Applications Development for a Parallel COTS Spaceborne Computer

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Remote Exploration and Experimentation Project

REE Vision

Move Earth-based Scalable Supercomputing Technology into Space

Background

- Funded by Office of Space Science (Code S) as part of NASA’s High Performance Computing and Communications Program
- Started in FY1996

REE Impact on NASA and DOD Missions by FY03

Faster - Fly State-of-the-Art Commercial Computing Technologies within 18 months of availability on the ground

Better - Onboard computer operating at > 300MOPS/watt scalable to mission requirements (> 100x Mars Pathfinder power performance)

Cheaper - No high cost radiation hardened processors or special purpose architectures
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Objectives

• **High Power Performance:**
  – Obtain power efficiencies of 300-1000 MOPS per watt
  – Develop an architecture that scales to 100 watts (depending on mission needs)

• **Fault-tolerance through system software:**
  – Enable reliable operation for 10 years and more (tolerate transient as well as permanent errors)
  – Using commercially available or derived components
  – Includes application services (such as Algorithm-Based Fault Tolerance)

• **New spaceborne applications:**
  – Run in embedded high-performance computers
  – Return analysis results to the earth; not just raw data
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Overview

Feasibility?
Study Phase

>30 MOPS/watt
Scalable Testbed

>300 MOPS/watt
Flight Prototype

Fault-Tolerance  Real-Time

Activity Type:
- Computing Testbed
- System Software
- Science Applications

Demo spaceborne applications on embedded high-performance computing testbed

Scalable Applications I
Scalable Applications II
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REE Implementation

• Use COTS hardware and software to the maximum extent possible
  – Assume that memory supports EDAC
  – Assume hardware detection of “standard” exceptions, but assume that some faults will go undetected
  – Fault tolerance achieved through software

• Keep overhead low
  – Emphasize techniques which do not require replication

• Maintain architecture independence
  – Design should not be tied to any particular hardware architecture

• “95%” rule
  – System does not have to be continuously available
  – Reset is acceptable recovery technique

• Target large applications, both parallel and distributed
  – Gigabytes of memory, gigaflops of processing
  – Scalable with high efficiency
  – Static load balancing sufficient
Current Partnerships

USAF Phillips Lab
Improved Space Architecture Concepts (ISAC)

- Inter-program coordination on a regular basis
- Joint participation on technical reviews and procurement actions
- Technical interactions to avoid duplicate investments and identify possibilities for joint investment
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Science Application Teams

• Background
  – Enabling new and better science is a primary goal for REE
  – A new generation of Mission Scientists is emerging which sees the value of significant onboard computing capability
    • Mission Scientists still want the most data bits possible sent back to the ground
    • But bandwidth to the ground is stagnant, while instrument data rates continue to rise dramatically
    • Ground operations costs are a major component of mission costs

• Science Application Teams chosen to:
  – Represent the diversity of NASA onboard computing of the future
  – Drive architecture and system software requirements
  – Demonstrate the benefit of highly capable computing onboard

• Science Application Teams will:
  – Prototype applications based on their mission concepts
  – Port and demonstrate applications on the 1st Generation Testbed
  – Use their experiences with REE to influence some of their mission design decisions
 equivalents downlink bandwidth from Jupiter

Moore’s Law shows the rate of increase of processing power.
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Next Generation Space Telescope Team

REE Principle Investigator: Dr. John Mather, NGST Study Scientist

SCIENCE OBJECTIVES
- Study the birth of the first galaxies
- Determine the shape and fate of the universe
- Study formation of stars and planets
- Observe the chemical evolution of the universe
- Probe the nature of dark matter

TECHNOLOGY HIGHLIGHTS
- Precision deployable and inflatable structures
- Large, low area density cold active optics
- Removing cosmic ray interactions from CCD readouts
- Simulation based design
- Passive cooling
- Autonomous operations and onboard scheduling
NGST Hardware/Software Requirements

• **General Configuration (tentative)**
  – Sensing array feeds shared store through DSP glue
  – Image blocks (1Kx1K) stored in files and accessed by parallel nodes through shared bus (50 MB/s)
  – Highly data-parallel; little code parallelism desired
  – Many opportunities for data sanity checks, especially in optical calibration

• **Image Processing**
  – Fast scan of a large volume of image data to reject bad pixels
  – Image compression (possibility of feature identification)
  – Significant I/O per flop, but little IPC

• **On-Board Optical Calibration**
  – Reads image, extensive iteration, adjusts actuators
  – 2D FFT is iteration’s core: low I/O per flop, but significant IPC
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NGST Fine Figure Control Loop

PSF-

Wrapped Wavefront

Un-Wrapped Wavefront

Misell Algorithm

Phase Unwrap

DM Correct

Perfect PSF (Strehl = 1.00)

DM Corrected PSF (Strehl = 0.90)

Resultant Corrected PSF

DM Corrected Wavefront (RMS WFE = λ/20)

R.G. Lyon
OSCAR Project
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Gamma Ray Large Area Space Telescope

REE Principal Investigator: Professor Peter Michelson, Stanford University, GLAST Principle Investigator

- GLAST will probe active galactic nuclei (spectral shape and cutoff), study gamma-ray pulsars, respond in real-time to gamma-ray bursts.
- GLAST will produce 5-10 Megabytes per second after sparse readout, mapping into 50 MIPS of computing requirements to meet the requirements for the baseline mission.
- New science addressed by GLAST focuses on transient events of a few days in AGNs and .01–100 seconds in gamma-ray bursts.
- REE could enable GLAST to produce 10x this data volume if it were to do most of its background discrimination in software. This would allow real-time identification of gamma-ray bursts, and permit the mission scientists to extract secondary science from the “background.”

GLAST is a high-energy gamma-ray observatory designed for making observations of celestial sources in the range from 10 MeV to 300 GeV.
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GLAST Triggering System

Hardware:
Level I trigger causes strip detector states to be latched and read out to tower DRAM.

Software: ~ 2 Kops/event
Same process runs on each tower using only data local to the tower.

A Level II trigger by any tower requires data to be assembled from all towers for Level III analysis.

Software: ~ 1 Mops/event
“Share” load over pool of processors.

Trigger Criteria
Three Consecutive Layers
Linearity and Anti-veto
Full Reconstruction

Cache until downlink opportunity
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Orbiting Thermal Imaging Spectrometer

REE Principal Investigator - Alan Gillespie/U. Washington, Member of the ASTER Science Team

• Similar to Sacagawea:
  – Polar-orbiting high-resolution imaging infrared spectrometer (8-12 μm)
  – 64 bands of 12-bit data over a 21 swath at 30 m/pixel every 3.1 sec
  – Raw data rate of 30 MB/s
  – Designed to map emissivity of the Earth's surface to:
    • Map lithologic composition
    • Enable surface temperature recovery over all surfaces

• Onboard Processing
  – Characterize and compensate for atmospheric effects
  – Calculate land surface temperatures and emissivity spectra
  – Automatically convert the emissivity data to a thematic map
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Orbiting Thermal Imaging Spectrometer

Data Flow

Data Acquisition and Calibration

Atmospheric Compensation

Surface Temperature Estimation

Atmospheric Analysis and Correction

Temperature/Emissivity Separation

Correction for Sky Irradiance

Image Analysis

Data Compression

Transmit
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Solar Terrestrial Probe Program

REE Principal Investigator - Steve Curtis/GSFC    STPP Study Scientist

• Solar Terrestrial Probe Goal
  – Real-time quantitative understanding of the flow of energy, mass, momentum and radiation from the sun to the earth
    • Solar processes, flares and mass ejections
    • Interplanetary space and solar wind
    • Earth’s magnetosphere and upper atmosphere

• Mission Onboard Processing Applications - Data Reduction!
  – Magnetospheric Constellation Mission
    • 50-100 identical, spinning 10 kg spacecraft with on-board plasma analyzers (ions and electrons), a magnetometer and an electrometer
    • Compute moments of a sample plasma distribution function onboard
  – Low Frequency Radio Astronomy Imaging (ALFA/SIRA mission)
    • 16-64 formation flying spacecraft using interferometry to produce low frequency maps and two dimensional imaging of solar disturbances.
    • Compute pairs of time series (120+) to find the correlation maximum
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Solar Terrestrial Probe Control Flows

Magnetospheric Constellation
- Read data
- Gain calibration
- Calculate spacecraft potential
- Calculate plasma moments
- Compensate for unreliable data
  - Fit Gaussian
  - Calculate moments
  - Assess results
  - Store moment data

SIRA
- Read sensor data
- Calculate Fourier transforms
- Average spectrum in time
- Filter and calibrate
- Cross multiply to form spectra
- Inverse Fourier transform of reduced data
- Store Data
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Autonomous Mars Rover Science

REE Principal Investigator: R. Steve Saunders/JPL   Mars ‘01 Lander PI

• Autonomous optimal terrain navigation
  – Stereo vision
  – Path planning from collected data
  – Autonomous determination of experiment schedule
  – Opportunistic scheduling

• Autonomous Field Geology
  – “Computational Geologist”
  – The rover returns analysis - not only data
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Autonomous Mars Rover Science Application

Components for REE Testbed

- Rover Images
- Stereo Vision
- Image Segmentation
- Texture Analysis
- Range Map
- Segmented Image
- Texture Features
- Texture Classification
- Mineral & Chemical Composition
- Vehicle Path Planning and Motion Control
- Geology Database
  - composition
  - size & shape
  - location maps
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Fault Tolerance

• Project Goals - High Performance with Low Power Using COTS
  – COTS will get us to high power performance
  – SEUs (radiation-induced Single Event Upsets) will be an issue

• Traditional Fault Tolerance Approaches for Spaceborne Systems
  – Radiation hardening
  – Replication

• Both approaches have a power performance penalty we can’t live with!
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Software Implemented Fault Tolerance

• Approach - Hardware/Software in Combination for a “95%” solution
  – Characterize the fault rates and effects for “typical” (95% of) NASA missions
  – Characterize the range of application fault tolerance requirements
    • Simplex: Restart only for High Throughput Tasks
    • Duplex: Compare and restart only - for correct results which are not time critical
    • Triplex: Operate through
  – Partner with leading FT Experts to design “good enough” SIFT techniques
  – Validate SIFT techniques by testing and experimentation

• Remember - the missions which need REE most would, in our absence, have to throw away opportunities to acquire data!
Faults and Errors

• Radiation environment causes faults
  – Most (>99.9%) of faults are transient, single event upsets (SEUs)

• Faults cause errors
  – Good Errors
    • Cause the node to crash
    • Cause the application to crash
    • Cause the application to hang
  – Bad Errors
    • Change application data
      – Application may complete, but the output may be wrong

• System Software can detect the good errors
  – Restarting the application/rollback/reboot is acceptable

• Applications must detect bad errors
  – Using Algorithm-Based Fault Tolerance (ABFT), assertion checking, other techniques
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Algorithm-Based Fault Tolerance

- Started in 1984 with Huang and Abraham
  - Initial motivation was systolic arrays
  - Abraham and his students continued to develop ABFT throughout 1980s
- Relationship to convolutional coding noticed
- Picked up in early 90s by a group of linear algebraists (Boley et al., Boley and Luk)
- ABFT techniques exist for many numerical algorithms
  - Matrix multiply, LU decomposition, QR decomposition, single value decomposition (SVD), fast Fourier transform (FFT)
  - Require an error tolerance
    - setting of this error tolerance involves a trade-off between missing errors and false positives
- ABFT can correct as well as detect errors
  - Currently, we are focusing on error detection, using result checking
    - If (transient) errors are detected, the routine is re-run
Receiver Operating Characteristic (ROC) curves (fault-detection rate vs. false alarm rate) for random matrices of bounded condition number (< 10^8), excluding faults of relative size < 10^{-8}
We have implemented a robust version of ScaLAPACK (on top of MPI) which detects errors using ABFT techniques

- To the best of our knowledge, this is the first wrapping of a general purpose parallel library with an ABFT shell
- Interface the same as standard ScaLAPACK with the addition of an extra error return code
- For reasonable matrices, we can catch >99% (>97% for SVD) of significant errors with no false alarms

ABFT version of FFTW recently completed, not yet fully tested

- Interface the same as standard FFTW with the addition of an extra error return code
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REE Results-to-Date

- Scalable applications have been delivered
  - 8 of 9 proposed applications have been delivered to JPL
  - 3 are currently running on an embedded system
- ABFT-wrapped libraries have been developed for linear algebra, FFT
  - Linear algebra routines have been rigorously tested
  - Next step is for the applications to use these libraries under fault injection experiments
- Similar progress is being made in the other REE activities
  - Zeroeth generation testbeds on-line at JPL
    - Beowulf cluster and prototype embedded system
  - First generation embedded testbed is being fabricated by Sanders
    - Delivery to JPL scheduled for 11/99
  - System software is being developed
    - Fault injector, fault detection and recovery mechanisms, scheduler, etc…
- A number of questions still need to be answered…
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REE Milestones

CT5: Complete studies of technology projections for embedded scalable high-performance computing architectures in space

SS5: Demonstrate software-implemented fault tolerance on 1st generation embedded computing testbed

GC6: Demonstrate scalable applications on 1st generation embedded computing testbed

GC8: Demonstrate spaceborne applications on embedded high-performance computing testbed

SS6: Demonstrate real-time capability with software-implemented fault tolerance for embedded scalable computers

CT8: Install 1st generation scalable embedded computing testbed operating at 30-200 MOPS/watt

CT10: Demonstrate flight prototype embedded scalable computer operating at 300-1000 MOPS/watt


9/99 Project Restart
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Open Questions

• What fault rates and fault effects will occur?
  (radiation environment is known; effect of environment is unknown)

• What percentage of faults can be detected without replication?
  (using ABFT and other techniques to check for incorrect answers)

• What is the overhead and coverage of ABFT?

• Is checkpointing/rollback sufficient to recover from faults?

• Can the state of REE applications be made sufficiently small that the overhead of checkpointing is not prohibitive?