Interfacing Interpreted and Compiled Languages to Support Applications on a Massively Parallel Network of Workstations (MP-NOW) *

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February 1, 2008

Abstract

The advent of Massively Parallel Network of Workstations (MP-NOW) represents an important trend in high performance computing. The rise of interpreted languages (e.g., Visual Basic, MATLAB, IDL, Maple and Mathematica) for algorithm development, prototyping, data analysis and graphical user interfaces (GUIs) represents an important trend in software engineering. However, using interpreted languages on a MP-NOW is a significant challenge. We present a specific example of a very simple, but generic solution to this problem. Our example uses an interpreted language to set up a calculation and then interfaces with a computational kernel written in a compiled language (e.g., C, C++, Fortran). The interpreted language calls the computational kernel as an external library. We have added to the computational kernel an additional layer, which manages multiple copies of the kernel running on a MP-NOW and returns the results back to the interpreted layer. Our implementation uses The Next generation Taskbag (TNT) library developed at Sarnoff to provide an efficient means for implementing task parallelism. A test problem (taken from Astronomy) has been implemented on the Sarnoff Cyclone computer which consists of 160 heterogeneous nodes connected by a “fat” tree 100 Mb/s switched Ethernet running the RedHat Linux and FreeBSD operating systems. Our first results in this ongoing project have demonstrated the feasibility of this approach and produced speedups of greater than 50 on 60 processors.

1 Introduction

The increasing power of cheap computers have made Massively Parallel Network of Workstations (MP-NOW) with super computing capability a reality (e.g., Beowulf \cite{16}, Shrimp \cite{3}, and Avalon \cite{1}). These machines have a variety of desirable features in comparison to Massively Parallel Processors (MPP) such as the Cray T3E, SGI Origin 2000, HP Exemplar and IBM SP. MP-NOW systems are readily available, offer the flexibility of both commodity hardware and software, and deliver superior price/performance in terms of $/Megaflop. All of these features along with

\footnote{This research was supported by Sarnoff Corporation internal R&D, DARPA grant F30602-96-CO297 and NSF grant AST 93-15368.}
competitive pressures on MPP system vendors suggest that MP-NOWs may be the future of high performance computing.

The MP-NOW concept has been under steady development for almost 15 years, beginning with early work at the National Security Agency [13, 12] and Fermi Labs. In recent years, the Beowulf project has provided the impetus for several MP-NOW systems (see [2]). One implementation, the HIVE (the Highly-parallel Integrated Virtual Environment), consists of a 50 node cluster in a “fat” tree network configuration rather than the typical homogeneous configuration provided by Ethernet or switched Ethernet. The root of the tree is the connection to the world. The tree has two levels: 10 “router” nodes and 40 “data” nodes.

Another MP-NOW is the SHRIMP (Scalable High-performance Really Inexpensive Multi-Processor) project, which investigates how to construct high-performance servers (see [17]). So far, four kinds of Shrimp multicomputers have been developed. One of them uses 16 Pentium PCs as the computing nodes and the Intel Paragon routing network as the network and implements a custom network interface. The other three use Pentium PCs, Pentium SMPs and Pentium-Pro SMPs as compute nodes, and use a Myricom routing network and network interfaces.

Perhaps one of the largest examples of a MP-NOW machine is the the Sarnoff Cyclone, which is a jointly funded project between DARPA and the Sarnoff Corporation. The Cyclone was built to test operating systems and systems software concepts related to deployment of hundreds to thousands of independent processes cooperating to solve a particular task. It consists of 160 heterogeneous nodes running Unix connected by a “fat” tree interconnect network (Gigabit root, 100 Megabit switched internal nodes). The peak performance for this cluster is approximately 24 Gigaflops at a cost of $10/Megaflop.

Increased power on the desktop has also spawned the wider use of interpreted languages for algorithm development, prototyping, data analysis and graphical user interfaces (GUIs). In fact, within certain scientific and engineering disciplines the use of interpreted languages has become the accepted standard for applications development (e.g., signal processing with MATLAB and satellite image processing with IDL). Several efforts are underway to merge these two trends to allow interpreted languages take advantage of parallel computers. These efforts take a variety of approaches from porting an interpreted language engine [1] to providing tools which automatically translate the interpreted language into a parallelizable form of a compiled language [8].

In spite of their widespread use in technically challenging fields, there are many types of calculations that do not run efficiently in interpreted languages. Interpreted languages tend to pass data to subroutines via copying, which allows some of the more powerful constructs of these languages. However, creating many duplicates of large arrays can be prohibitive. Interpreted languages also are very inefficient at handling large loop operations, and programmers are highly encouraged to vectorize their programs to avoid loops. To avoid these limitations most interpreted languages provide simple methods for linking in compiled subroutines (written in C, C++ or Fortran). This allows the programmer to take full advantage of an interpreted language for developing the parts of an application that are generally most time consuming in a compiled language (e.g., GUI, I/O and graphics) while still being able to use a compiled language where performance constraints require it. This simple model for enhancing the performance of interpreted languages is widely used and has the advantage of being highly portable.

Our approach to using interpreted languages on a MP-NOW is to take advantage of the ability of most interpreted languages to call externally compiled subroutines. We break our application into an interpreted layer and a compiled layer. In the interpreted layer all the “code intensive” operations are performed (i.e., GUI, I/O, program management) while in the compiled layer resides a computational kernel which does the CPU intensive component. Within the compiled layer we also insert the tools necessary to manage multiple instances of the computational kernel on a
Many tools have been developed for scheduling processes on a MP-NOW (e.g., Load Sharing Facility [10] and DQS [3]), which provide various features for starting and monitoring distributed tasks. Complete meta-computing environments have also been developed (e.g., Globus [7] and Condor [4]) which encompass distributing computing along with collaborative tools. Each of these systems can dispatch, checkpoint, and migrate arbitrary binary object programs.

To support applications which can be broken down into multiple independents tasks, Sarnoff has designed and developed a task management framework for clusters: The Next generation Taskbag (TNT) based on Poet [5]. TNT is a client/server based Applications Programming Interface (API) for distributing and managing multiple tasks on a MP-NOW. TNT shares many of the desirable features found in the aforementioned systems (e.g., fault tolerance, load balancing, job monitoring, and job rescheduling). The most notable difference is that the TNT library is fundamentally a simple framework for task parallelism, and thus is designed to be compiled directly into the distributed application and does not require any system wide resources or installation. This capability is essential for allowing interpreted languages to take advantage of task based parallelism through externally compiled computational kernels.

In the rest of this paper we present a specific demonstration of our overall approach. Section two describes the Sarnoff Cyclone MP-NOW. Section three presents the details of the interpreted language we used for this project (IDL: Interactive Data Language). Section four talks about the API and other features of the TNT library. Section five describes some of the applications that this approach lends itself to, with particular emphasis on problems in Astronomy and Astrophysics. Section six describes the implementation of our test problem. Section seven gives the parallel scaling results. Section eight gives our conclusions and plans for further work.

2 The Sarnoff Cyclone MP-NOW

The Sarnoff Cyclone is a large, heterogeneous workstation cluster. This cluster has been used for a variety of computational tasks, from real-time MPEG-2 software encoding to distributed World Wide Web queries. Figure 1 provides a mosaic image of the current Cyclone cluster.

Specifically, there are a total of 160 nodes in the cluster: 128 Dual CPU machines, and 32 Single CPU machines. Each dual CPU node has 2 200 MHz Intel P55C (Pentium) processors, 64 MBytes of RAM and 3 GBytes of disk. Sixteen of the single CPU machines have 533 MHz Digital Alphas, 64 MBytes of RAM and 6 GBytes of disk. Finally, most of the remaining 16 single CPU machines have a 90 MHz P54C, 32 MBytes of RAM and 258 MBytes of disk (we also have a dual 450 MHz Pentium II node and a few 200 MHz Pentium nodes). There are two networks connecting the nodes of the dual CPU cluster: the public and private (see Figure 2 for details).

The public network is a “fat” tree interconnect with two 8-port Gigabit switches at the root and 12 12-port 100 Mbit switches at the nodes, each connecting 12 PCs at the leaves. The 100 Mbit switches are connected to the Gigabit switches via fiber-optic cable; the PCs to the 100 Mbit switches via CAT 5 twisted-pair cable.

The private network contains 12 100 Mbit switches all connected to a single 12-port 100 Mbit switch. All connections in the private network are CAT 5 twisted-pair cable. The Sarnoff cluster can currently support up to 192 PCs, with 100 Mbit node-to-node bandwidth.

The current cluster was designed and built in late 1997 for approximately $250K. Today, the same amount of dollars would purchase a cluster with double the compute power (dual 400 MHz Pentium II), double the secondary memory (6 GB disks) and double the primary memory (128 MB RAM), and almost double the system bus (from 66 MHz to 100 MHz).
3 The IDL Interpreted Language

There are many interpreted languages in wide use today. Visual Basic has $O(10^6)$ users worldwide while MATLAB, IDL, Mathematica and Maple each have $O(10^5)$ users. MP-NOW systems can take advantage of these tools and their large user bases because they are built out of the same components and use the same OSes. Interpreted languages are designed to run on. These languages provide many of the same features and mainly differ in the applications of their primary users. Visual Basic predominates in the business arena, MATLAB is extremely common in the signal processing community, IDL has been adopted for many satellite image processing applications and Mathematica and Maple are used in mathematical contexts. Rather than go into the details of each of these packages we have chosen to focus on IDL as a representative example.

IDL (Interactive Data Language) from Research Systems, Inc. originally was focused on image processing, but now it includes capabilities for building GUIs, doing 3D visualization and engaging in fully object oriented programming. Like most interpreted languages it is very efficient at manipulating multi-dimensional arrays and provides a rich notation for accessing and modifying these data structures. For example, the IDL vector statement: array[i:i+n] = cos(array[j:j+n]) is fairly straightforward in its meaning: replace elements i through i+n with the cosine of the values in elements j through j+n. To perform a similar function in a compiled language would require several lines of code as well as the use of intermediary arrays which IDL creates and uses implicitly.

The price for this rich set of tools is that there are certain specific types of calculations that do not run efficiently in interpreted languages. The implicit copying of arrays enables some of the more powerful constructs of the these languages, but creating many duplicates of large arrays can be prohibitive in very large memory applications. Interpreted languages are also inefficient at handling large loop operations, which require the explicit generation and evaluation of all the code in the loop. In general, programmers are encouraged to express loops in vector notation.

There are applications where loops or very large arrays are unavoidable, in which case most interpreted languages provide a simple interface for linking in compiled subroutines (written in C, C++ or Fortran). This allows the programmer to take full advantage of an interpreted language for developing the parts of an application that are generally most time consuming in a compiled language (e.g., GUI, I/O, and graphics) while still being able to use a compiled language where performance constraints require it. This simple model for enhancing the performance of interpreted languages is widely used and is shown schematically in Figure F.

In IDL and most interpreted languages the calling of externally compiled routines requires three pieces: a wrapper function, the external library function, and a special set of compilation instructions. To illustrate these three components consider a simple program that adds two vectors together. The first piece is the IDL wrapper function which takes the IDL arrays as input and calls the external library function. The wrapper function shown below also computes the number of elements and allocates the output array for storing the result. Calling an external function requires using the IDL CALL_EXTERNAL function which takes as inputs the name of the library, the specific library function, and the arguments to be passed.

```idl
FUNCTION add_arrays,a,b
    ;Get size of array.
    N = N_ELEMENTS(a)
    ;Make output array.
    c = a
```
Call external function, pass data.

flag = CALL_EXTERNAL("add_arrays.so", "_add_arrays_", N, a, b, c)
RETURN,c
END

The second component is the compiled function itself. Shown below is the code necessary to add two arrays together and return the result in a third array. This is an ordinary C function except that the pointers to the arguments are passed through the argv array and need to be recast into their original types:

```c
float add_arrays(int argc, void *argv[])
{
    /* Declare local names of inputs. */
    long N; float *a, *b, *c; long i;

    /* Cast the pointers in argv to local names. */
    N = (long>(()long *)argv[0]);
    a = (float *) argv[1]; b = (float *) argv[2]; c = (float *) argv[3];

    /* Add vectors. */
    for(i=0; i<N; i++) {
        c[i] = a[i] + b[i];
    }

    /* Return flag value. */
    return(1.0);
}
```

The third and final component consists of the special compilation instructions that enable the library function to be used by IDL. This is usually the one architecture/OS dependent aspect of calling external functions. As an example, the instructions for compiling the `add_arrays` subroutine within the Linux environment are:

```
cc add_arrays.c -fPIC -o add_arrays.o -c add_arrays.c
ld -shared -o add_arrays.so add_arrays.o
```

Although the details of this process for other interpreted languages differ, the overall approach is the same. Once constructed, this method provides a seamless interface between the interpreted and compiled environments and each is completely independent of the other.

Our approach to using interpreted languages on a MP-NOW is to take advantage of this ability of most interpreted languages to call externally compiled subroutines. We break our application into an interpreted layer and a compiled layer. In the interpreted layer all the “code intensive” operations are performed (i.e., GUI, I/O, program management) while in the compiled layer resides a computational kernel which does the CPU intensive component. Within the compiled layer we also insert the tools necessary to manage multiple instances of the computational kernel on a MP-NOW. This approach to implementing parallelism places specific constraints on the type of tool than can be used. Specifically, the parallel layer must be callable from a compiled subroutine. In addition, the parallel tool cannot require a large framework which cannot be imposed onto an existing interpreted language which is unalterable by the user. The TNT library described in the next sections satisfies both of these constraints.
The Next generation Taskbag (TNT) is a client-server based Applications Programming Interface (API) framework for distributing and managing multiple tasks on a MP-NOW. TNT is a C based library which can be used in any compiled program. As such, it is possible to insert the appropriate TNT calls into the compiled layer called by an interpreted language (see Figure 4).

The operation of a typical TNT application is shown in Figure 5. The server creates a “Taskbag” of work for clients. The clients are then executed remotely on a number of processors. The processors that the program is run on can be specified either automatically or interactively via a “Chooser” (see Figure 6). The clients connect with the server and request a task or taskbag (a group of tasks). When they have completed their tasks they return the results back to the server and ask for more tasks.

The TNT library was developed on Linux (RedHat 5.0) and tested on FreeBSD, NetBSD, and Solaris. The entire library is written in C using TCP sockets for server-client communication. Server communicate with the clients using ports, which allows simultaneous servers to be active and listening to different port numbers. The library has many features, including: multiple server support, interactive server, and inherent load balancing. These features are detailed below.

In TNT, a server can call client functions and a client can call server functions. This enables the creation of hierarchies of servers. For example, a “root” server can partition a large taskbag into many sub-taskbags and distribute them to a collection of sub-servers. These sub-servers will then distribute tasks to the clients. This allows for a more efficient distribution of work across the cluster nodes.

Additionally, the server is interactive. Current commands include: status, clients and quit. The status command displays the clients connected to the server and what task each client is currently working on. The clients command displays all of the client hostname and socket number pairs. Finally, quit gracefully terminates the server by allowing the clients to finish the current task but not allowing additional tasks to be given out. Once all clients have returned the current task, the server closes. In a future version of TNT, we will allow a customizable server command set (implemented with the Tcl library). The API will have functions that allow the programmer to specify additional commands (or modifications to intrinsic commands).

Finally, TNT is inherently load balancing in the sense that when a client finishes a task it requests additional work. If there are no tasks remaining then the client exits and frees up the processor. The processors that run faster will pick up more work and slower processors will pick up less work. There is no static assignment of work to processors.

4.1 TNT API Overview

The available functions in the TNT library are grouped into two categories: server and client. Next we provide a brief overview of available function classes for each group.

4.1.1 Server Functions

Network Initialization Network initialization sets the server to allow client connections on a specified network port.

Registry The server maintains a list of active clients. This list is called the registry. The server may add clients, remove clients and verify clients. These functions are usually called in response to a client request for addition, removal or verification.
Taskbag Operations The server can add and remove tasks from the taskbag. There are also functions for locating tasks in the taskbag.

4.1.2 Client Functions

Server Connection Given a hostname and port, the client calls a function to connect to the server. This sets up a persistent socket connection with the given server.

Registration After the client has established a connection with the server, it requests registration from the server. The server will respond with success or failure. A failure indicates that the client is already registered or invalid parameters were provided.

Request Task (or Taskbag) Once the client is registered with the server, it will typically enter a request task loop. In this loop, the client will return the previous, completed task (null, if initial task) and request a new task.

Close Session Once the server indicates that there are no more tasks, the client calls a function to close the current session. This will cause the server to remove the client from the registry and close the socket connection.

4.2 TNT Essentials

The essentials of the TNT API can be summarized as follows:

| Basic TNT API |
|---------------|
| – TNT client/server templates contain calls to TNT library. |
| – Programmer replaces default functions in templates. |
| – Typical application requires programmer to write the following functions: |
|   **Server** |
|   ApplicationServerInit() passes data from the interpreted layer to the TNT server. |
|   FillTaskbag() passes data to the clients by placing tasks in Taskbag. |
|   PrintTaskbagResults() returns result of computation back to Main. |
|   **Client** |
|   ApplicationClientInit() performs any client initialization. |
|   ProcessTask() calls the unmodified computational kernel. |
|   **Server and Client** |
|   InitCmdLineVars() initializes any user-configurable application variables. |
|   ParseCmdLine() parses command-line arguments and sets any user-configurable variables. |
The TNT API consists of template server and client programs each containing several function calls, which are customized by the programmer to a particular application. In a typical application, three server functions `ApplicationServerInit()`, `FillTaskbag()` and `PrintTaskbagResults()`; two client functions `ApplicationClientInit()`, `ProcessTask()` and two command-line argument functions `InitCmdLineVars()`, `ParseCmdLine()` are modified. `ApplicationServerInit()` performs any server-specific initialization, `FillTaskbag()` passes data from the server to the clients, `PrintTaskbagResults()` sends results of computation back to the main program, and `ProcessTask()` calls the unmodified computational kernel.

### 4.3 Overhead

One of the essential benefits of using the TNT library with a compiled language is the very low overhead it introduces at the coding, system, compute and communication levels.

The primary coding overhead occurs in creating the interface between the interpreted language and the computational kernel (see section 3). If a compiled computational kernel is required because the nature of the calculation does not lend itself to an interpreted language, then this overhead will have already been incurred. However, if the computational kernel is readily programmed in an interpreted language, then the overhead of converting the kernel to a compiled language and interfacing is required in order to subsequently take advantage of the TNT tools. A secondary amount of coding overhead is necessary to insert the TNT client/server framework. This consists of creating the appropriate wrapper functions as well as packing and unpacking the data into “tasks” by the server and client.

The TNT library is built using TCP sockets and does not require any other system resources (e.g. daemons, shell programs, etc...) other than those necessary to launch the interpreted language and the clients. After launch the computational kernel is executed via an external library call, which induces no more overhead than that required for other library calls. The computational kernel starts the server, and may start the clients. The clients can be launched interactively or directly by the application through remote shell commands. In cases where very rapid launching is required (e.g. applications with a real-time constraint) higher performance multi-launch mechanisms can be used [19].

The computational overhead of this approach is limited to the overhead of packing the data into tasks on the server and unpacking the data on the client side. Additional overhead might be required to divide the work up into tasks (e.g., computing subsets of indices) and for pooling the results returned by each client.

As with any mechanism for distributing work across a MP-NOW, communication overhead is unavoidable and managing this overhead is often critical to achieving good performance. In addition, the client/server model is strictly limited to independent, non-communicating tasks. The primary communication overhead comes from the server transferring the data associated with a given task to the requesting client and any results that are sent back by the client to the server. If the amount of data being sent is large compared to the subsequent computations being performed then communication time can easily dominate.

### 5 Task Parallel Applications

Task parallelism is one of the most common types of parallelism that exist in a wide array of science and engineering applications. Many of these applications also fit the model whereby a small amount of code accounts for a majority of the computations and can benefit from an approach that allows much of the code to be written in an interpreted language. The TNT based approach presented
here is generally applicable to any task parallel problem. An analysis of even a small fraction of these applications is beyond the scope of this paper. However, it is possible to examine several applications in the fields of Astronomy and Astrophysics to determine the usefulness of the TNT based approach.

Astronomy and Astrophysics are among the largest consumers at national computing centers [14]. These applications can be grouped into two general classes: astrophysical simulations and astronomical data analyses. Within these categories, there are two primary ways parallel computing resources are exploited: parameter space studies (running the same “small” program many times with different inputs) and large data intensive calculations that require multiple computers to complete.

The parameter space studies map onto a task parallel approach trivially. Examples of this type of calculation are: calibration of supernova models over a range of compositions [18, 15] to determine the size of the Universe; calibration of star models over a range of ages, compositions and masses to determine the age of the Universe; comparison of stellar oscillation data against hypothetical planetary arrangements for finding extra-solar planets.

Data intensive calculations are much more challenging to map onto a task parallel model. However, these types of calculations do stress the limits of task parallelism. Examples of the kind data intensive calculations that can be mapped onto task parallelism are particle simulations, correlation analysis and pattern detection.

Frequently in astrophysics it is desirable to simulate physical systems as the interaction of many particles. For example, to simulate the motion of stars moving about the galaxy it is necessary to compute the force of every star (particle) on every other star. A similar situation occurs when the behavior of gaseous objects is modeled as a collection of particles. In this case the behavior of an individual particle is a function of its nearest neighbors.

Astronomical databases often consist of the positions of a large number of objects. One of the most common analyses performed on these data sets is computing the correlation function of one type of object (e.g. red stars) with another (e.g. blue stars). The essence of the correlation function is computing the relative distances every object.

Another type of analysis that is performed on astronomical datasets is pattern recognition or cluster detection. In this case the dataset is convolved with a filter for the type desired object, such as a high spatial concentration of stars. The essence of this operation is finding all the objects that are near another object and using this subset of data to evaluate the filter at that point.

The common feature of the above data intensive problems is that they use the same computational kernel. This kernel takes as its input a list of positions and returns as its output the distance of each point from every other point or a list of the nearest points. Exploring the performance of this one kernel provides information on the utility of the TNT based approach to all the above examples.

6 Implementation

In the previous section several problems in Astronomy and Astrophysics were described with a common computational kernel. This kernel has been implemented using the TNT based approach described above. The calculation is set-up using code written in IDL which calls a computational kernel written in C.

More specifically, the computational kernel takes as its arguments a set of N vectors \( \mathbf{x}_1, \ldots, \mathbf{x}_i, \ldots, \mathbf{x}_N \) each with \( D \) elements. The individual elements of the vectors can be made up of real, complex, integer, string or mixed type data. Within the kernel there is a function called distance(\( \mathbf{x}_i, \mathbf{x}_j \))
which returns a positive real value corresponding to the separation of the vectors \( \mathbf{x}_i \) and \( \mathbf{x}_j \) in the \( D \) dimensional space. The goal is to compute the distance between every pair of vectors and to return a list of the \( M \) nearest neighbors to each point.

The algorithm used to solve this problem is a simple direct calculation that involves performing \( N^2 \) distance calculations and \( N \) sorts each requiring \( O(N \log N) \) operations. This method is not the most efficient in all circumstance, however it is the most general and works for all values of \( D \) and all distance functions. This test problem is simple to parallelize by putting \( N/\#\text{CPU} \) vectors on each processor. Furthermore, by adjusting the parameters \( N \) and \( \#\text{CPU} \) this problem can readily probe both the computation dominated and communication dominated regimes.

7 Results

Our test problem has been implemented on the Sarnoff Cyclone. The execution times for various configurations of problem size and \( \#\text{CPU} \) are shown in Table 1. As a baseline, we look at the single CPU behavior as a function of \( N \). Figure 1 shows that this problem scales in the predicted \( N^2 \log N \) fashion. The same behavior is also exhibited for larger numbers of CPUs.

The parallel performance results are shown in Figure 2 for two problem sizes using 1, 5, 20, and 60 CPUs. Speedup of the smaller problem is primarily constrained by the time required to dispatch the parallel tasks, which becomes significant when the computation time becomes on the order of a few seconds. The bigger problem scaled much better, as the task dispatch overhead is much smaller relative to the computation time. The main limit to the speedup of the bigger problem size are network communication between the client CPUs and the TNT server.

8 Conclusions and Future Work

With less than 3 weeks of total effort we were able to successfully implement this paradigm on a readily obtainable MP-NOW system. Subsequent porting of similar applications should take only 1 or 2 days of effort. The TNT API is simple and provides good performance, resulting in speedups of greater than 50 on 60 CPUs. Continued development of the TNT library will broaden the types of problems that can be addressed as well as increase the range of available OSes and architectures. As the Cyclone computer and TNT library are further improved we expect to see the performance for this test problem improve further.

TNT uses a client/server framework which naturally lends itself to problems that exhibit a large amount of coarse grained parallelism. In addition, this model allows for dynamic load balancing as well as rescheduling of non-completed tasks. The client/server model is not applicable to problems that require a large amount fine grained parallelism or intertask communication. For these types of problems other tools have been developed for the Sarnoff Cyclone.

In the future we plan to extend the TNT library and to test it with additional interpreted languages (e.g. MATLAB). We also plan to use the current TNT/IDL implementation on several scientific data processing applications, which will provide a further evaluation of the ease of use and performance.

Acknowledgments

Jeremy Kepner would particular like to thank his Ph.D. advisor Prof. David Spergel for supporting this work.
References

[1] Avalon: An Alpha/Linux Cluster Achieves 10 Gflops for $150k, http://cnls.lanl.gov/avalon

[2] Beowulf Project at CESDIS, http://www.beowulf.org/

[3] M. A. Blumrich, R. D. Alpert, Y. Chen, D. W. Clark, S. N. Damianakis, C. Dubnicki, E. W. Felten, L. Ifode, K. Li, M. Martonosi and R. A. Shillner, Design Choices in the SHRIMP System: An Empirical Study, Proceedings of 25th Annual ACM/IEEE International Symposium on Computer Architecture (June 1998),

[4] Condor High Throughput Computing, http://www.cs.wisc.edu/condor

[5] J.L. Durant, C. Yam, M. Bui-Pham, P. Wyckoff and R. Armstrong, Poet on Daisy: Experiences in Parallel Computing on Commodity Workstation Clusters, The Combustion Research Bulletin (January 1997) No. 98, http://www.ca.sandia.gov/CRF/Publications/CRB/v98/Abstract/v98abs-42.html

[6] DQS – Distributed Queuing System, http://www.scri.fsu.edu/~pasko/dqs.html

[7] The Globus Project: A Status Report. I. Foster, C. Kesselman, Proc. IPPS/SPDP ’98 Heterogeneous Computing Workshop, pg. 4-18, 1998.

[8] HeteroRT: Heterogeneous Embedded Real-Time Environment, http://www.darpa.mil/ito/Summaries97/F274_0.html

[9] Legion: A Worldwide Virtual Computer, http://legion.virginia.edu/

[10] Load Sharing Facility, http://www.platform.com/

[11] Bridging the Development Gap, Mercury Computer Systems, Inc. http://www.darpa.mil/ito/Summaries97/D351_0.html

[12] R. Minnich and D. Pryor, Radiative Heat Transfer Simulation on a SPARCStation Farm, Concurrency: Practice and Experience (June 1993), 345-357

[13] M.T. Mock, Distributed Processing on Powerful Personal Computers: Interim Results, DoD (1984), TR-R53-13-84

[14] Alliance/NCSA Access, volume 11, number 1, Fall/Winter 1999

[15] S. Perlmutter et al, Cosmology from Type Ia Supernovae: http://xxx.lanl.gov/abs/astro-ph/9812473

[16] D. Ridge, D. Becker, P. Merkey, T. Sterling and P. Merkey, Beowulf: Harnessing the Power of Parallelism in a Pile-of-PCs, Proceedings, IEEE Aerospace, 1997

[17] Shrimp project overview, http://www.cs.princeton.edu/shrimp

[18] NERSC and the fate of the Universe: http://www.lbl.gov/supernova/NERSC-supernova.html

[19] Vector EXexecute: http://www.lanl.gov/~rminnich
Table 1: MP-NOW execution times in seconds for various numbers of points (N) and processors (#CPU) and a constant number of neighbors (M = 100).

| #CPU = 1 | N = 6,000 | N = 12,000 | N = 30,000 | N = 60,000 | N = 120,000 |
|----------|-----------|------------|------------|------------|-------------|
|          | 116       | 535        | 4,080      | 18,600     | 94,000      |
| #CPU = 5 | 24.5      | 107        | 826        | 3,990      | 18,600      |
| #CPU = 20| 7.8       | 29         | 213        | 1,010      | 4,820       |
| #CPU = 60| 5.5       | 15.1       | 78         | 356        | 1,790       |
Figure 1: **Sarnoff Cyclone MP-NOW** There are a total of 160 heterogeneous nodes in the cluster: 128 dual 200 MHz Intel P55C (Pentium) workstations, each with 64 MBytes of RAM and 3 GBytes of disk; 16 533 MHz Digital Alphas (not shown in image), each with 128 MBytes of RAM and 6 GBytes of disk; 13 90 MHz P54C workstations, each with 32 MBytes of RAM and 500 MBytes of disk; 2 200 MHz P55C workstations, each with 32 MBytes of RAM and 500 MBytes of disk; and a dual 450 MHz Pentium II workstation, with 64 MBytes of RAM and 4 GBytes of disk. There are two networks connecting the nodes of the 128 node dual Pentium CPU cluster: the public (yellow) and private (red) (see Figure 2 for details). Additionally, there is a 4x4 array of monitors which can present a composite 4000x4000 pixel image. The monitors are controlled by the nodes shown on either side.
Figure 2: **Cyclone Architecture** Topology of the Cyclone cluster. The public network (shown in bold) is a “fat” tree interconnect with two Gigabit switches at the root and 12 100 Mbit switches at the nodes. The 100 Mbit switches are connected to the Gigabit switches via fiber-optic cable; the PCs are connected to the 100 Mbit switches via CAT 5 twisted-pair cable. The private network contains 12 100 Mbit switches all connected to a single 12-port 100 Mbit switch. All connections in this network are CAT 5 twisted-pair cable.
Figure 3: **Single CPU Application Architecture.** Application architecture before implementation on an MP-NOW. GUI and other “high level” operations are written in the interpreted layer, which calls the compute kernel written in a compiled language.
Figure 4: **MP-NOW Application Architecture.** Application architecture after implementation on an MP-NOW. An additional “TNT” layer has been added to the compute kernel which invokes and manages multiple copies of the compute kernel on a MP-NOW.
A typical TNT application consists of a server with many clients, communicating via TCP/IP. The server: places tasks into Taskbag; listens on a specific port for requests for tasks from clients; dispatches tasks to requesting clients; accepts results from clients; monitors status of clients and re-assigns tasks of dropped clients; when all tasks are completed, returns results back to the main program. The client(s) loop over the Taskbag is until it is empty. On each iteration a client will: send requests for work to server on a specific port; read data sent by server over network; call compute kernel with the data; send results of computation back to server over network.
Figure 6: TNT CPU “Chooser”. Interactive “Chooser” tool used by applications programmer to select client nodes on a MP-NOW. The user chooses what clients will execute the given command. In the case of the taskbag application, the command would be an application-specific client executable. It should be noted, however, that the client executable must reside locally on each node or be NFS mounted on each node – the chooser will not distribute the executable.
Figure 7: **Problem Scaling.** Single processor CPU times as a function of problem size for the example pattern recognition problem.
Figure 8: **Parallel Performance.** Speedup vs #CPU for two different problem sizes. The black line indicates linear speedup. The larger problem size shows nearly linear speedup: a factor of 52 on 60 CPUs. Task dispatch overhead is evident on the smaller problem size.
Biographies

Jeremy Kepner received his B.A. in Astrophysics from Pomona College (Claremont, CA). He obtained his Ph.D. focused on Computational Science from the Dept. of Astrophysics at Princeton University in 1998, after which he joined MIT Lincoln Lab. His research has addressed the development of parallel algorithms and tools and the application of massively parallel computing to a variety of data intensive problems. E-mail: jvkepner@astro.princeton.edu or kepner@ll.mit.edu

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Ron Minnich is on the research staff of the Advanced Computing Lab at Los Alamos National Labs. His current research involves cluster computing, high performance networking, adaptive network card architectures, and operating systems support for distributed computing. Recent work includes a process-private name space for Linux to support trusted, wide-area distributed computing; the MINI ATM interface, which provides a Virtual Interface Architecture model to programs; and the construction of the Cyclone cluster at the Sarnoff Corporation. He received his Ph.D. at the University of Pennsylvania in 1991. E-mail: rminnich@acl.lanl.gov
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