, mapX);
Y = zeros(n, mapY);
Y(:, :) = fft(X);

Clear globals

\[ \text{pMATLAB\_Finalize;} \]

Map to sets of processors

Distributed matrices

Parallel FFT and "Corner Turn" Redistribution

- Can parallelize code by changing a few lines
- Built on top of MatlabMPI (pure Matlab)
- Moving towards Matlab*P interface
pMatlab Library Functionality

• “Core Lite” Provides distributed array storage class (up to 4D)
  – Supports reference and assignment on a variety of distributions:
    Block, Cyclic, Block-Cyclic, Block-Overlap

  Status: Available

• “Core” Overloads most array math functions
  – good parallel implementations for certain mappings

  Status: In Development

• “Core Plus” Overloads entire Matlab library
  – Supports distributed cell arrays
  – Provides best performance for every mapping

  Status: Research
Outline

• Introduction

• Approach

• Performance Results
  • MatlabMPI
  • pMatlab

• Future Work and Summary
MatlabMPI vs MPI bandwidth

- Bandwidth matches native C MPI at large message size
- Primary difference is latency (35 milliseconds vs. 30 microseconds)
MatlabMPI bandwidth scalability
Linux w/Gigabit Ethernet

- Bandwidth scales to multiple processors
- Cross mounting eliminates bottlenecks
MatlabMPI on WindowsXP

MATLAB 6.5

Workspace

Name     Size    bytes
------    ----    -----
MPI_COMM_WORLD  1x1    311
comm        1x1    311
comm_size   1x1    94
_cpus       1x8    740
my_rank     1x1    98

Command Window

>> RUN
No pid files found
Nothing to delete.

Launching MPI rank: 3 on: SLAVE
Launching MPI rank: 2 on: SLAVE
Launching MPI rank: 1 on: SLAVE
Launching MPI rank: 0 on: SLAVE

unix_launch =
start /b MatMPI\Dos_Commands.SLAVE.0.bat

Z:\projects\MPI-Jumpstart-Kit\MatlabMPI\pc>start /b MatMPI\my_rank: 0
SUCCESS

>>
MatlabMPI Image Filtering Performance

- Achieved “classic” super-linear speedup on fixed problem
- Achieved speedup of ~300 on 304 processors on scaled problem
“Cognitive” Algorithms

- Challenge: applications requiring vast data; real-time; large memory
- Approach: test parallel processing feasibility using MatlabMPI software
- Results: algorithms rich in parallelism; significant acceleration achieved with minimal (100x less) programmer effort

<table>
<thead>
<tr>
<th>Application</th>
<th>Algorithm</th>
<th>CPUs / Speedup / Effort</th>
</tr>
</thead>
<tbody>
<tr>
<td>Contextual vision</td>
<td>Statistical object detection</td>
<td>16 / 9.4x / 3 hrs</td>
</tr>
<tr>
<td>Text processing</td>
<td>Expectation maximization</td>
<td>14 / 9.7x / 8 hrs</td>
</tr>
<tr>
<td>Image segment.</td>
<td>Belief propagation</td>
<td>12 / 8x ~ x / 4 hrs</td>
</tr>
</tbody>
</table>

Coarse Grained
Image Parallel
(Static Client Server)

Medium Grained
Sentence Parallel
(Block Cyclic Dynamic Client Server)

Fine Grained
Pixel Parallel
(Block Nearest Neighbour Overlap)
Current MatlabMPI deployment

- Lincoln Signal processing (7.8 on 8 cpus, 9.4 on 8 duals)
- Lincoln Radar simulation (7.5 on 8 cpus, 11.5 on 8 duals)
- Lincoln Hyperspectral Imaging (~3 on 3 cpus)
- MIT LCS Beowulf (11 Gflops on 9 duals)
- MIT AI Lab Machine Vision
- OSU EM Simulations
- ARL SAR Image Enhancement
- Wash U Hearing Aid Simulations
- So. Ill. Benchmarking
- JHU Digital Beamforming
- ISL Radar simulation
- URI Heart modeling

- Rapidly growing MatlabMPI user base
- Web release creating hundreds of users
  [http://www.ll.mit.edu/MatlabMPI](http://www.ll.mit.edu/MatlabMPI)
Outline

• Introduction

• Approach

• Performance Results
  • MatlabMPI
  • pMatlab

• Future Work and Summary
pMatlab vs. MatlabMPI bandwidth

- Bandwidth matches underlying MatlabMPI
- Primary difference is latency (35 milliseconds vs. 70 milliseconds)
Parallel Matlab Clutter Simulation Performance

- Achieved “classic” super-linear speedup on fixed problem
- Serial and Parallel code “identical”

Fixed Problem Size (Linux Cluster)

<table>
<thead>
<tr>
<th>Number of Processors</th>
<th>Speedup</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>2</td>
<td>10</td>
</tr>
<tr>
<td>4</td>
<td>100</td>
</tr>
<tr>
<td>8</td>
<td>100</td>
</tr>
<tr>
<td>16</td>
<td>100</td>
</tr>
</tbody>
</table>

```
% Initialize
pMATLAB_Init; Ncpus=comm_vars.comm_size;

% Map X to first half and Y to second half.
mapX=map([1 Ncpus/2].{1:Ncpus/2});
mapY=map([Ncpus/2 1].{1:Ncpus/2});

% Create arrays.
X = complex(rand(N,M,mapX),rand(N,M,mapX));
Y = complex(zeros(N,M,mapY));

% Initialize coefficients
coefs = ...
weights = ...

% Parallel filter + corner turn.
Y(:,:,1) = conv2(coefs,X);
% Parallel matrix multiply.
Y(:,:,1) = weights*Y;

% Finalize pMATLAB and exit.
pMATLAB_Finalize; exit;
```
Eight Stage Simulator Pipeline

Parallel Data Generator
- Initialize
- Inject targets
- Convolve with pulse
- Channel response

Parallel Signal Processor
- Pulse compress
- Beamform
- Detect targets

Matlab Map Code
- map3 = map([2 1], {}, 0:1);
- map2 = map([1 2], {}, 2:3);
- map1 = map([2 1], {}, 4:5);
- map0 = map([1 2], {}, 6:7);

Example Processor Distribution
- 0, 1
- 2, 3
- 4, 5
- 6, 7
- all

- Goal: create simulated data and use to test signal processing
- parallelize all stages; requires 3 “corner turns”
- pMatlab allows serial and parallel code to be nearly identical
- Easy to change parallel mapping; set map=1 to get serial code
```matlab
pMATLAB_Init; SetParameters; SetMaps; %Initialize.
Xrand = 0.01*squeeze(complex(rand(Ns,Nb, map0),rand(Ns,Nb, map0)));
X0 = squeeze(complex(zeros(Ns,Nb, map0)));
X1 = squeeze(complex(zeros(Ns,Nb, map1)));
X2 = squeeze(complex(zeros(Ns,Nc, map2)));
X3 = squeeze(complex(zeros(Ns,Nc, map3)));
X4 = squeeze(complex(zeros(Ns,Nb, map3)));

... for i_time=1:NUM_TIME % Loop over time steps.

X0(:,:) = Xrand; % Initialize data
for i_target=1:NUM_TARGETS
    [i_s i_c] = targets(i_time,i_target,:);
    X0(i_s,i_c) = 1; % Insert targets.
end
X1(:,:) = conv2(X0,pulse_shape,'same'); % Convolve and corner turn.
X2(:,:) = X1*steering_vectors; % Channelize and corner turn.
X3(:,:) = conv2(X2,kernel,'same'); % Pulse compress and corner turn.
X4(:,:) = X3*steering_vectors'; % Beamform.
[i_range,i_beam] = find(abs(X4) > DET); % Detect targets
end
pMATLAB_Finalize; % Finalize.
```
Outline

• Introduction
• Approach
• Performance Results

• Future Work and Summary
Peak Performance vs Effort

- Same application (image filtering)
- Same programmer
- Different langs/libs
  - Matlab
  - BLAS
  - BLAS/OpenMP
  - BLAS/MPI*
  - PVL/BLAS/MPI*
  - MatlabMPI
  - pMatlab*

pMatlab achieves high performance with very little effort

pMatlab achieves high performance with very little effort
Airborne Sensor “QuickLook” Capability

- RAID Disk Recorder
- Data Files
- Streaming Sensor Data
- 28 CPU Bladed Cluster Running pMatlab
- Analyst Workstation Running Matlab
- SAR GMTI (new)

Streamlining Sensor Data Performance

- Number of Processors: 1, 2, 4, 8
- Linear vs pMatlab vs Matlab with Hyperthreading

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pMatlab Future Work

1. Demonstrate in a large multi-stage framework

2. Incorporate Expert Knowledge into Standard Components

3. Port pMatlab to HPEC systems
Summary

- MatlabMPI has the basic functions necessary for parallel programming
  - Size, rank, send, receive, launch
  - Enables complex applications or libraries

- Performance can match native MPI at large message sizes

- Demonstrated scaling into hundreds of processors

- pMatlab allows user’s to write very complex parallel codes
  - Built on top of MatlabMPI
  - Pure Matlab (runs everywhere Matlab runs)
  - Performance comparable to MatlabMPI

- Working with MIT LCS, Ohio St. and UCSB to define a unified parallel Matlab interface
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  - Stan Ahalt and John Nehrbass (Ohio St.)
  - Alan Edelman and Ron Choy (MIT LCS)
  - John Gilbert (UCSB)
  - Antonio Torralba and Kevin Murphy (MIT AI Lab)

- **Centers**
  - Maui High Performance Computing Center
  - Boston University
  - MIT Earth and Atmospheric Sciences
Web Links

MatlabMPI
http://www.ll.mit.edu/MatlabMPI

High Performance Embedded Computing Workshop
http://www.ll.mit.edu/HPEC
Beam Reconstruct Performance

- Linear
- pMatlab
- w/Hyperthreading

Speedup vs. Number of Processors

1 2 4 8

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