Numerical Experiments in Concurrent Multiprocessing with the Relap-5 Nuclear Reactor System Code

H. Makowitz
Cray Research, Inc., 1440 Northland Drive, Mendota Heights, Minnesota 55120, U.S.A.

ABSTRACT

Numerical experiments[1,2] performed on a SIMD-PVP architecture computing machine (Single Instruction Multiple Data - Pipeline Vector Parallel) e.g. a CRAY X-MP/48, demonstrate that present day Nuclear Rector Systems codes can be restructured for concurrent multi-processing and show wall clock performance improvements of 1.5 to 3.0 on a 4-CPU machine, depending on plant model, problem type, and problem length. In addition, algorithm development studies indicate that up to a 20% speed up can be obtained by a new class of parallel numerical methods. Faster than real time simulation has been demonstrated utilizing RELAP5/MOD1 and a PWR plant model characteristic of licensing and/or safety analysis calculations. A theoretical analysis indicates that 5 to 10 times faster than real time computation may be possible for this class of problems utilizing this or the next generation of SIMD-PVP architecture machines such as the CRAY X-MP/48, and new computer codes optimized for such machines. System analysis indicates that up to 95% of a Nuclear Reactor System Simulation Algorithm may be suitable for parallel computation.

INTRODUCTION

With the development of scientific computers capable of multiprocessing (e.g. two or more CPU's) as well as Vector Processing such as the CRAY-XMP-2 and XMP-4 (with two and four CPU's respectively), concurrent vector and scalar computation has become a real possibility, when minimizing the wall clock time of an ongoing calculation is desirable. This is true when an attempt is made to model an ongoing or recent accident. Numerical experiments on the XMP-2 and XMP-4 with the RELAP5 Reactor System Code have been performed, were concurrence defined as Multitasking was implemented, by modifying the global system numerics and code structure. Faster than real time, 1000 seconds plus, simulations have been demonstrated utilizing RELAP5/MOD1 and a PWR plant model characteristic of licensing and/or safety analysis calculations for a 4 inch small break accident sequence, using a 4-CPU machine. Theoretical limits are discussed.

METHODOLOGY

Reactor system codes such as RELAP5 are composed of models of several different physical processes, which are combined by either implicit or explicit coupling, by ordering of calculational procedures or matrix inversion of system variables. These codes typically consist of heat transfer, fluid flow, and neutronics models with equation of state capability, as well as data management and graphics. When computational parallelism and concurrent execution of code (e.g. Multitasking) are desired the degree of granularity of code must be decided on first. This granularity can vary in size from a cell mesh point to a subroutine, to a major portion of a reactor system's component. In this study the basic granular unit is a physical process model, e.g. Heat Transfer, Fluid Flow, etc.

A hybrid numerical scheme is used, where an explicit coupling between physical processes is attempted for N_1^* time steps and an implicit iterative step for M_1 iterations and N_0 steps follows. Although a numerical scheme of this type is probably not suitable for rapid phase change problems, for typical "slow" plant transients and "small" break calculations of full scale reactor systems it is adequate, and lead to wall clock speed up factors of 1.5 to 3.0 on the XMP-4. A general model of speed up due to concurrence is constructed below.

THEORY

Consider a program where U% of the code must be run in single processor mode and M% can be multitasked. For N processors and unit normalization of wall clock time (e.g. M+U=1), the total wall clock time for multitasking T_N is given by T_N = (M/N)+U+O where O is the additional overhead due to the multitasking. Since M=1-U, and the speed up factor S_N is T_N^{-1} due to unit normalization, in the limit as N goes to an infinite number of processors, T_{INF}=[U+O] and S_{INF}=1/[U+O] where S_N=N/[1+(N-1)U+NO].

Hence it can be seen that unless the entire computer code can be multitasked, (e.g. there is no requirement for single threaded, single processor work), the number of processors, N_{MAX}, is a small number rarely greater than one hundred for $(S_N/S_{INF})\sim$ 9/10. Defining the ratio (S_N/S_{INF}) as $Z_{MAX} \leq 1$ where a $Z_{MAX} \leq 9/10$ value is typical of practical requirements and cost/performance, N_{MAX} the maximum number of processors to obtain a Z_{MAX} fraction of maximum theoretical performance is given by $N_{MAX} = Z_{MAX}\,[1-U] \,/\, [(U+O)\,(1-Z_{MAX})]$.

As can be seen from the above theoretical model, the smaller the percentage of work that has to be run in single processor mode, "U", the greater the speedup factor "S_N", unless the multitasking overhead "O" saturates the performance improvement for a given number of processors.

ANALYSIS

An M=0.70 value has been obtained for the RELAP5/MOD1 Nuclear Reactor System Code. A complete description of both numerical experiments and straight through multitasking for RELAP5 can be found in Ref.2. Figure 1.0 illustrates the experimentally obtained S_N values for straight through multitasking as well as S_{ALG} for a N_1^*/N_0 ratio of 1/80 where N_0 is the number of implicit steps. Overhead studies[2] indicate that O is at best a linear function of N.

Faster than real time, 1000 second, simulations have been demonstrated with the original multitasked RELAP5/MOD1 algorithm (e.g. same numerical values as a single processor) for as good as round off error numerical accuracy. A PWR model (Fig. 2.0) based on the Zion I PWR [3] was used. Proprietory data was removed and/or modified and point kinetics was added by INEL/NRC staff personnel. The model contains 139 volumes, 142 junctions, 83 heat slabs, 22 control variables and point kinetics. It models a 4" cold leg break for a four loop PWR plant, equating the three operating loops to one and utilizing the second loop for the break. The timing results for $1 \leq N \leq 4$ CPU's are shown in Fig. 3.0 for straight through multitasking, 1000 second, simulations.

A system analysis, Fig. 4.0 indicates that an $M \leq 0.95$ may be possible if parallel techniques and philosophy where adapted, to new Nuclear Reactor System Codes and Algorithm development. As can be seen in the figure, a "Nodal" approach to building the matrices, followed by a parallel sparse matrix solution for an implicit finite difference formulation will most likely achieve optimum performance for SIMD-PVP machines.

CONCLUSION

Ongoing numerical experiments performed on SIMD-PVP architecture e.g. the CRAY XMP-4 and XMP-2, demonstrate that present day Nuclear Reactor System codes can be restructured for concurrent multiprocessing and show wall clock perform-ance improvements of 1.5 to 3.0 on a 4 CPU machine, depending on plant model, problem type, and problem length. A theoretical analysis indicates that for typical problems where "U" $\geq$10% the number of processors to obtain a maximum performance improvement, N_{MAX}, assuming "O"$\sim$1% is less than 100. Significant gains can be seen for $N \leq 16$ (e.g. 2/3 S_{INF}) where, $S_{INF} \sim 9$, is the theoretical maximum speed up factor in wall clock time for U = 10% and O = 1%. At present for RELAP5/MOD1, $S_N \leq 3.0$ and $N_{MAX} \leq 6$ with O = 2.5%/CPU. Assuming that future hardware, software and codes will reduce this overhead and achieve high M values, say M = 0.96 and O = 0.4%/CPU, then one may obtain a $N_{MAX} \leq 16$ and $S_N \leq 10$.

Such speed up factors are highly desirable when an attempt is made to model in detail (e.g. 3-D) an ongoing or recent accident. Real time capability has been demonstrated for the model problem considered (1-D). Ten times faster than real time capability may be possible with $N \leq 16$ for 1-D problems characteristic of todays licensing and/or safety analysis calculations.

However, higher granularity, new algorithms such as (parallel) sparse matrix solvers for SIMD-PVP architectures and significant redistribution of work within individual modules would be required to achieve these theoretical limits for Nuclear Reactor System codes, such as RELAP5. Also, full utilization of the Vector Processing capability of computing machines such as the XMP can result in order of magnitude [4] (e.g. 5-20x) speed-up factors in addition to the gain that can be achieved by concurrent multiprocessing. At present Reactor Systems Codes, such as RELAP5, do not show significant Vector Processing utilization. It should be noted, however, that a speed-up improvement due to Vector Processing is not independent of that due to concurrent multiprocessing and hence to maximize performance an optimization between granularity, and vectorizability of the solution algorithm needs to be performed, when new Nuclear Reactor system codes are being written, or optimization of existing codes is undertaken. However, with proper optimization, for Vector and Concurrent multiprocessing and use of faster two phase flow algorithms, such as the Two Step Method [5,6] "Faster than Real Time First Principles" calculations are a demonstrated near term possibility. For complex and realistic model simulations of slow plant transients and small break calculations, with the use of SIMD-PVP architecture computing machines, numerous faster than real time capabilities are possible.

Hence, projects like the NPA [7] (Nuclear Plant Analyzer) can be seen in a new light, where "Faster than Real Time Simulation", advanced graphics systems and "Artificial Intelligence" systems (such as Expert Systems) can play a major role in increasing the reliability and operator response performance of future Nuclear Power Systems.

REFERENCES

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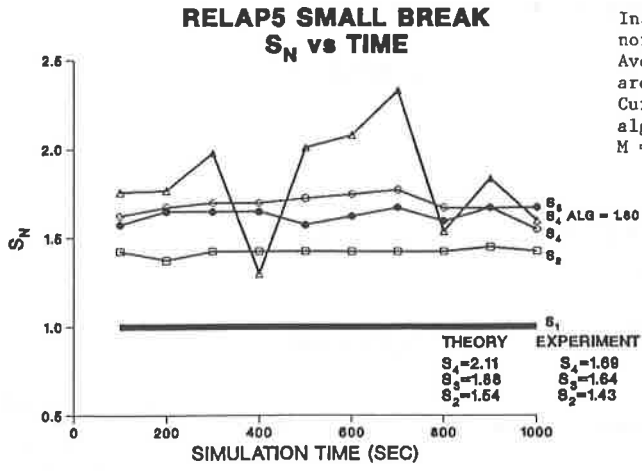
FIG. 1.0



Instantaneous S_N vs Time normalized to S_1 for M = 0.70. Averaged experimental values are compared to theory. S_4ALG Curve represents the new algorithm results with M = 0.70.

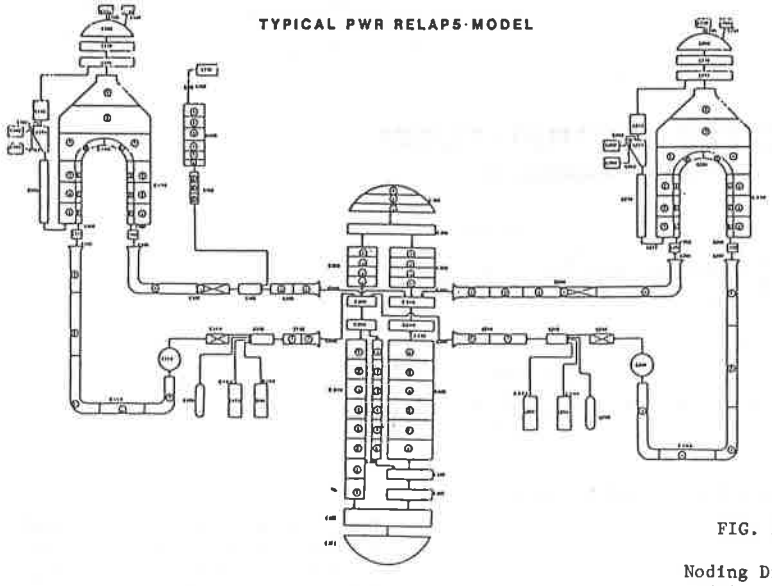


FIG. 2.0

Noding Diagram [3] of PWR model used in this study.

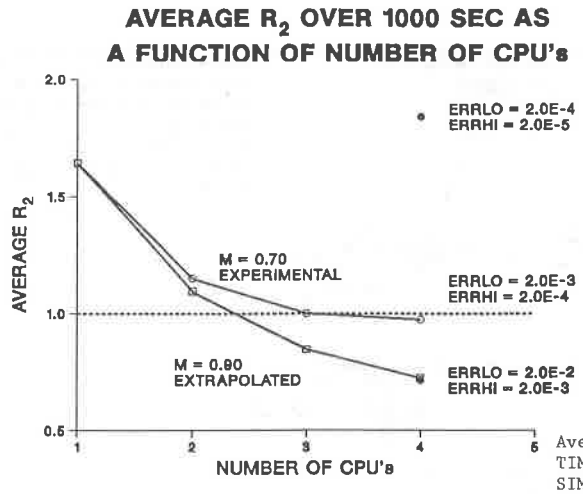


FIG. 3.0

Average R_2 values (R_2 = CLOCK TIME/REAL TIME (e.g. TIME TO SIMULATE VS TIME FOR THE PHENOMENON TO OCCUR) as a function of N the number of CPU's. M = 0.70 curve (experimental) shown vs M = 0.90 (extrapolation) for "as good as round off" accuracy. Results for 10X stronger and 10X weaker convergence criterion are also shown.

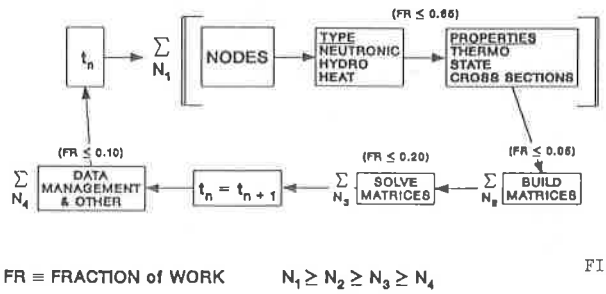


FIG. 4.0

System Analysis of a hypothetical Nuclear Reactor System Code. FR indicates the fraction of work per time step spend performing a particular task. Levels of parallelism are indicated by N_i ordering.