An Energy Characterization Framework for Software-Based Embedded Systems

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Outline

- Introduction
- Energy characterization framework
- Training bench generation
- Experimental results
- Summary
Power consumption at a processor on embedded system has a big portion.

Power Distribution in a PDA class sample device

Cliff Brake, Accelent Systems, Inc. (May, 2003)
Power consumption at a processor depends on the software being executed.

SW designer should think power dissipation by SW that he is developing.
Energy Analysis Tool

We propose a characterization technique to find a good energy model for a processor.

Fast, accurate, and processor-independent Instruction level energy estimation.

Analyze energy bottle neck from software

Use GDB as ISS
Experimental Result

Energy estimation for JPEG encoder executed on a M32R-II processor

- 2.5 hours
- < 1 min.

Energy estimation for JPEG encoder executed on a SH3-DSP processor

- 6 hours
- < 1 min.
Related Work (1/2)

High-level energy estimation

- Instruction-level modeling
  - Energy estimation by instruction-set simulator
  - Instruction level energy modeling by measuring the average power consumption of each instruction while executed in a loop


- Structural modeling of the underlying hardware architecture
  - Make power models by estimating capacitance on the circuit
  - Keep track of which units are accessed per cycle by cycle-level performance simulation

Our Approach

Energy Characterization

Target System (Netlist)  Cell Library  Training Bench  Target Software

Energy Consumption Model

Energy Estimation

\( P_1: \) # instruction/data cache misses
\( P_2: \) # taken branches executed
\( P_3: \) # load/store instructions executed

...  ...
Characterization-based energy estimation

Characterization-based macro-modeling

- Regression analysis to model software energy
- Model the energy consumption using linear expression

\[ E = \sum_{j=1}^{p} c_j P_j \]

- \( p \): number of parameters
- \( c_j \): corresponding coefficients
- \( P_j \): parameters of the model

\[
\begin{pmatrix}
P_{1,1} & P_{1,2} & \ldots & P_{1,p} \\
P_{2,1} & P_{2,2} & \ldots & P_{2,p} \\
\vdots & \vdots & \ddots & \vdots \\
P_{n,1} & P_{n,2} & \ldots & P_{n,p}
\end{pmatrix}
\begin{pmatrix}
E_1 \\
E_2 \\
\vdots \\
E_n
\end{pmatrix}
= \begin{pmatrix}
c_1 \\
c_2 \\
\vdots \\
c_n
\end{pmatrix} = \left( P^T P \right)^{-1} P^T E

Evaluate set of parameters
Obtain the energy consumption by low-level estimator
Obtain coefficient using regression analysis

Overview of Energy Characterization

- Energy consumption model based on linear expression
- Evaluate energy from each divided instruction frames

Energy consumption model:

\[ E_i' = c_1 P_{11} + c_2 P_{12} + c_3 P_{13} + \ldots \]

\[ E_2' = c_1 P_{21} + c_2 P_{22} + c_3 P_{23} + \ldots \]

\[ \vdots \]

\[ E_n' = c_1 P_{n1} + c_2 P_{n2} + c_3 P_{n3} + \ldots \]

Extract by instruction-set simulation

Estimate energy at gate level

Instruction frame 1

Instruction frame 2

\ldots

Instruction frame n

Solve the set of \( c_i \) which minimizes

\[ \sum_{i=1}^{n} | E_i' - E_i | \]
Error Sources of this characterization

- Parameter set selection
- Non-linear effects
- Training bench
- ...

Motivational Example

Training bench dominates model accuracy!!

What is expected for a ‘good’ training bench?
Criteria on Training Bench (1/2)

If parameter value of each frames is constant or mono-tone

Difficult to derive energy consumed by parameter

If parameter value of each frames is randomized

Suitable to derive energy consumed by parameter

Criterion 1

*Standard deviation of parameter value*
Criteria on Training Bench (2/2)

\[ E = c_1 P_1 + \ldots + c_{\text{cache \_miss}} P_{\text{cache \_miss}} + c_{\text{branch \_miss}} P_{\text{branch \_miss}} \]

If correlation is strong between two parameters

Difficult to derive energy consumption by each parameters

Criterion 2

Correlation between parameters
Training Bench Generation

Template of Training Bench

- Execute power hungry instructions repeatedly
- Produce many cache misses
- Produce many RAW hazards
- Produce many pipeline stalls

Instruction Trace

- Standard deviations of parameter values \( \sigma \)
- Correlation factors of two parameters \( \rho \)

\[ \forall \sigma > 100 \]
\[ \forall \rho < 0.5 \]
Experiment

- Target system

- Processors
  - M32R-II, SH3-DSP
  - 0.18 μm CMOS library
## Experimental Result - Energy estimation error

Compared to the gate level estimation

* _O : compiled with a “-O3” optimize option

<table>
<thead>
<tr>
<th></th>
<th>M32R-II</th>
<th>SH3-DSP</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Average Error</td>
<td>Maximum Error</td>
</tr>
<tr>
<td>JPEG</td>
<td>2.70 %</td>
<td>10.32 %</td>
</tr>
<tr>
<td>JPEG_O</td>
<td>6.09 %</td>
<td>16.46 %</td>
</tr>
<tr>
<td>MPEG2</td>
<td>1.54 %</td>
<td>3.97 %</td>
</tr>
<tr>
<td>MPEG2_O</td>
<td>1.78 %</td>
<td>5.15 %</td>
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<tr>
<td>compress</td>
<td>5.00 %</td>
<td>6.41 %</td>
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<td>compress_O</td>
<td>4.35 %</td>
<td>7.18 %</td>
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<td>FFT</td>
<td>1.55 %</td>
<td>6.87 %</td>
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<tr>
<td>FFT_O</td>
<td>1.45 %</td>
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<td>8.58 %</td>
</tr>
<tr>
<td>DCT_O</td>
<td>1.47 %</td>
<td>8.07 %</td>
</tr>
<tr>
<td>Total</td>
<td><strong>2.74 %</strong></td>
<td><strong>16.46 %</strong></td>
</tr>
</tbody>
</table>
Experimental Result

Energy estimation for JPEG encoder executed on a M32R-II processor

Energy estimation for JPEG encoder executed on a SH3-DSP processor
Summary

- Proposed energy characterization framework for processor-based embedded system
- Error is on an average 3% and worst case 16%

Future work
- Compare result to board level measurement
- Extend current work to multi-core processor systems
- Extend to systems running on RTOS
Thank You!