Normally-Off MCU Architecture for Low-power Sensor Node

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Outline

- Introduction
- Lower power requirements of sensor nodes in smart society
- Challenges for low-power sensor node
- Proposal for normally-off architecture for low-power sensor node
- Summary and Conclusions
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Paradigm shift for power savings

- Intermittent system operation by NVRAM will be a promising solution to low-power requirements.

SRAM based operation:
- Active
- Standby
- Large SRAM standby leak

eFlash based operation:
- Active
- Standby
- eFlash start-up
- Data evacuation to eFlash

NVRAM based operation:
- Active
- Standby

Features:
- Fast power-on/off
- No DC current during standby

Advantages:
- Very low power consumption
- Reliability improvement of Trs in peripheral circuits
“Normally-off computing technology” is enable to cut off the power, except for the component in work truly even in operation as a system, with synergy of NVRAM and power gating technology.

Maximize the power-off period with activity localization

Dependence of activity

- If $t < \text{BET}$, No chance for Power-Off
- If $t > \text{BET}$, Chance for Power-Off

Unit A
- Activity Localization
- Unit B
- $\text{op}2 \rightarrow \text{op}3 \rightarrow \text{op}4 \rightarrow \text{op}7$
- $\text{op}1 \rightarrow \text{op}5 \rightarrow \text{op}6 \rightarrow \text{op}8$
Technologies to realize “Normally-Off Computing”

- Power-Off as long as possible, as large area as possible, if QOS is satisfied.
- Power-Off during IDLE-Time of circuits, function blocks, chips, units and systems.
- Application-independent Computing Platform based on Power-gating, Software-control and OS API.

“Normally-Off Computing” is a System-level platform technology with combining HW and SW technologies.
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Cyber-Physical System is a fundamental technology in Smart City

- The advanced service can be realized with collecting real-time information in the social and natural environments.

Therefore, sensor nodes become used extensively to gather the real-time information.
Production volume of Sensor Node

- Production Volume: ~10B pcs/year
- This volume will be much increased with the development of cyber-physical systems.

It becomes very important how to reduce the power consumption of huge sensor nodes.

**PC & Server**
- 0.3B pcs/year

**Mobile Phone & Terminal**
- 1.5B pcs/year

**Embedded Sensor-node**
- 10B pcs/year

(Production Volume: 2011 Data)
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Conventional Sensor node

- Sensor-modules are in “Normally-On”.
- Microcontroller is in “Normally-On” or “Intermittent”.

[Diagram showing sensor nodes and microcontroller connections]
Challenge for Low-power Sensor nodes

**Power consumption change of sensor nodes**

- **Istby (~10uA)**
- **Power On Overhead**
- **50ms~10s**
- **50ms~10s**
- **Power (Data communication)**
- **Sensing**
- **CPU processing**
- **50us~100ms**

**Breakdown of power consumption of sensor system**

- **MCU (Stand-by): 66%**
- **Sensor (Always Power-on): 13%**
- **MCU (Active): 10%**
- **Telecom: 11%**

**Challenge for low-power consumption**

- Maximize power-off period. (MCU and Sensor is power on, when necessary)
- Reduce the active current.
Power On/Off Overhead

- Power On and Off has Power and Time overhead.
- “Normally-off Computing” should manage the overhead to reduce total-power.

Maximize Power-Off period
- Longer Off-time, and More frequently

Minimize Power-on energy
- Lower active current, and Shorter On-time
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Normally-Off Architecture for Low-power Sensor node

- Sensor-modules are in “Normally-Off”.
- Microcontroller is in “Normally-Off”.

![Diagram of Normally-Off Architecture for Low-power Sensor node]
Normally-Off Architecture for Low-power Sensor node (Continue)

- Challenge is how to control the following key components.
  - Normally-Off Power Manager (a)
    - “Power Manager” controls power on/off in all units with data of “Power Statement Register”, and
    - Manages task-level scheduling for activity localization.
  - Sensor Controller (b)
    - Simple processing (e.g. data sampling) which was carried out in the microcontroller, are performed in “Sensor Controller”.
  - Sensor Data Buffer (c)
    - Sensor data are stored in “Sensor Data Buffer”. After that, microcontroller performs the processing at once to reduce the number of power-on of microcontroller.
Normally-Off Architecture for Low-power Sensor node (Continue)

- CPU in Microcontroller (d)
  - Proposed architecture is consists of heterogeneous CPUs with Sensor Controller(b) and CPU(d).
  - Sensor required high load task, such as a Image sensor, is directly processed at CPU(d).
  - Task processed at Sensor Controller(b) and CPU(d) respectively should be optimized with task-level scheduling method.

Thus, it is possible to reduce the operating frequency of the microcontroller, and to maximize the power-off time of microcontroller.
Normally-Off Power Management (1)
Autonomous standby mode transition

- Current microcontroller has some standby modes.
- “Normally-Off Power Manager” also supports the “Autonomous standby mode transition technology” to select optimal standby mode for programmer’s usability improvement.

![Graph showing consumption energy and task cycle with standby modes and Break Even Times (BETs).](Image)
Normally-Off Power Management (2)

**Activity Localization technology**

- Sensing data is buffered in sensor data buffer, and after that, microcontroller is activated and performed the process at once.

- It is possible to optimize the number of power on/off cycles and decrease power consumption energy.

**Conventional PG control**

- Sensor → MCU

**Hierarchical PG control**

- Sensor → Sensor data buff. → MCU

Equations:

- \( T_{d}' := T_d - T_{buf} \) effective deadline
- \( T_{buf} \) : buffer OH

Diagram:

- Time scale with Power-on and Stand-by phases.
- Data sampling and processing for \( N \) inst. bundle.
Evaluation Board

- Evaluation board is consist of,
  - Sensor (Temperature, Brightness, Pyroelectric (Motion))
  - Microcontroller
  - Other Peripheral circuits
Evaluation Results

- Power consumption energy is reduced by 67%.

[Diagram showing energy consumption comparison between conventional and hierarchical PG control.]

[Condition]
- 3 sensors (Temp., Brightness, Pyroelectric)
- Sampling cycle = 1s
- Processing period = 4ms
- Room temp.
Demonstration of Normally-Off Microcontroller system

- Demonstrate effectiveness and adaptability of normally-off microcontroller system.
- Demand transportation system with Normally-Off sensors (Pyroelectric, Camera) are under development as a demonstration with Future University Hakodate.

Demand transportation system based on Intelligent bus stop
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Summary and Conclusion

- Production volume of sensor nodes is much increased with the development of cyber-physical systems.

- Normally-off architecture of microcontroller for future low-power sensor node has been proposed to reduce the power consumption of huge sensor nodes.

- To realize true low-power effects with normally-off computing technology, a co-design of hardware and software technology is very important.

- In this work, the power consumption energy is reduced by 67%.

- Normally-Off Computing is a candidate for future low power sensor networks.
Thank you for your attention.