Introduction to Embedded Systems
55:036
January 18, 2007

Acknowledgement

- The bulk of the material in this lecture is adapted from:

What is a Computer?

- Most of us think of “desktop” computers
  - PC’s
  - Laptops
  - Mainframes
  - Servers

- But, there is another kind of computing system that is far more common

Embedded Systems

- Embedded computing systems
  - Computing systems embedded within electronic devices
  - Hard to define. Nearly any computing system other than a desktop computer
  - Billions of units produced yearly, versus millions of desktop units
  - Perhaps 50 per household and per automobile
Embedded Systems are Everywhere

Picture is from the cover of Embedded Systems Design, A Unified Hardware/Software Approach, by Frank Vahid and Tony Givargis

A “short list” of embedded systems

Today, almost all nontrivial electronic systems include one or more embedded processors

Embedded Systems vs. Desktop Computing

• Most Embedded Systems are single-functioned
  – Executes a single program, repeatedly
• Generally, Embedded Systems are tightly-constrained
  – Low cost, low power, small, fast, etc.
• Most Embedded Systems are reactive and real-time
  – Continually react to changes in the system’s environment
  – Must compute results in “real-time”

An Embedded System Example: Digital Camera
Embedded Design Challenge: Optimizing Design Metrics

- Obvious design goal:
  - Construct an implementation with desired functionality
- Key design challenge:
  - Simultaneously optimize numerous design metrics
- Design metric
  - A measurable feature of a system’s implementation
  - Optimizing design metrics is a key challenge

Embedded Systems Design Metrics

- Common metrics:
  - Unit cost: the monetary cost of manufacturing each copy of the system, excluding NRE cost
  - NRE cost (Non-Recurring Engineering cost): The one-time monetary cost of designing the system
  - Size: the physical space required by the system
  - Performance: the execution time or response time of the system
  - Memory: The amount of memory required to hold the program and data
  - Power: the amount of power consumed by the system

Design Metrics May Be At Odds With One Another

- Expertise with both software and hardware is needed to optimize design metrics
  - Not just a hardware or software expert, as is common
  - A designer must be comfortable with various technologies in order to choose the best for a given application and constraints
Time-to-market: a Critical Design Metric

- Time required to develop a product to the point it can be sold to customers
- Market window
  - Period during which the product would have highest sales
- Average time-to-market constraint is about 8 months
- Delays can be costly

NRE and Unit Cost Metrics

- Costs:
  - Unit cost: the monetary cost of manufacturing each copy of the system, excluding NRE cost
  - NRE cost (Non-Recurring Engineering cost): The one-time monetary cost of designing the system
  - total cost = NRE cost + unit cost * # of units
  - per-product cost = total cost / # of units
- Example
  - NRE: $2000, unit: $100
    - For 10 units
      - total cost = $2000 + 10*$100 = $3000
      - per-product cost = $300
Amortizing NRE cost over the units results in an additional $200 per unit

The Performance Design Metric

- Widely-used performance measure, widely-abused
  - Clock frequency, instructions per second – not good measures
  - Digital camera example – a user cares about how fast it processes images, not clock speed or instructions per second
- Latency (response time)
  - Time between task start and end
  - e.g., Camera's A and B process images in 0.25 seconds
- Throughput
  - Tasks per second, e.g. Camera A processes 4 images per second
  - Throughput may involve more than just latency due to concurrency, e.g. Camera B may process 8 images per second (by capturing a new image while previous image is being stored).
- Speedup of B over A = B’s performance / A’s performance
  - Throughput speedup = 8/4 = 2

NRE and Unit Cost Metrics

- Compare technologies by costs – best depends on quantity
  - Technology A: NRE=$2,000, unit=$100
  - Technology B: NRE=$30,000, unit=$30
  - Technology C: NRE=$100,000, unit=$2

- But, must also consider time-to-market
Embedded Processor Technologies

- General-Purpose
- Single-Purpose
- Application-Tailored

General-Purpose Processors

- Programmable device used in a variety of applications
  - Also known as “microprocessor”
- Features
  - Program memory
  - General datapath with large register file and general ALU
- User benefits
  - Low time-to-market and NRE costs
  - High flexibility
- Intel “Pentium” the most well-known, but there are hundreds of others

Single-Purpose Processors

- Digital circuit designed to execute exactly one program
  - a.k.a. coprocessor, accelerator or peripheral
- Features
  - Contains only the components needed to execute a single program
  - No program memory
- Benefits
  - Fast
  - Low power
  - Small size

Application-Tailored Processors

- Programmable processor optimized for a particular class of applications having common characteristics
  - Compromise between general-purpose and single-purpose processors
- Features
  - Program memory
  - Optimized datapath
  - Special functional units
- Benefits
  - Some flexibility, good performance, size and power
A Key Player in Embedded Design: The Microcontroller

• Compromise between general-purpose and application-tailored processor
• Simple processor architecture
  – reduced instruction set and functionality
  – small data path (often only 4 or 8 bits versus 32 or 64 bits for typical general purpose processor)
• On-board memory (volatile and non-volatile)
• Multiple on-chip devices to support embedded applications
  – timers
  – digital I/O
  – serial I/O
  – support for various interfacing protocols—e.g. I²C
• Available in many different configurations, performance levels, etc.

Processor Comparison

<table>
<thead>
<tr>
<th>Processor</th>
<th>Clock speed</th>
<th>Periph. Bus Width</th>
<th>Memory</th>
<th>Peripherals</th>
<th>Power</th>
<th>Trans.</th>
<th>Price</th>
</tr>
</thead>
<tbody>
<tr>
<td>General Purpose Processors</td>
<td></td>
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<tr>
<td>Intel PIII 1GHz</td>
<td>2x16</td>
<td>L1, 256K</td>
<td>L2, MMX</td>
<td>32 ~900</td>
<td>97W</td>
<td>~7M</td>
<td>$900</td>
</tr>
<tr>
<td>IBM PowerPC 750X</td>
<td>550 MHz</td>
<td>2x32</td>
<td>L1, 256K</td>
<td>32/64 ~1300</td>
<td>5W</td>
<td>~7M</td>
<td>$900</td>
</tr>
<tr>
<td>MIPS R5000</td>
<td>250 MHz</td>
<td>2x32</td>
<td>2 way set assoc.</td>
<td>32/64 NA</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
<tr>
<td>StrongARM SA-110</td>
<td>233 MHz</td>
<td>None</td>
<td>268</td>
<td>1W</td>
<td>2.1M</td>
<td>NA</td>
<td>NA</td>
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<tr>
<td>Microcontroller</td>
<td></td>
<td></td>
<td></td>
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</tr>
<tr>
<td>Intel 8051</td>
<td>12 MHz</td>
<td>4K ROM, 128 RAM, 32 I/O, Timer, UART</td>
<td>8</td>
<td>~1</td>
<td>~0.2W</td>
<td>~10K</td>
<td>$7</td>
</tr>
<tr>
<td>Motorola 68HC811</td>
<td>3 MHz</td>
<td>4K ROM, 192 RAM, 32 I/O, Timer, SPI</td>
<td>8</td>
<td>~0.1W</td>
<td>10K</td>
<td>$5</td>
<td></td>
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<tr>
<td>Digital Signal Processors</td>
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</tr>
<tr>
<td>TI C5416</td>
<td>160 MHz</td>
<td>128K, SRAM, 3 T1, Ports, DMA</td>
<td>13</td>
<td>5</td>
<td>NA</td>
<td>NA</td>
<td>$34</td>
</tr>
<tr>
<td>Lucent DSP32C</td>
<td>80 MHz</td>
<td>16K Inst., 2K Data, Serial Ports, DMA</td>
<td>40</td>
<td>3</td>
<td>NA</td>
<td>NA</td>
<td>NA</td>
</tr>
</tbody>
</table>


The Advantages of Microcontrollers

• Low cost due to high volume production
• Low “chip count” due to integrated on-board features
• Good development tools and environments
• Extensive product families allow tailoring of processor to system design metrics
• Short product design cycles (compared to custom hardware design).
• Compatible with hardware/software co-design
  – Many microcontrollers are available as “VHDL Cores” for integration into a custom VLSI chip

Most Embedded Applications Require only Modest Computational Power

![Figure 1-3: Microcontroller unit shipments per year, vs. data word length (Dash/2)](image)
A Low End Microcontroller
PIC18F452 Microcontroller

PIC18F452 Features
• Clock rate up to 40 MHZ
• 32KB program memory (FLASH)
• 1536B data memory (RAM)
• 256B data EEPROM
• 35 digital I/O bits
• 4 timers
• 2 PWM/Capture/Compare modules
• UART for serial I/O
• 10-bit A/D converter (8 channels)
• 18 interrupt sources
• Cost: Approx $5.00 in quantity