Multiple Embedded Processors for Fault-Tolerant Computing

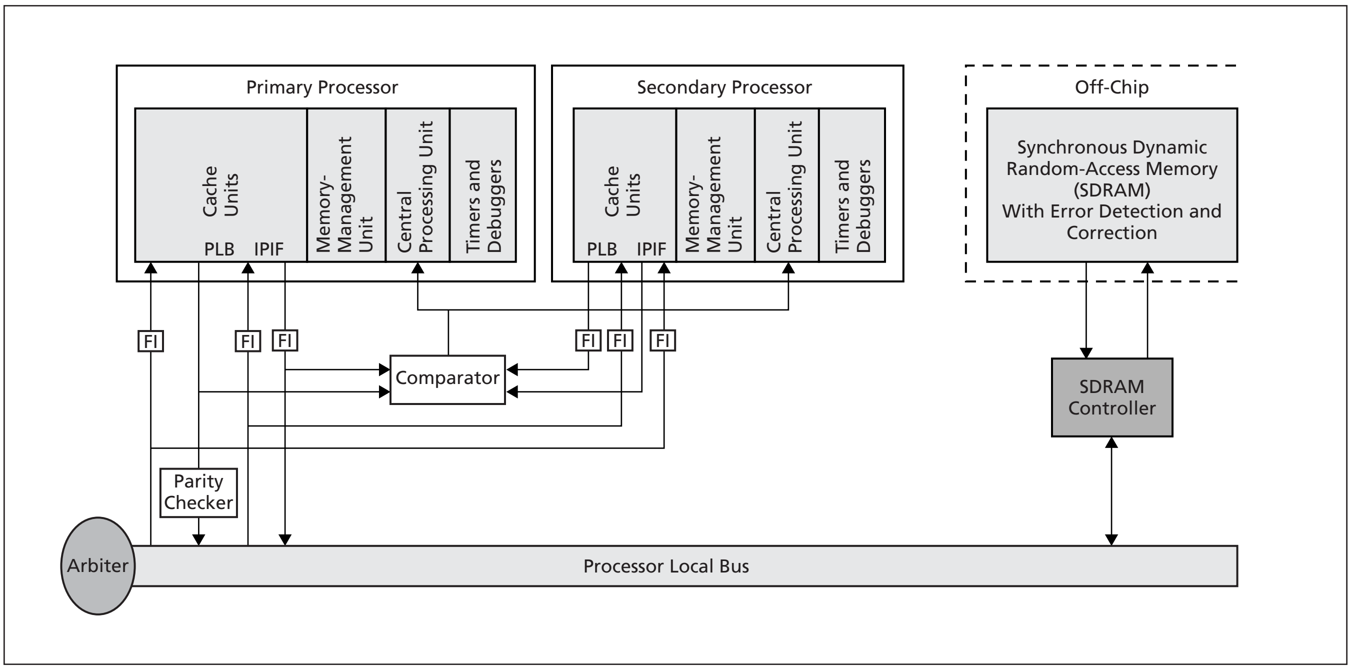
Outputs of processors would be compared to detect and correct bit errors.

NASA's Jet Propulsion Laboratory, Pasadena, California

A fault-tolerant computer architecture has been conceived in an effort to reduce vulnerability to single-event upsets (spurious bit flips caused by impingement of energetic ionizing particles or photons). As in some prior fault-tolerant architectures, the redundancy needed for fault tolerance is obtained by use of multiple processors in one computer. Unlike prior architectures, the multiple processors are embedded in a single field-programmable gate array (FPGA). What makes this new approach practical is the recent commercial availability of FPGAs that are capable of having multiple embedded processors.

A working prototype (see figure) consists of two embedded IBM PowerPC®405 processor cores and a comparator built on a Xilinx Virtex-II Pro FPGA. This relatively simple instantiation of the architecture implements an error-detection scheme. A planned future version, incorporating four processors and two comparators, would correct some errors in addition to detecting them.

This work was done by Gary Bolotin, Robert Watson, Sunant Katanyoutanant, Gary Burke, and Mandy Wang of Caltech for **NASA's Jet Propulsion Laboratory**. *Further information is contained in a TSP (see page 1).*
NPO-40575



Faults Are Detected in this prototype system by comparison of the outputs of the two processors, which are embedded in a single FPGA. The legend "FI" denotes locations where faults are inserted for testing purpose.

Hybrid Power Management

Ultracapacitors offer numerous advantages over rechargeable batteries.

John H. Glenn Research Center, Cleveland, Ohio

An engineering discipline denoted as hybrid power management (HPM) has emerged from continuing efforts to increase energy efficiency and reliability of hybrid power systems. HPM is oriented toward integration of diverse electric energy-generating, energy-storing, and energy-consuming devices in optimal configurations for both terrestrial and outer-space applications. The basic concepts of HPM are potentially applicable at power levels ranging from nanowatts to megawatts. Potential applications include terrestrial power-generation, terrestrial transportation, biotechnology, and outer-space power systems.

Instances of this discipline at prior stages of development were reported (though not explicitly labeled as HPM) in three prior *NASA Tech Briefs* articles: "Ultracapacitors Store Energy in a Hybrid Electric Vehicle" (LEW-16876), Vol. 24, No. 4 (April 2000), page 63; "Photovoltaic Power Station With Ultracapacitors for Storage" (LEW-17177), Vol. 27, No. 8 (August 2003), page 38; and "Flasher Powered by Photovoltaic Cells and Ultracapacitors" (LEW-17246), Vol. 24, No. 10 (October 2003), page 37. As the titles of the cited articles indicate, the use of ultracapacitors as energy-storage devices lies at the heart of HPM. An ultracapacitor is an electrochemical energy-storage device, but unlike in a conventional rechargeable electrochemical cell or battery, chemical reactions do not take place during operation. Instead, energy is stored electrostatically at an electrode/electrolyte interface. The capacitance per unit volume of an ultracapacitor is much greater than that of a conventional capacitor because its electrodes have much greater surface area per unit volume and the separation between the electrodes is much smaller.

Power-control circuits for ultracapacitors can be simpler than those for batteries, for two reasons: (1) Because of the absence of chemical reactions, charge and discharge currents can be greater than those in batteries, limited only by the electrical resistances of conductors; and (2) whereas the charge level of a battery depends on voltage, temperature, age, and load condition, the charge level of an ultracapacitor, like that of a conventional capacitor, depends only on voltage.

HPM offers many advantages over the conventional power-management approach in which batteries are used to store energy:

- Whereas a typical battery can be charged and discharged about 300 times, an ultracapacitor can be charged and discharged more than a million times. The longer lifetimes of ultracapacitors contribute to reliability; this is especially significant in such critical applications as medical and spacecraft power systems.
- The longer lifetimes of ultracapacitors greatly reduce life-of-system costs, including the indirect costs of maintenance and downtime.
- The longer lifetimes of ultracapacitors reduce adverse environmental effects, inasmuch as it will probably never be necessary to replace and dispose of ultracapacitors in most applications, whereas batteries must be replaced frequently.
- Disposal problems and the associated contributions to life-of-system costs can be reduced because the chemical constituents of ultracapacitors are less toxic and less environmentally harmful than are those of batteries. Indeed, ultracapacitors are somewhat recyclable.
- Excellent low-temperature performance makes ultracapacitors suitable for storing energy in applications at temperatures too low for batteries.
- The consistent performance of ultracapacitors over time enables reliable operation not possible with batteries.
- Unlike batteries, ultracapacitors can be safely left completely discharged for indefinitely long times.
- Whereas the charge-discharge efficiency in conventional power management using rechargeable batteries is typically about 50 percent, the charge-discharge efficiency in HPM typically exceeds 90 percent.

In an economically important class of applications, HPM can be combined with regenerative braking to increase fuel economy in hybrid electric land vehicles. This concept has been demonstrated in tests of NASA's Hybrid Electric Transit Bus, in which fuel economy was found to increase by 21 percent when regenerative braking with HPM was used.

This work was done by Dennis Eichenberg of **Glenn Research Center**. *Further information is contained in a TSP (see page 1).*

Inquiries concerning rights for the commercial use of this invention should be addressed to NASA Glenn Research Center, Innovative Partnerships Office, Attn: Steve Fedor, Mail Stop 4–8, 21000 Brookpark Road, Cleveland, Ohio 44135. Refer to LEW-17520-1.

Magnetometer Based on Optoelectronic Microwave Oscillator

This miniature instrument could also function as an atomic clock.

NASA's Jet Propulsion Laboratory, Pasadena, California

A proposed instrument, intended mainly for use as a magnetometer, would include an optoelectronic oscillator (OEO) stabilized by an atomic cell that could play the role of a magnetically tunable microwave filter. The microwave frequency would vary with the magnetic field in the cell, thereby providing an indication of the magnetic field. The proposed magnetometer would offer a combination of high accuracy and high sensitivity, characterized by flux densities of less than a picotesla. In comparison with prior magnetometers, the proposed magnetometer could, in principle, be constructed as a compact, lightweight instrument: It could fit into a package of about 10 by 10 by 10 cm and would have a mass <0.5 kg.

As described in several prior *NASA Tech Briefs* articles, an OEO is a hybrid of photonic and electronic components that generates highly spectrally pure microwave radiation, and optical radiation modulated by the microwave radiation, through direct conversion between laser light and microwave radiation in an optoelectronic feedback loop. As used here, "atomic cell" signifies a cell containing a vapor, the constituent atoms of which can be made to undergo transitions between quantum states, denoted hyperfine levels, when excited by light in a suitable wavelength range. The laser light must be in this range. The energy difference between the hyperfine levels defines the microwave frequency.

In the proposed instrument (see figure), light from a laser would be introduced into an electro-optical modulator (EOM). Amplitude-modulated light from the exit port of the EOM would pass through a fiber-optic splitter having two output branches. The light in one branch would be sent through an atomic cell to a photodiode. The light in the other branch would constitute the microwave-modulated optical output. Part of the light leaving the atomic cell could also be used to stabilize the laser at a frequency in the vicinity of the desired hyperfine or other quantum transition. The microwave signal from the output of the photodiode would be amplified (if necessary, as explained below) and fed back into the EOM. This system would oscillate if the amplification in the closed loop exceeded the linear absorption of the loop. The microwave amplifier may be unnecessary to sustain stable oscillations, depending on the power of the laser radiation at the photodetector and on particular features of the modulator and optical delay line.

As described in the preceding paragraph, the proposed instrument could function as either an atomic clock or a magnetometer: If the instrument were designed to lock the microwave oscillation to a clock transition (a suitable hyperfine or other quantum transition characterized by a frequency that does not vary measurably with applied fields), then the instrument would function as an atomic clock. If, on the other hand, the instrument were designed to utilize a transition having a frequency that varies with an applied magnetic field, then the