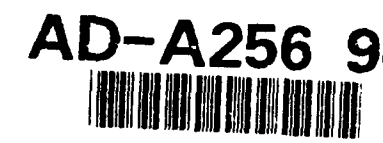

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FINAL REPORT

COMPILER ASSISTED RECOVERY FOR FAULT-TOLERANT HIGHLY PARALLEL MULTIPROCESSOR ARCHITECTURES

Supported by SDIO/IST

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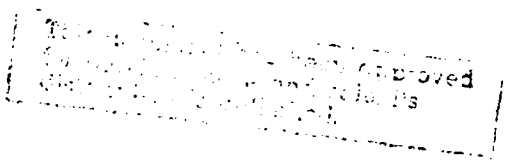
W. Kent Fuchs and Wen-Mei Hwu
Center for Reliable and High-Performance Computing
Coordinated Science Laboratory
University of Illinois
1101 W. Springfield Ave.
Urbana, IL 61801
(217) 333-9731
FAX: (217) 244-5686
fuchs@crhc.uiuc.edu

Scientific Officer:
Dr. Keith Bromley
Code 7601 T
Naval Ocean Systems Center
271 Catalina Boulevard
San Diego, CA 92152-5000

August 1991



A. Description of the Scientific Research Goals

The purpose of this research was to develop and implement compiler assisted strategies for recovery through multiple instruction reexecution (rollback) in highly parallel computer architectures utilizing hierarchical shared memories. The goal was to facilitate very rapid recovery from high rates of transient and intermittent failures in SDI environments. We worked to achieve this goal with minimal impact on system performance and little hardware overhead by exploiting the hardware features already present in recently developed high performance processor architectures. Our objective was to demonstrate that through appropriate compilation techniques these hardware features can be utilized to perform rapid recovery, without significant architecture redesign. Our research effort concentrated on multiprocessor machines with hierarchical memory structures, due to the architectural trend toward hierarchical memory, shared variable, multiprocessor architectures and due to the current lack of understanding as to how rapid recovery can be accomplished in this class of machines.

B. Summary of Significant Results

Our research results include the development of techniques for rapid recovery in multiprocessor systems by compiler strategies for insertion and maintenance of checkpoints as well as new memory management protocols for rapid recovery from transient failures. Additional results include the development of a memory management protocol for rapid recovery in shared virtual memory environments and also distributed shared memory architectures. We integrated the checkpointing process with shared virtual memory protocols and also developed a twin-page storage management protocol for rapid recovery from failures. The strategy allows for recovery without explicit undoes or propagated rollbacks. Our compiler-based checkpointing results focus on the development of techniques for maintaining desired checkpoint intervals and performing live variable analysis for minimizing the size of checkpoints.

We developed a method of applying optimizing compiler techniques to signature monitoring to reduce performance overhead and simplify monitor hardware. We showed that some previous signature insertion approaches have exponential algorithm complexity and we developed an algorithm with O(N^2) complexity. We have implemented this technique in the GNU optimizing compiler and evaluated the effectiveness of this approach with large production application programs. In addition, we developed approaches for bounding the error detection latency (for fast recovery) and evaluated the impact on performance and memory overheads.

C. List of Publications/Reports/Presentations

1. Papers Published in Refereed Journals

K. L. Wu, W. K. Fuchs, "Recoverable Distributed Shared Virtual Memory, *IEEE Transactions on Computers*, vol. 39, no. 4, April 1990, pp. 460-469.

C. Stunkel, B. Janssens, W. K. Fuchs, "Address Tracing for Parallel Machines," *IEEE Computer*, (Special Issue on Experimental Research in Computer Architecture), vol. 24, no. 1, January 1991, pp. 31-38.

2. Non-Refereed Publications and Published Technical Reports

N. Warter and W. W. Hwu *Compiler-Assisted Signature Monitoring*, CRHC-90-6, August 1990, Center for Reliable and High-Performance Computing, University of Illinois, Urbana-Champaign.

3. Presentations

a. Invited

W. K. Fuchs, "Trace Driven Evaluation of Fault-Tolerant Parallel Architectures," *IEEE International Workshop on Measurement and Modeling of Computer Dependability*, Los Angeles, CA, April 1990.

W. K. Fuchs, "Memory Management for Error Recovery in Parallel Architectures," *IFIP Working Group on Dependable Computing* Langdale, UK, July 1990.

W. K. Fuchs, "Fault-Tolerant Computing in Parallel Architectures," *ACCA Computer Science Seminar Series* Argonne National Laboratory, Argonne, IL, Oct. 1990.

W. K. Fuchs, "Compiler-Assisted Recovery in Parallel Architectures," *Fault-Tolerant Computing Workshop*, AT&T, Naperville, IL, May 1989.

W. K. Fuchs, "Fault Tolerance in VLSI Architectures," General Motors Research, May 1989.

W.W. Hwu, "Compilation Support for Superscalar Processors," 18th International Symposium on Computer Architecture, May 27-30, 1991, Toronto, Canada.

b. Contributed (See list of refereed published conference papers below.)

4. Books (and book chapters)

none

5. Refereed Published Conference Papers

K. L. Wu, W. K. Fuchs, "Recoverable Distributed Shared Virtual Memory: Storage Structures and Memory Coherence" *Proceedings of the 19th Annual IEEE International Fault-Tolerant Computing Symposium*, June 1989, pp. 520-527.

C. C. Li, W. K. Fuchs, "CATCH- Compiler Assisted Techniques for Checkpointing," *Proceedings of the 20th Annual IEEE International Fault-Tolerant Computing Symposium*, June 1990, pp. 74-81.

C. C. Li, W. K. Fuchs, "Maintaining Scalable Checkpoints on Hypercubes," *International Conference on Parallel Processing*, Aug. 1990, pp. 98-104.

J. Long, W. K. Fuchs, J. A. Abraham, "A Forward Recovery Strategy Using Checkpointing in Parallel Systems," *International Conference on Parallel Processing*, Aug. 1990, pp. 272-275.

C. C. Li, W. K. Fuchs, "Graceful Degradation on Hypercube Multiprocessors Using Data Redistribution," *Proceedings Fifth Distributed Memory Computing Conference*, April 1990, pp. 1446-1454.

K. L. Wu, W. K. Fuchs, "Twin Page Storage Management for Rapid Transaction-Undo Recovery," *Proceedings IEEE Computer Software and Applications Conference*, Nov. 1990, pp. 295-300. (Also reprinted as IBM Technical Report RC 15912, 7/10/90.)

N. J. Warter and W. W. Hwu "A Software Based Approach to Achieving Optimal Performance for Signature Control Flow Checking," Conference Proceedings of the Twentieth Annual International Symposium on Fault-Tolerant Computing, Newcastle upon Tyne, UK, June 26-28, 1990, pp. 442-449.

T. M. Conte and W. W. Hwu, "Benchmark Characterization for Experimental System Evaluation," Proceedings of the 23rd Annual Hawaii International Conference on Systems Sciences, Jan. 2-5 1990, pp 6-18.

C. Stunkel, B. Janssens, W. K. Fuchs, "Collecting Address Traces from Parallel Computers," *Proceedings 25th Annual Hawaii International Conference on System Sciences- Experimental Research in Computer Architecture*, vol. 1, Jan. 1991, pp. 373-383.

P.P. Chang, W.Y. Chen, S.A. Mahlke, N.J. Warter and Wen-mei W. Hwu, "IMPACT: An Architectural Framework for Multiple-Instruction-Issue Processors," *Conference Proceedings of the 18th Annual International Symposium on Computer*, Toronto, Canada, May 28, 1991.

S. A. Mahlke, N. J. Warter, W. Y. Chen, P. P. Chang, W. W. Hwu, "The Effect of Compiler Optimizations on Available Parallelism in Scalar Programs," *Proceedings of the 20th Annual International Conference on Parallel Processing*, St. Charles, IL, Aug 12-16, 1991.

6. Submitted Journal Papers

K. L. Wu, W. K. Fuchs, "Twin Page Storage Management for Rapid Transaction-Undo Recovery," *IEEE Transactions on Software Engineering*, Submitted 1991.

C. C. Li, W. K. Fuchs, "Compiler-Assisted Full Checkpointing," *IEEE Transactions on Software Engineering*, Submitted 1991.

N. J. Warter and W. W. Hwu, "An Efficient Methodology for Signature Monitoring," *IEEE Transactions on Computers*, submitted 1990.

W. W. Hwu and P. P. Chang, "Efficient Instruction Sequencing with Inline Target Insertion," *IEEE Transactions on Computer*, accepted for publication.

University of Illinois at Urbana-Champaign

Prof. Wen-mei Hwu
Center for Reliable and High Performance Computing
Coordinated Science Laboratory
1101 W. Springfield Avenue
Urbana, Illinois 61801

(217) 244-8270
FAX: (217) 244-1764
USENET: ihnp4!uiucdcs!bach!hwu
CSNET: hwu@crhc.uiuc.edu

August 27, 1991

Dr. Keith Bromley
Code 7601 T
Naval Ocean Systems Center
271 Catalina Boulevard
San Diego, CA 92152-5000

Dear Dr. Bromley,

Enclosed please find the final report for grant N00014-88-K-0656 by Kent Fuchs and myself. In the last three years, this grant has resulted in several significant research results published in major conferences and journals. We have summarized these results in the report. Please feel free to contact us if there is any other information that we should provide regarding the project.

Our business office manager just informed us that he had yet to receive the final allocation of $8,000 from ONR to balance the account. Please transfer the fund at your earliest convenience.

All in all, we would like to thank you again for your support in the last three years. We look forward to discussing other research opportunities with you in the future.

Sincerely,

Wen-mei Hwu

Enclosure.