Leveraging Open-Source Power Measurement Standard Solution

Genesis of a new power measurement initiative

Patrick Titiano,
System Power Management Expert,
BayLibre co-founder.
www.baylibre.com
Problem Statement

• Power Management optimization is key for power-hungry battery-operated devices
  – Who never had to complain about its phone / smart watch / connected device not able to keep up a single day?

• But the community have limited power measurements equipment
  – Community boards (and even custom dev. boards) poorly designed for power measurements
    • Missing shunt resistors / probe points on key power rails
  – Expensive high-precision lab equipment
  – Existing low-cost solutions but with limited performances (i.e. accuracy)
  – No standard power measurement connector

• Risks:
  – Merging patches hurting device power consumption
  – Limited possibilities for hobbyists to provide/contribute to power-optimized open-source solutions

• The community needed a high-perf low-cost standard solution for power measurements
Menu of the Day

• Power Measurement Basics
  – Board Requirements
  – ADC resolution
  – Shunt Resistor selection

• The “ACME” Initiative
  – Rationale

• Demo

• Q & A
Power Measurement Basics

Test points, ADC resolution, Sampling Rates, Shunt Resistor selection, ...
Power Measurement Technique (1)

- To measure power, both voltage and current have to be measured.
  - \( P \) (Watt) = \( U \) (Volt) * \( I \) (Ampere)
Power Measurement Technique (2)

• To measure the supply voltage:
  – No extra onboard component required, but only 2 test points (Vdd + gnd) at current sink (e.g. SoC) ends.

• To measure the current consumption:
  – An additional shunt resistor shall be placed in series with the power line.
  – Following Ohm's law (U = R * I, i.e. I = V_{shunt} / R_{shunt}), by measuring the voltage drop at the resistor ends and knowing the resistor value, the current can be calculated.
  – Accurate current measurement requires high-precision shunt resistor.
    • As per Ohm's law, there is a 1 to 1 ratio between resistor value tolerance and measurement precision.
      – E.g. 5% resistor -> 5% current measurement accuracy, 0.1% resistor -> 0.1% current measurement accuracy
    • Also a very low temperature coefficient variation is required (e.g. 110ppm/°C)
Power Measurement Technique (3)

– The choice of the shunt resistor value is of highest importance
  • Further details in next slides

– Current and voltage are dynamic analog variables.
  • Must be sampled at a sufficient rate (e.g. > 1Ksample/s),
  • Otherwise good amount of consumed energy may be missed => inaccurate measurement

– Voltage and current shall be measured at the same time for proper instantaneous power consumption computation.

– Averaging power consumption of a given amount of \([U, I]\) measurements is done by averaging \((U \times I)\).
  • A common error is to average \(U\) and \(I\), then compute the \(U_{avg} \times I_{avg}\)
  • \(P_{avg} = \text{avg}(U \times I) \neq U_{avg} \times I_{avg}\)
Analog to Digital Conversion (1)

• It is actually all about voltage measurement
  – Current converted to voltage using a shunt resistor (Ohm's law)

• Analog voltage values converted to digital values by ADC (Analog to Digital Conversion) dedicated circuitry

• Some Key parameters in ADC component selection:
  – ADC Min/Max voltage
  – Resolution (8-bit, 12-bit, 16-bit, 24-bit, ...)
  – Sampling rate (1Ksample/s, 1Msample/s, ...)
  – Minimum offset
Shunt Resistor Selection (1)

• The value of the shunt resistor is dictated by:
  – The ADC voltage range \( (V_{shunt_{max}}, V_{shunt_{min}}) \)
  
  – The current range to be measured:
    • \( R_{shunt} = \frac{V_{shunt_{max}}}{I_{shunt_{max}}} \)

  – The acceptable voltage drop supported by the device to be measured:
    • E.g. device requiring 5V ± 5%, then \( V_{shunt_{max}} < 250\text{mV} \)

  – The max. power the resistor can dissipate:
    • \( P_{shunt} = R_{shunt} \times I_{shunt_{max}}^2 \)
Shunt Resistor Selection Example (1)

• Example:
  – Conditions:
    • ADC TI INA226:
      – 16-bit ADC,
      – $V_{\text{shunt max}} = 81.92\text{mV}$,
      – $V_{\text{shunt min}} = 2.5\text{uV}$
    • $I_{\text{max}} = 1.5\text{A}$
    • Device operating range: $5V \pm 5\%$
  – Matching shunt resistor:
    • $R_{\text{shunt}} = 54.6\text{m}\Omega \approx 50\text{m}\Omega$
    • $P_{\text{shunt}} = 0.123\text{W} \Rightarrow 1/2\text{W shunt resistor OK}$
    • $V_{\text{shunt max}} = 81.92\text{mV} < 250\text{mV} \Rightarrow$ within device operating range
## Shunt Resistor Selection Example (2)

### Shunt Voltage vs Acceptable Drop-Out & INA226 Shunt Voltage Input Range

<table>
<thead>
<tr>
<th>shunt value (ohms)</th>
<th>current range (A)</th>
<th>Contact value (ohms)</th>
<th>Contact drop (V)</th>
<th>shunt power (W)</th>
<th>acceptable drop-out (V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.005</td>
<td>5</td>
<td>0.02</td>
<td>0.1</td>
<td>0.125</td>
<td>0.05</td>
</tr>
<tr>
<td>0.005</td>
<td>4</td>
<td>0.02</td>
<td>0.08</td>
<td>0.08</td>
<td>0.02</td>
</tr>
<tr>
<td>0.005</td>
<td>3</td>
<td>0.02</td>
<td>0.06</td>
<td>0.045</td>
<td>0.015</td>
</tr>
<tr>
<td>0.005</td>
<td>2</td>
<td>0.02</td>
<td>0.04</td>
<td>0.02</td>
<td>0.01</td>
</tr>
<tr>
<td>0.005</td>
<td>1</td>
<td>0.02</td>
<td>0.02</td>
<td>0.005</td>
<td>0.005</td>
</tr>
<tr>
<td>0.005</td>
<td>0.5</td>
<td>0.02</td>
<td>0.01</td>
<td>0.0013</td>
<td>0.0025</td>
</tr>
<tr>
<td>0.005</td>
<td>0.25</td>
<td>0.02</td>
<td>0.005</td>
<td>0.0003</td>
<td>0.0025</td>
</tr>
<tr>
<td>0.005</td>
<td>0.1</td>
<td>0.02</td>
<td>0.002</td>
<td>0.0003</td>
<td>0.0005</td>
</tr>
<tr>
<td>0.005</td>
<td>0.05</td>
<td>0.02</td>
<td>0.0002</td>
<td>0.0003</td>
<td>0.0005</td>
</tr>
<tr>
<td>0.005</td>
<td>0.01</td>
<td>0.02</td>
<td>2E-05</td>
<td>5E-06</td>
<td>5E-06</td>
</tr>
</tbody>
</table>

| 0.1                | 5                | 0.02                 | 0.1              | 2.5            | 5E-06                   |
| 0.1                | 4                | 0.02                 | 0.06             | 1.0            | 5E-06                   |
| 0.1                | 3                | 0.02                 | 0.06             | 0.9            | 0.3                     |
| 0.1                | 2                | 0.02                 | 0.04             | 0.4            | 0.2                     |
| 0.1                | 1                | 0.02                 | 0.02             | 0.1            | 0.1                     |
| 0.1                | 0.5              | 0.02                 | 0.01             | 0.025          | 0.05                    |
| 0.1                | 0.25             | 0.02                 | 0.005            | 0.0063         | 0.025                   |
| 0.1                | 0.1              | 0.02                 | 0.002            | 0.001          | 0.01                    |
| 0.1                | 0.05             | 0.02                 | 0.001            | 0.0003         | 0.005                   |
| 0.1                | 0.01             | 0.02                 | 0.0002           | 1E-05          | 0.001                   |
| 0.1                | 0.001            | 0.02                 | 2E-05            | 1E-07          | 0.0001                  |

**InA226 measure range:**
- 10μV to 81.92mV
- Voltage range: 0 - 2V, 2V - 4V, 4V - 5V, 5V - 12V

- Close to ADC limits
- Exceed shunt max power (1/2W)
- Exceed accepted drop-out

- Shunt voltage (V)
Assessing Current Measurement Range

• Depending on shunt resistor value and ADC characteristics, different current ranges may be measured
  – With full ADC performance (all ADC bits relevant)
  – With reduced but acceptable performance (not all ADC bits used)

• Example:
  – TI INA226: 16-bit ADC, $V_{\text{shunt}} = [81.92\,\text{mV} - 2.5\,\mu\text{V}]$
  – Shunt Resistor: $10\,\text{mΩ} / 500\,\text{mW}$
  – => optimum range: $[0.5\,\text{A} - 5\,\text{A}]$ (at least 10 bits relevant)
  – => extended range: $[1\,\text{mA} - 0.5\,\text{A}]$ (only 3 to 10 bits relevant)
**Current Measurement Range Example**

Exceeds accepted drop-out (considering $13\text{m}\Omega$ contact resistance (HE10 connector))

Bits not significant (voltage close to ADC limits)
The “ACME” initiative

Another Cute Measurement Equipment

Objectives, key features & decisions, status
ACME Cape: Why?

• As power management experts, we used to be frustrated by the existing equipment, either
  – Not matching our needs / not adapted,
  – Windows-only / not Linux-friendly,
  – Proprietary drivers,
  – Limited/ not flexible proprietary application suite,
  – Limited automation capabilities,
  – Too expensive,
  – Too complicated to use,
  – Not accurate enough,
  – Lack of standard power measurement connector (ad hoc solutions only)
  – ...

• => We decided to close all these gaps and provide the community with the most flexible low-cost but high-perf solution
  – Challenging, isn’t it?! 😊
ACME Cape: key requirements

- Main target: hobbyists
- Leverage main community boards
- Current, Voltage, Power, Temperature measurements
- Multi-channel
- Full Open Source SW suite, from drivers up to apps
- Support data post-processing
- Support automation
- Support remote power-switching
- Support USB, Jack power connection
- Support most common embedded devices current range
- Define a standard power measurement connector
- Low-cost / High-perf / Evolutive
ACME Cape: Here It Is!
ACME Cape: Key Features

• Leverage Beagle Bone Black for data processing (1GHz CPU)
• Multi-channel
  – 8, up to 16 with Cape stacking
• All-in-one solution for power measurement, power control, and temperature measurement
• Flexible / Evolutive
  – Extension connector for use with other HW than BBB
  – New probes can be designed, w/o HW change required on ACME cape
• Complete Open Source SW Suite
• Standard ACME Probe Connector (free of charge)
• Low-cost
ACME Cape: Key Decisions

• Probes include the ADC for best accuracy
  – No more long wires between shunt and ADC

• Use TI INA226 & TMP435 components featuring upstream Linux drivers

• Flexible Client/Server SW Architecture
  – To handle any sort of usage (local/remote/simultaneous/…)

• Define a standard low-cost power measurement connector (free of charge) and provide power probes following this standard

• Scalable HW design to reduce cost
ACME Cape: Standard PM Connector

• Objectives:
  – Provide a standard way to get development board ready for power measurements
    • No more HW modification
  – Get rid of proprietary / ad hoc solutions
    • Today: new board = new HW tweaks = no reuse
  – Ultra low-cost, low footprint, easy integration for board manufacturers
  – Open standard / free of charge (no licensing fee)

• Our solution: the ACME Probe Connector
  – Leveraging good old world-famous HE10 connector
  – Handle up to 6A (3A single line)
  – Shunt resistor may or may not be populated on the PCB
    • HE10 ACME probes available with or without shunt resistor
  – Proof of concept demonstrated on SAMA5D3-XPlained board
## ACME Cape vs NI-DAQ

<table>
<thead>
<tr>
<th>Feature</th>
<th>NI-DAQ NI USB-6002</th>
<th>ACME Solution</th>
</tr>
</thead>
<tbody>
<tr>
<td>ADC Resolution</td>
<td>16-bit</td>
<td>16-bit</td>
</tr>
<tr>
<td>Sample rate</td>
<td>6 Ksamples/s</td>
<td>7 Ksamples/s</td>
</tr>
<tr>
<td>Accuracy</td>
<td>6 mV</td>
<td>2.5 uV</td>
</tr>
<tr>
<td>Channels</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>(only 4 for power meas. (U + I))</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Power Probes (incl. shunt)</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>USB Power Probe</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Jack Power Probe</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Standard Power Connector</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Temperature Probes</td>
<td>No</td>
<td>Yes</td>
</tr>
<tr>
<td>Remote Power Control</td>
<td>No (only I/O avail.)</td>
<td>Yes</td>
</tr>
<tr>
<td>Visualization App.</td>
<td>Yes (proprietary, MS Windows)</td>
<td>Yes (multi-platforms)</td>
</tr>
<tr>
<td>Remote Control App.</td>
<td>Yes (LabVIEW)</td>
<td>Yes</td>
</tr>
<tr>
<td>Automation</td>
<td>Yes (LabVIEW)</td>
<td>Yes (scripting)</td>
</tr>
<tr>
<td>Open Source drivers &amp; app.</td>
<td>No</td>
<td>Yes!</td>
</tr>
</tbody>
</table>
ACME Cape: Status

• First batch of capes and probes built & fully operational:
  – 20x capes
  – 40x HE10 probes
  – 20x Jack probes
  – 20x USB probes
  – 20x temperature probes

• Version 0.1 of SW Suite available, including:
  – Server (daemon) running on Beagle Bone Black
  – Pseudo real-time visualization browser application
  – Pseudo real-time visualization Qt5 application
  – Automation tools
  – Dedicated web page: www.baylibre.com/acme
  – Feedback e-mail: acme@baylibre.com

• Opening beta testing /feedback collection phase
  – Recruiting beta testers, please apply! 😊
ACME Cape: What’s next?

- Beta testing /feedback collection phase
  - We need you! ☺
  - acme@baylibre.com

- Continue SW suite development

- Prepare HW rev. B
  - Reduce production cost towards mass production

- Prepare Kickstarter funding for larger production – Early 2015

- Get the ACME probe connector adopted by board manufacturers

- Finally become your preferred solution for power measurements ☺
Demo

Multi-channel power measurement
Thank you!