An Enabling Framework for Master-Worker Applications on the Computational Grid [*]

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Abstract

We describe MW – a software framework that allows users to quickly and easily parallelize scientific computations using the master-worker paradigm on the computational grid. MW provides both a "top level" interface to application software and a "bottom level" interface to existing grid computing toolkits. Both interfaces are briefly described. We conclude with a case study, where the necessary Grid services are provided by the Condor high-throughput computing system, and the MW-enabled application code is used to solve a combinatorial optimization problem of unprecedented complexity.

1 Introduction

By its very definition, the Grid [12] is a powerful and complex computing environment. In order to help harness its power, a large number of different programming efforts are underway that seek to provide robust middleware services [11] [16] [19] [10] [3] [24]. For users hoping to parallelize a large, single, coordinated application over the Grid, the overhead required to learn and assemble these Grid-enabling software components could (at this stage of their implementation) be discouraging. Thus, to enable a larger community of users to build applications running in parallel on the Grid, higher-level programming frameworks leveraging existing Grid services software are needed. NetSolve [5] provides an API to access and schedule Grid resources in a seamless way but it is not suited for writing

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non-embarrassingly parallel codes. Everyware [25] is a heroic effort that shows that an application can draw computational power transparently from the Grid, but Everyware is not abstracted as a programming tool at this stage of its implementation. CARMI/Wodi [22] was a useful programming interface for developing master-worker based parallel applications to run on the Grid, but it was strongly tied to the Condor-PVM [21] software tool, limited to applications with fixed work cycles, and finally abandoned.

Our abstract programming framework MW is a complete, easy to use tool whereby users can distribute large, diverse, scientific computations in a Grid computing environment. The focus is on parallel applications with weak synchronization and reasonably large grain size that can be fit into a master-worker paradigm without significant loss of efficiency. To parallelize such algorithms on Grid computing platforms, users must address issues such as fault tolerance, task scheduling, and interprocess communication. By handling some of these issues automatically and exposing others, MW provides an API for rapidly implementing Grid-enabled master-worker algorithms. MW also abstracts an Infrastructure Programming Interface (IPI) such that it can be ported to use various Grid software toolkits without any changes from the application developer. MW has been used in the MetaNEOS project [20] to implement efficient parallel numerical optimization algorithms with complex control structures. The marriage of efficient algorithms with Grid computational resources has allowed the solution of problems of record-breaking sizes [2] [4] [17]. Other authors have also focused on providing support for master-worker applications in a dynamic computing environment; Piranha [13] and Bayanihan [23] are notable examples.

The paper is organized as follows. In Section 2, we introduce MW, and we describe the interfaces to both application software and Grid infrastructure software. Section 3 discusses additional features of MW that help developers build efficient and robust applications. Section 4 presents a case study where the Grid services are provided by Condor[19], and the application code is used to solve a combinatorial optimization problem of unprecedented complexity. Conclusions about this line of research are also given.

2 MW

MW is a software framework that allows a user to easily parallelize a master-worker application on Grid resources. MW is a set of C++ abstract classes providing interfaces to both application programmer and Grid-infrastructure programmer. To Grid-enable an application with MW, the application programmer must re-implement a small number of virtual functions. Likewise, to port the MW framework to a new Grid software toolkit, the Grid infrastructure programmer need only re-implement a small number of virtual functions.

2.1 Infrastructure Interface

To distribute a master-worker computation on the Grid, we at least require software that can perform

- Communication – Portions of the computation and results must be passed between master and workers,
- Resource Management – The state of the available computational resources on the Grid must be known.

Our usage of the term *resource management* is a bit broader than most. In this context, resource management encompasses

- Resource request and detection – Asking for and identifying available processors,
- Infrastructure querying – Determining information about processors and the interconnections between them,
- Fault-detection – Noticing when processors leave the computation,
- Remote execution – Starting processes on remote machines when they become available.

There are a number of tools being built that provide these basic services, as well as features necessary to other Grid applications (such as security and remote data access). The *Infrastructure programming interface* (IPI) abstracts the core communication and resource management requirements for master-worker applications into the MWRMComm class. To allow MW applications to interact with existing Grid-services software, a concrete instance of the abstract MWRMComm class is derived, where the functionality required by MWRMComm is provided by the services in the specific Grid software toolkit.

2.1.1 Communication

The sole communications functionality required by MWRMComm is that point-to-point messages can be sent between the master and the worker processes. As such, MWRMComm has the (pure) virtual functions:

- `pack(<type> array, int size)`
- `unpack(<type> array, int size)`
- `send(int to_whom, int message_tag)`
- `recv(int from_whom, int message_tag)`

All messages must be buffered by the MWRMComm implementation, and the `send()` function should be implemented as a nonblocking call. These design criteria are due to the fact that processors may disappear during the course of the computation. Since the Grid is heterogeneous, the `pack()` and `unpack()` functions must account for different native data types. In MWRMComm, the `recv()` routine should be implemented as a blocking function call, for reasons described in Section 2.1.2.

2.1.2 Resource management

The application programmer may make a resource requests by calling the function `MWRMComm::set_target_num_workers( int num_workers )`. It is up to the MWRMComm implementation to make appropriate resource requests in an attempt to garner this number of workers for the master-worker application, and also to make new requests if participating workers leave the computation.

An important design decision for MW is that both communication and resource management functionality is included in a common class. MW relies on an upcall mechanism from the resource management software to signal changes in the state of the computational resources. The changes are signalled as messages received by the master with specific tags such as `HOSTADD` and `HOSTDELETE`. Thus, an implementation of the (blocking) `MWRMComm::recv()` function on the master process should not only test for incoming messages from workers, but also check for changes to the state of the existing computational resources and report these changes as messages.

For example, when a `HOSTADD` message is received, the MWRMComm specification requires that the function call `MWRMComm::start_worker(MWWorkerID *w)` will (attempt to) start a remote process on the machine that has been added, and will assign a unique process identifier in the MWWorkerID. When a `HOSTDELETE` message is received, MWRMComm requires that the unique process identifier be packed in the message buffer.

A final important function in the MWRMComm class is `MWRMComm::get_worker_info( MWWorkerID *w )`. This function uses underlying Grid services to populate the MWWorkerID class with "useful" information about the remote processor. Data members of the MWWorkerID class include the architecture, operating system, amount of memory, disk space, and speed of the remote machine.

Clearly, this is not the entire specification of the MWRMComm class. Indeed, we consider the IPI that we have laid out in MW to be a work in progress. The interface will likely change, and additional functionality will be added as warranted. Due the layered design of MW, application programs will be shielded from the interface changes.

2.1.3 Example MWRMComm Implementations

There are currently two implementations of the MWRMComm class. Both rely on the resource management facilities provided by the Condor high-throughput computing system [19]. As such, the MWDriver must deal with many processor faults, since the default Condor behavior is to vacate a running process when the owner of the machine returns.

In one implementation, communication is done with PVM, and in the other, communication is done by using Condor's remote I/O mechanism [18] to write a series of shared files. Preliminary plans are being made for a port to the Globus software toolkit [11]. Table 1 highlights how the Grid service software provides (or could provide) the functionality required by MWRMComm.

The additional software layer acts as a filter, hiding complexity of Grid service software, but also potentially hiding underlying functionality and knowledge of how the communication and resource management services are performed. A significant challenge is how to impart this functionality and knowledge to the application programmer, while still presenting a simple interface. MW errs on the side of simplicity, with the thought that additional Grid service functionality will be made available to the application programmer as needed.

An advantage of the layered approach is that some advances in Grid services software can be leveraged by the application programmers to increase application performance. For our Condor-based MWRMComm implementations, two examples include flocking [9], where geographically distributed Condor pools are conceptually linked as one, and glide-in [8], where processors from an existing Globus resource can be added to a Condor pool on a temporary basis. These advanced Condor features are used by the application presented in Section 4.

2.2 MW Application Programming Interface

In a companion work [15], we argue that many scientific applications can be parallelized quite effectively for a Grid environment by using the master-worker paradigm. Our specific experience is with algorithms for solving numerical optimization problems and many of these algorithms share the following characteristics:

- Incremental Data Requirement,
- Weak Synchronization,
- Dynamic Grain Size.

The MW API was designed to provide an interface that would be *easy* for application programmers to use, but

Services	Condor-PVM	Condor-Files	Globus
Communication	Messages buffered and passed through PVM `pvm_pk()` in XDR format.	Messages passed through shared worker files via Condor Remote I/O.	Messages passed and handled via Nexus `nexus_send_rsr()`.
Resource Request and Detection	Requests formulated with Condor Class Ads, served by Condor matchmaking, and detection is notified by `pvm_notify()`.	Requests formulated with Condor Class Ads, served by Condor matchmaking and detected, by checking Condor logs.	Requests in Globus RSL handled and queued by GRAM via `gram_client_job_request()`.
Info Querying	Information collected via condor_status command	Information collected via condor_status command	Information queried from MDS via LDAP protocol.
Fault Detection	Faults detected by Condor-PVM and passed through `pvm_notify()`.	Faults detected by checking Condor logs.	Faults detected by HBM local monitors are collected by HBM data collector agent running on master.
Remote Execution	Job started by `pvm_spawn()`.	Job started by condor_startd daemon on remote resource.	Job started by GRAM when requests are served.

Table 1. Summary of How Grid Services are Provided

also would allow these algorithmic characteristics to be exploited to build efficient master-worker applications.

In order to parallelize an application with MW, the application programmer must re-implement three abstract base classes – MWDriver, MWTask, and MWWorker.

2.2.1 MWDriver

To create the MWDriver, the user need only implement four pure virtual functions:

- `get_userinfo(int argc, char *argv[])` – Processes arguments and does basic setup.
- `setup_initial_tasks(int *n, MWTask ***tasks)` – Returns a set of tasks on which the computation is to begin.
- `pack_worker_init_data()`– Packs the initial data to be sent to the worker upon startup. Use of this function allows the application to exploit an *incremental data requirement*.
- `act_on_completed_task(MWTask *task)` – Is called every time a task finishes. Some actions that the user could take include adding more tasks or making calculations based on the result of the task. Tasks are added by calling the `MWDriver::addTasks(MWTask **tasks)` base method.

By carefully deciding on actions to take in the `act_on_completed_task()` method, the user can take advantage of *weak synchronization* inherent in the parallel application.

The MWDriver manages a set of MWTasks and a set of MWWorkers to execute those tasks. The MWDriver base class handles workers joining and leaving the computation, assigns tasks to appropriate workers, and rematches running tasks when workers are lost. All this complexity is hidden from the application programmer. Further, the MWDriver offers more advanced functionality, as explained in Section 3.

2.2.2 MWTask

The MWTask is the abstraction of one unit of work. The class holds both the data describing that task and the results computed by the worker. By deciding on the size of the task, the application can use *dynamic grain size* to its advantage, easing contention at the master process, and increasing parallel efficiency. The derived task class must implement functions for sending and receiving its data between the master and worker. The names of these functions are self-explanatory: `pack_work()`, `unpack_work()`, `pack_results()`, and `unpack_results()`. These functions will call associated `pack()` and `unpack()` functions in the MWRMComm class.

2.2.3 MWWorker

The MWWorker class is the core of the worker executable. Two pure virtual functions must be implemented:

- `unpack_init_data()`– Unpacks the initialization information passed in the MWDriver's `pack_worker_init_data()`.
- `execute_task( MWTask *task )`– Given a task, computes the results.

After doing some basic initialization, the MWWorker sits in a simple loop. Given a task, it computes the results, reports the results back, and waits for another task. The loop finishes when the master asks the worker to end. It is an easy matter to bring in other libraries, such as highly optimized FORTRAN routines to the worker. They can be linked with the C++ code, and called by the `execute_task()` function.

3 Additional Functionality

A number of other useful features that are available through methods in the base MWDriver class.

3.1 Checkpointing

Because the MWDriver reschedules tasks when the processors running these tasks fail, applications running on top of MW are fault tolerant in the presence of all processor failures—except for the master processor. In order to make computations fully reliable, MWDriver offers features to logically checkpoint the state of the computation on the master process on a user-defined frequency. To enable checkpointing, the user must implement functions for writing and reading the state contained in its application's master and task classes. Use of the master checkpoint facility is demonstrated in Section 4.

3.2 Normalized Performance Measurement

The heterogeneous and dynamic nature of the Grid makes application performance difficult to assess. Standard performance measures such as wall clock time and cumulative CPU time do not separate application code performance from computing platform performance. By normalizing the CPU time spent on a given task with the performance of the corresponding worker, the MWDriver aggregates time statistics that are comparable between runs. The normalization factor can be based on vendor information such as MIPS or KFLOPS, if this information is available from the underlying Grid service software. Alternatively, MW allows the user to register an application specific benchmark task that is sent to all workers that join the computational pool. The speed at which the benchmark task is completed is used as the normalization factor.

If we make the following definitions:

- $\alpha(i)$ – Worker i, $(i \in \mathcal{I})$, performance normalization factor,
- $U(i)$ – Wall clock time that worker i is available,
- $w(j)$ – Index of worker who solved task j, $(j \in \mathcal{J})$,
- $t(j)$ – CPU time spent in solving task j,
- $\mathcal{W}$ – Wall clock time,
- T – Cumulative worker CPU time: $\sum_{j \in \mathcal{J}} t(j)$.

We can then define the following statistics:

- $\mathcal{T}$ – Normalized cumulative time :

$$\mathcal{T} = \sum_{j \in \mathcal{J}} \alpha(w(j)) * t(j),$$

- $\mathcal{P}$ – Equivalent Pool Performance :

$$\mathcal{P} = \frac{\sum_{i \in \mathcal{I}} \alpha(i) * U(i)}{\sum_{i \in \mathcal{I}} U(i)},$$

- $\mathcal{N}$ – Average number of workers :

$$\mathcal{N} = \frac{\sum_{i \in \mathcal{I}} U(i)}{\mathcal{W}},$$

- η – Parallel efficiency :

$$\eta = \frac{\sum_{j \in \mathcal{J}} t(j)}{\sum_{i \in \mathcal{I}} U(i)}.$$

Table 3.2 shows the variations of performance statistics between runs of a Grid-enabled application (presented in Section 4). The same problem instance was solved eight times, each time on a different set of processors. A user-defined benchmark task was used to define the normalization factor.

As expected, the statistics exhibit large variance of $\mathcal{W}$ and T due to the dynamic and heterogenous nature of the computing platform. However, there is little variance of $\mathcal{T}$, which can therefore be used to do comparisons between runs and assess the application performance. Use of the normalized performance measurement has proved invaluable for tuning parameters of various Grid-enabled applications, like the one presented in Section 4.

	Mean	Std. Dev.	Min	Max
$\mathcal{W}$	915	1019	489	1780
T	22182	27900	8844	37671
$\mathcal{T}$	5864	341	5739	6054
$\mathcal{P}$	7.27	7.16	3.2	12.4
$\mathcal{N}$	27.5	21.7	16	39
η	0.87	0.07	0.84	0.92

Table 2. Mean, Variance and Extreme Value on 8 different runs.

3.3 Task Scheduling

Internally, the MWDriver manages a list of workers and a list of tasks. Task scheduling is accomplished by assigning the first task in the task list to the first idle worker in the worker list. In MWDriver, there is an interface to specify that the task list be ordered by a user-defined key, ensuring that "important" tasks are performed first. The worker list may be similarly ordered, so that "good" machines are the first to receive tasks. By default, the worker list is ordered using the machine KFLOPS information (if provided by the Grid software implementing MWRmComm), or by the benchmark factor if the user has registered an application specific benchmark task.

While this is a rudimentary scheduling algorithm, it has proven sufficient for all applications implemented to date with MW. The applications have had no need to match specific tasks with specific workers. Also, the applications to date have not been data-intensive, so use of advanced services such as the Network Weather Service [26] to improve scheduling has not been warranted.

4 Application to Combinatorial Optimization

MW has been used in the MetaNEOS project [20] to implement several grid-enabled parallel optimization solvers [7] [14] [17]. One solver has been specialized to solve the quadratic assignment problem (QAP) [6]. Despite its simple statement—to minimize the assignment cost of n facilities to n locations—it is extremely difficult to solve even modest sized instances of the QAP. Problems with $n > 20$ are difficult; problems with $n > 30$ have not even been attempted yet. By embedding a new relaxation technique [1] into a branch-and-bound framework, and implementing the resulting solver within MW, we managed to solve what is regarded by experts in the field as the most difficult QAP instance (size n=27) to provable optimality [2].

In order to use the computational resources with maximum efficiency, the parallelization strategy of the branch-and-bound tree search has been carefully designed. Issues such as the proper ordering of the task list and the selection of the grain size were carefully considered in order to minimize communication overhead and contention at the master process without introducing large parallel search anomalies. By using the intuitive MW API, implementing the parallel version of the sequential branch-and-bound code was extremely simple and fast. The MW-ized QAP application code was compiled to use the Condor/File-Based `MWRMComm` implementation.

The computational pool was composed of machines from the Condor pool and a Linux cluster at the University of Wisconsin, a flocked Condor pool at the University of New Mexico, a flocked Condor pool at the National Institute for Nuclear Physics (Bologna, Italy), and the SGI/Origin2000 at Argonne National Laboratory acquired via Globus through the glide-in mechanism. Further information about the computational pool is summarized in Table 3.

Number	Arch-OS	Where	How	(Peak) GFLOPS
179	INTEL/LINUX	Wisc	Main Pool	13.88
34	INTEL/LINUX	UNM	Flocked	1.12
64	INTEL/LINUX	INFN	Flocked	2.76
150	INTEL/SOLARIS	Wisc	Main Pool	7.64
35	SUN/SOLARIS	Wisc	Main Pool	1.44
8	SUN/SOLARIS	INFN	Flocked	0.38
32	SGI/IRIX	Argonne	Glide-in	3.84
502	-	-	-	31.06

Table 3. The Computational Pool.

Figure 1 depicts the cumulative evolution of the number of machines of each type during our run. A few events are of note. At 11:30AM a glide-in request was made for 32 SGI processors on Argonne's Origin for a period of 12 hours. (The reader can note these machines appear in Figure 1 around this time). At 6:30 PM, the Condor scheduling daemon was reconfigured to allow flocking with the INFN Condor pool in Bologna, Italy. The job was stopped manually at 11PM, and we restarted it at 8AM from the master's checkpoint file, as explained in Section 3.1. When restarted, we did not place a new glide-in request.

In all, 87,036 tasks, each consisting of a number of nodes of the branch and bound tree, were sent from the master to workers. It is impossible to predict the number of nodes in a task, resulting in a wide variance in task grain sizes. The task grain sizes varied from 0.01 CPU seconds to over 1200 CPU seconds, with a mean value of 190.6 seconds. 567,793,866 nodes were explored in solving the problem. Figure 2 shows a moving average of the number of nodes evaluated per second. Over the course of the computation, we used an average of 211.3 machines and with a peak of 285. The parallel efficiency obtained during the run was

$\eta = 0.83$. The average performance of the computational pool was 195 times the performance of one of the dedicated Linux nodes. Neglecting parallel search anomalies, the solution of this problem in sequential would have required around over 177 days of computation with the sequential algorithm on a dedicated Linux node. The marriage of Grid resources with the advanced algorithm allowed the solution of a heretofore unsolved problem.

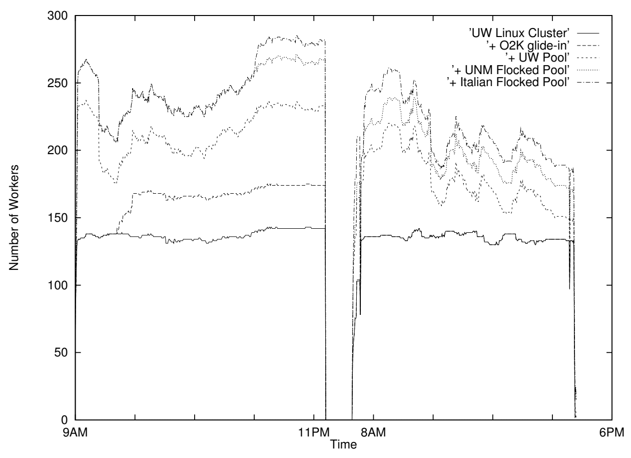

Figure 1. Number of Workers

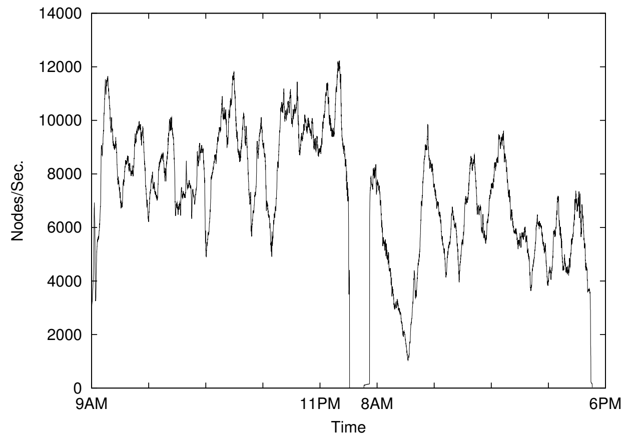

Figure 2. Nodes Per Second

5 Conclusions and Future Work

MW has allowed algorithm developers to bring together a large number of heterogeneous, geographically dispersed resources to solve extremely large problems. The simple API of MW provided a convenient programming model enabling the user to focus on algorithmic features without worrying on the details of setting up computations, and the IPI has allowed a better portability of the resulting code to different grid computing environments.

It is the continued goal of this work to draw further application developers by providing a simple interface, access to Grid resources, and useful functionality at no expense to the application code. We also wish to entice Grid infrastructure developers to support MW by providing a simple, well-defined interface, and interesting and useful applications. There is still work to be done to turn these goals into realities.

Further information about MW is available from

`http://www.cs.wisc.edu/condor/mw`

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