EDF-DVS Scheduling on the IBM Embedded PowerPC 405 LP


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Why DVS?

- Energy management
  - vital design constraint especially in battery-constrained embedded systems

- Dynamic Voltage Scaling (DVS)
  - processor core voltage $\uparrow$ or $\downarrow$ depending on computation demands
    - $V \downarrow \iff f \downarrow$
    - $P \propto V^2 \times f$

- DVS in real time systems
  - calculate safe operation frequency
    - all tasks are guaranteed to meet its deadlines
Why PowerPC 405LP?

- Hardware support for DVS
- Software support to change voltage
  - via. user-defined operating points
    - for e.g., 266 MHz @ 1.8 V to 33 MHz @ 1 V
    - easy to define
  - can define any “stable” frequency/voltage pair
- ability to execute instructions even when frequency/voltage is changed
  - contemporary processors with DVS support enter sleep mode during frequency/voltage transitions
How?

- Real-time earliest deadline first (EDF) scheduling policy as part of user-level threads package under Linux
- 4 hard real-time software DVS techniques
  - static
  - cycle-conserving
  - look-ahead
  - feedback
- Oscilloscope and analog data acquisition board to measure voltage and current and calculate power
- Custom changes to the development board
  - separate measurements of voltage, current of processor, memory and I/O components
PowerPC 405LP

- Diskless Monta Vista Embedded Linux variant
- 50% reduced capacitance
  - DVS switching faster ($\leq 200 \mu s$)
- DVS switching
  - synchronous (blocking)
    - conventional DVS-capable processors
  - asynchronous (non-blocking)
    - execution may proceed during switch
PowerPC 405LP (cont.)

- System call for asynchronous switch
  - voltage ramped up to max
  - time to reach new voltage level is estimated

- High-resolution timer interrupt triggered
  - power management unit reprogrammed
  - new processor frequency activated
  - voltage settles in a controlled manner to new operating point
PowerPC 405LP (cont.)

- Dynamic power management (DPM) facility
  - defines stable operating points (frequency/voltage pairs)

- Operating states
  - system states (idle, task activity, sleep)

- DPM Policy
  - defines set of operating points for each operating state
  - synchronous switching

- DPM task state
  - allows application to select operating points
  - asynchronous switching
Implementation

- EDF Scheduler on 405LP under Linux
- Kernel-level threads
  - complex kernel modifications – error-prone
  - more control over execution
- User-level threads
  - simplicity of design
  - develop generic and portable threads library
  - facilitate easier debugging
  - less control over execution and resources
  - however, OS background activity minimal
### Static RT-DVS EDF

<table>
<thead>
<tr>
<th>Task</th>
<th>Exec time</th>
<th>Period</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>3</td>
<td>8</td>
</tr>
<tr>
<td>2</td>
<td>4</td>
<td>20</td>
</tr>
<tr>
<td>3</td>
<td>3</td>
<td>10</td>
</tr>
</tbody>
</table>

\[ U = \frac{3}{8} + \frac{4}{20} + \frac{3}{10} = 0.875 \]

\[ f = 0.875 \times f_{\text{max}} \]
Cycle-Conserving RT-DVS EDF

- $U = \frac{2}{8} = 0.25$
- $U = \frac{1}{8} + \frac{2}{20} = 0.3$
- $U = \frac{3}{8} + \frac{2}{20} + \frac{2}{10} = 0.675$

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Look-Ahead RT-DVS EDF

D₁ D₃
future T₁
future T₃

normalized freq

1
0.75
0.5
0.25
0
4
8
12
16
20
T₃
Feedback RT-DVS EDF

- Greedy scheme:
  - assign all idle time/slack to running task
- Assuming all other tasks at the maximum frequency (speed)
- Capitalize on early completion of current task
  - early completion \( \rightarrow \) more slack for other tasks
  - repeat scaling on next task
Worst-Case Timing Analysis

- No tool support to derive WCETs of tasks on PPC405LP
- Timing loop computes average execution of N instances of the task taking into account loop overhead and cold cache misses

\[ t_{work} = \frac{(t4 - t3) - (t2 - t1)}{N} \]
Experimentation Methodology

- Need to measure voltage/current at a high rate
  - Multimeters – coarse-grained and low precision
- High frequency analog data acquisition board
  - current measured as voltage level over a resistor with 1V drop per 360 mA
- Oscilloscope
  - visualizing voltages and currents
  - high precision
## Valid Frequency/Voltage Pairs

<table>
<thead>
<tr>
<th>Setting</th>
<th>0</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Frequency (MHz)</td>
<td>33</td>
<td>44</td>
<td>66</td>
<td>133</td>
<td>266</td>
</tr>
<tr>
<td>Voltage (volts)</td>
<td>1.0</td>
<td>1.0</td>
<td>1.1</td>
<td>1.3</td>
<td>1.7</td>
</tr>
</tbody>
</table>
## DVS Overhead

<table>
<thead>
<tr>
<th>Activity</th>
<th>Sync. DVS</th>
<th>Async. DVS</th>
<th>Signal handling</th>
</tr>
</thead>
<tbody>
<tr>
<td>Overhead</td>
<td>117-162 μs</td>
<td>8-20 μs</td>
<td>0.07-0.6 μs</td>
</tr>
</tbody>
</table>
# Task Sets

<table>
<thead>
<tr>
<th>Task</th>
<th>Task Set 1 (msec)</th>
<th>Task Set 2 (msec)</th>
<th>Task Set 3 (msec)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Period ($P_i$)</td>
<td>WCET ($C_i$)</td>
<td>Period ($P_i$)</td>
</tr>
<tr>
<td>1</td>
<td>2400</td>
<td>400</td>
<td>600</td>
</tr>
<tr>
<td>2</td>
<td>2400</td>
<td>600</td>
<td>320</td>
</tr>
<tr>
<td>3</td>
<td>1200</td>
<td>200</td>
<td>400</td>
</tr>
</tbody>
</table>

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Energy Savings of DVS Techniques

![Bar Chart]

- **Task Set 1**
- **Task Set 2**
- **Task Set 3**

Percentage energy savings w.r.t. naive DVS scheme:
- static
- CC
- LA
- fe

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Energy Savings of fast DVS modulation

![Bar chart showing energy savings of asynchronous DVS over synchronous DVS for different task sets.](chart)

- Task Set 1
- Task Set 2
- Task Set 3
Oscilloscope – Loose Task Set

- Static DVS, medium utilization, loose WCET
- Cycle-conserving DVS
- Look-ahead DVS, medium utilization, loose WCET
- Feedback DVS, medium utilization

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P=ac² conference 10/06/04
Oscilloscope – Tight Task Set

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Conclusions

- Successfully created an infrastructure for investigating EDF-DVS schemes on IBM PowerPC 405LP
- Benefits in energy reduction of up to 5% for fast DVS modulation
  - continue execution while switching voltage/frequency
- Aggressive real-time DVS scheduling algorithms can achieve up to 54% reduction in energy consumption over naive DVS scheme
  - energy over hyperperiod of real-time tasks
  - modulate both processor voltage and frequency