Thinking Small at the University of Kentucky

Although people often think of the primary contributions of computer technology as being PCs, the Internet, or supercomputing for "grand challenge" problems, by far the most direct impact of computer technology on society has been the ability to make a wide range of ordinary devices "intelligent." Programmable control is everywhere – except in devices that are too small to fit a microcontroller. The nanocontrollers we propose require orders of magnitude less circuitry, enabling nanocontrollers to fit alongside or under the devices they control in applications like:

- Imaging sensors used in digital cameras loose image quality due to applying the same gain and integration time settings to all pixels. With a nanocontroller *under each pixel*, each pixel can be adjusted independently and calibrated corrections for defects applied, yielding much greater dynamic range and lower noise.
- Chemical and/or biological sensor array chips use small changes in the electrical properties of carbon nanotubes to detect and measure the levels of a wide range of chemical and biological toxins; a million-sensor chip would naturally output a million weak analog signals to be decoded elsewhere. Placing a nanocontroller *under each sensor* not only allows calibrated correction of sensor defects in software, but also would allow data to be directly output as digital PPM concentrations of the toxins sensed – or even as digitized audio messages saying what protective gear is needed.
- DLP (Digital Light Processor) video projectors pivot tiny mirrors to turn pixels on or off with intermediate shades obtained by linear PWM (Pulse Width Modulation). However, human eyes respond logarithmically to light, and a using a nanocontroller *under each pixel* can correct the modulation for this, yielding smoother shading while simplifying off-chip control logic.

Not all nanocontroller applications are controlling physically small devices; for example, large programmable sheets of printed organic semiconductor materials offers equally impressive possibilities. To enable these and other applications, nanocontrollers must have the following properties:

- **Minimal Circuit Size**: no more than a few hundred transistors per nanocontroller
- **Predictable Real-Time Behavior**: computations must meet real-time control constraints
- **Localized Input/Output**: each nanocontroller must talk with the device it controls
- **Coordination As A Parallel Computer**: nanocontrollers must work together to reduce external I/O to an acceptable level (e.g., summarizing sensed values rather than passing them all off-chip)
- **Each Nanocontroller Independently Programmable**: nanofabricated devices often have significant manufacturing variations that require individualized correction, perhaps even different algorithms
- **Reprogrammability**: it must be possible (but not necessarily fast) to reprogram a part to correct for defects that develop over time or to enhance functionality

The key to this is actually a compiler technology that allows millions of independent programs to be merged into a single state machine while preserving relevant timing properties. This technology, called META-STATE CONVERSION, makes independent program memories unnecessary – nanocontroller circuit complexity is not proportional to program complexity! In combination with aggressive use of new compile-time optimization technologies (from gate-level logic optimization to a new genetic algorithm for code ordering and register allocation) and a very simple 1-bit datapath, digital nanocontrollers require at most a few hundred transistors; switched-analog nanocontrollers might be feasible using just a few dozen transistors.

As of Summer 2006, all the key nanocontroller technologies have been demonstrated except for the placement of logic under nanofabricated sensors. However, it will take a large-scale center integrating computer engineering systems research with nano- and micro- fabrication technologies to fully develop the approach and its applications. For more information, contact Prof. Hank Dietz via email **hankd@engr.uky.edu** or phone (859) 257 4701, or see **http://aggregate.org/KYARCH/**