Synchronous Programming of Device Drivers for Global Resource Control in Embedded Operating Systems

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Supervisors: Florence MARANINCHI & Laurent MOUNIER

Synchrone Team

Synchron 2010

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Context: Wireless Sensor Networks

Components

- $\mu$-Controller (MCU)
- Radio Transceiver(s)
- Sensors
- Battery
- ...
Context: Wireless Sensor Networks

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- Radio Transceiver(s)
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Constraints, Problems

- Slow Computations
- Small Memory
- Battery-Awareness
- ...

Context: Wireless Sensor Networks
Example WSN Hardware Platform

Wsn430

Diagram showing the hardware platform with blocks labeled CPU, MCU, ROM, RAM, and Timers.
Example WSN Hardware Platform

Wsn430
Example WSN Hardware Platform

Wsn430
Example WSN Hardware Platform

Wsn430
Example WSN Hardware Platform
Wsn430

- MCU
- ROM
- RAM
- Timers
- I/O
- GPIO
- USART0
  - I^2C
  - SPI
  - UART
- USART1
  - SPI
  - UART
- LEDs
- Humid.
- SID
- Radio
- Flash
Example WSN Hardware Platform

Wsn430

Shared Resources (Hardware Modules, Buses...)
Hardware Behavior: MCU Automaton

TI MSP430 Operating Modes

Discrete States
**Hardware Behavior: MCU Automaton**

**TI MSP430 Operating Modes**

- **Discrete States**
- **Power Consumption**

---

**Figure 2-10. MSP430x1xx Operating Modes For Basic Clock System**

<table>
<thead>
<tr>
<th>Mode</th>
<th>CPU and Clocks Status</th>
</tr>
</thead>
<tbody>
<tr>
<td>LPM0</td>
<td>CPU Off, MCLK Off, SMCLK On, ACLK On</td>
</tr>
<tr>
<td>LPM1</td>
<td>CPU Off, MCLK Off, SMCLK On, ACLK On</td>
</tr>
<tr>
<td>LPM2</td>
<td>CPU Off, MCLK Off, SMCLK Off, DCO Off, ACLK On</td>
</tr>
<tr>
<td>LPM3</td>
<td>CPU Off, MCLK Off, SMCLK Off, DCO Off, ACLK On</td>
</tr>
<tr>
<td>LPM4</td>
<td>CPU Off, MCLK Off, DCO Off, ACLK Off</td>
</tr>
</tbody>
</table>

- **Active Mode**
  - CPU Is Active
  - Peripheral Modules Are Active

- **LPM0**
  - CPU Off, MCLK Off, SMCLK On, ACLK On
  - DC Generator Off if DCO not used in active mode

- **LPM1**
  - CPU Off, MCLK Off, SMCLK On, ACLK On
  - DC Generator Off if DCO not used in active mode

- **LPM2**
  - CPU Off, MCLK Off, SMCLK Off, DCO Off, ACLK On
  - DC Generator Off

- **LPM3**
  - CPU Off, MCLK Off, SMCLK Off, DCO Off, ACLK On

- **LPM4**
  - CPU and all clocks disabled

---

**Figure 2-9. Typical Current Consumption of 13x and 14x Devices vs Operating Modes**

- **VCC**
  - 3 V
  - 2.2 V

<table>
<thead>
<tr>
<th>Operating Modes</th>
<th>AM</th>
<th>LPM0</th>
<th>LPM2</th>
<th>LPM3</th>
<th>LPM4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Current (µA)</td>
<td>340</td>
<td>70</td>
<td>65</td>
<td>17</td>
<td>2</td>
</tr>
</tbody>
</table>

- **ICC @ 1 MHz**
  - VCC = 3 V
  - VCC = 2.2 V
Hardware Behavior: Radio Automaton

Chipcon CC1100 Simplified Control State Diagram

**Default state when the radio is not receiving or transmitting. Typ. current consumption: 1.6 mA.**

- **IDLE**
  - Used for calibrating frequency synthesizer upfront (entering receive or transmit mode can then be done quicker). Transitional state. Typ. current consumption: 8.2 mA.
  - Default state when the radio is not receiving or transmitting. Typ. current consumption: 1.6 mA.

**Frequency synthesizer on**

- Frequency synthesizer is ready to start transmitting. Transmission starts very quickly after receiving the STX command strobe. Typ. current consumption: 8.2 mA.
- Frequency synthesizer startup, optional calibration, settling
  - Frequency synthesizer is turned on, can optionally be calibrated, and then settles to the correct frequency. Transitional state. Typ. current consumption: 8.2 mA.

**Procedure**

1. **IDLE**
   - IDLE
   - TX FIFO underflow
   - RX FIFO overflow
   - Optional freq. synth. calibration

2. **Transmit mode**
   - TX FIFO underflow
   - RX FIFO overflow
   - Optional freq. synth. calibration
   - TX OFF MODE = 00
   - RX OFF MODE = 00
   - TX MODE = 00
   - RX MODE = 00
   - Optional transitional state. Typ. current consumption: 8.2 mA.

3. **Receive mode**
   - TX FIFO underflow
   - RX FIFO overflow
   - Optional freq. synth. calibration
   - TX OFF MODE = 00
   - RX OFF MODE = 00
   - TX MODE = 00
   - RX MODE = 00
   - Optional transitional state. Typ. current consumption: 8.2 mA.

**Typical current consumption**

- Typ. current consumption: from 14.4 mA (strong input signal) to 15.4 mA (weak input signal).
- Typ. current consumption: 13.5 mA at -6 dBm output, 16.9 mA at 0 dBm output, 30.7 mA at >10 dBm output.

**Lowest power mode.**

- Most register values are retained.
- Current consumption typ 400 nA, or typ 900 nA when wake-on-radio (WOR) is enabled.

**Sleep**

- All register values are retained. Typ. current consumption: 0.16 mA.

**Crystal oscillator off**

- In FIFO-based modes, reception is turned off and this state entered if the RX FIFO overflows. Typ. current consumption: 1.6 mA.
Hardware Behavior: Radio Automaton

Chipcon CC1100 Simplified Control State Diagram

+ ADC + MCU + Flash Memory + ...
Hardware Behavior: Radio Automaton

Chipcon CC1100 Simplified Control State Diagram

+ ADC + MCU + Flash Memory + ...

Control of Global Power Consumption?

Typ. current consumption: 13.5 mA at -6 dBm output, 16.9 mA at 0 dBm output, 30.7 mA at +10 dBm output.

In FIFO-based modes, transmission is turned off and this state entered if the TX FIFO becomes empty in the middle of a packet. Typ. current consumption: 1.6 mA.

Typ. current consumption: 13.5 mA at -6 dBm output, 16.9 mA at 0 dBm output, 30.7 mA at +10 dBm output.

In FIFO-based modes, reception is turned off and this state entered if the RX FIFO overflows. Typ. current consumption: 1.6 mA.

Typ. current consumption: from 14.4 mA (strong input signal) to 15.4 mA (weak input signal).

Optional transitional state. Typ. current consumption: 8.2 mA.

Typ. current consumption: 8.2 mA.
Programming WSNs: Usual Practice

Applications

Operating System Support / Abstractions

- Multitasking
- System Services
- Hardware Device Drivers
Programming WSNs: Usual Practice

Applications

Operating System Support / Abstractions

▶ Multitasking
▶ System Services (Network Stack, File Systems…)
▶ Hardware Device Drivers
Programming WSNs: Usual Practice

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Operating Systems Programming for WSNs

- Device Drivers designed *Locally*

(Network Stack, File Systems...)
Programming WSNs: Usual Practice

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- *Ad hoc* Solutions for Resource Management & Power-Awareness
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(Network Stack, File Systems...)

Operating Systems Programming for WSNs

- Device Drivers designed \textit{Locally}
- \textit{Ad hoc} Solutions for Resource Management & Power-Awareness

⇒ Decentralized Knowledge!
Problems

Recap
Problems

Recap

- Shared Resources
Problems

Recap

- Shared Resources
- Power Management
Problems

Recap

- Shared Resources
- Power Management

➡️ Need for Global Control!
Outline

- Preliminary Remarks
- Proposal
- Implementation
- Summary
Outline

- **Context**

- **Preliminary Remarks**
  - Communicating Boolean Mealy Machines
  - From Automata to Device Drivers

- **Proposal**

- **Implementation**

- **Summary**
Communicating Boolean Mealy Machines

Synchronous Product
Communicating Boolean Mealy Machines

Synchronous Product
Communicating Boolean Mealy Machines

Synchronous Product
Communicating Boolean Mealy Machines

Synchronous Product
Communicating Boolean Mealy Machines

```
node SE (a: bool) returns (c: bool);
var inB0, inB1, inA0, inA1, m_A0, m_B0, A0, B0, b: bool;
let
  inA1 = not m_A0;  inA0 = m_A0;  b = a and inA1;
  inB1 = not m_B0;  inB0 = m_B0;  c = b and inB1;
  A0 = not a and inA0 or a and inA1; m_A0 = true -> pre A0;
  B0 = not b and inB0 or b and inB1; m_B0 = true -> pre B0;
  tel;
```
Communicating Boolean Mealy Machines

Reactive Kernel

```c
bool M1, M2, INIT;       // state variables
void init () { INIT = 1; } // initialization
```
Communicating Boolean Mealy Machines

Reactive Kernel

```c
bool M1, M2, INIT;         // state variables
void init () { INIT = 1; } // initialization

void run_step (bool a) {
    bool L1, L2, L3, L4, L5, L6;

    L2 = INIT | M1;
    L5 = INIT | M2;
    L4 = ~L5 & a;
    L1 = ~L2 & L4;
    L6 = L5 & ~a;
    L3 = L2 & ~L4;

    main_O_c (L1);
    M1 = L3 | L1;
    M2 = L6 | L4;
    INIT = 0;
}
```
From Automata to Device Drivers

- **cmd\_x()**: Sequencial code sending command $x$ to the device
- **goto X**: Software request
- **irq\_j**: Hardware request / signal
- **int\_j**: Internal device event (e.g. end of transmission, etc.)
From Automata to Device Drivers

\[ cmd_x(\cdot) \] Sequencial code sending command \( x \) to the device

\[ \text{goto } X \] Software request

\[ \text{irq}_i \] Hardware request / signal

\[ \text{int}_j \] Internal device event (e.g. end of transmission, etc.)
Outline

- Context
- Preliminary Remarks
- Proposal
  - Overview
  - Structure
    - Adaptation Layer
    - Control Layer
    - Device Driver Machines
    - Controller
  - Further Possibilities
    - Best Low-Power Mode
    - Other Possibilities
- Implementation
Principles of the Solution

(Para-)Virtualization Concept

- Interception and Control of Software Operations
- *Global* Resource Control $\Rightarrow$ Centralized Knowledge
- May Forbid (or Enforce) Operations
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⇒ Centralized Knowledge
Overview

Hardware Platform

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<th>Timer(s)</th>
<th>Interconnects</th>
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<tr>
<td></td>
<td></td>
<td>Radio Transceiver</td>
</tr>
</tbody>
</table>
Overview

Hardware Platform

- MCU
- Timer(s)
- Interconnects
- Radio Transceiver
- Flash Memory

Operating System

+ Application(s)
+ Network stack
+ ...

Task(s)

OS Scheduler

Device Drivers
Overview

Operating System
+ Application(s)
+ Network stack
+ ...

Task(s)

OS Scheduler

Adaptation Layer

Control Layer

Resource Models & Controller

Hardware Platform

MCU

Timer(s)

Interconnects

Radio Transceiver

Flash Memory
Structure: Adaptation Layer
Modified part of the Operating System

- Simplified Device Drivers
Structure: Adaptation Layer

Modified part of the Operating System

- Simplified Device Drivers

Interacts with the Control Layer

- Emitting *software requests* to the Control Layer
Structure: Adaptation Layer

Modified part of the Operating System

- Simplified Device Drivers

Interacts with the Control Layer

- Emitting *software requests* to the Control Layer

- Receiving *output events* from the Control Layer
  - Notifications (Hardware Events, Acknowledgments)
Structure: Adaptation Layer

Modified part of the Operating System

- Simplified Device Drivers

Interacts with the Control Layer

- Emitting *software requests* to the Control Layer
  - Using `on_sw()`

- Receiving *output events* from the Control Layer
  - Notifications (Hardware Events, Acknowledgments)

```c
turn_adc_on()
if (on_sw(adc_on) == ack_a)
    return success;
timer_wait(some_time);  // Consider we can
turn_adc_on();  // try again later
```
Structure: Adaptation Layer

Modified part of the Operating System

▶ Simplified Device Drivers

Interacts with the Control Layer

▶ Emitting *software requests* to the Control Layer
  ▶ Using `on_sw()`

▶ Receiving *output events* from the Control Layer
  ▶ Notifications (Hardware Events, Acknowledgments)

```c
turn_adc_on ()
  if (on_sw (adc_on) = acka)
    return success;
timer_wait (some time);  // Consider we can
turn_adc_on ();           // try again later
```

▶ Callbacks (Virtual IRQs)
Overview

Operating System
+ Application(s)
+ Network stack
+ ...

Task(s)

Adaptation Layer

Control Layer
Resource Models & Controller

Hardware Platform

MCU
Timer(s)
Interconnects
Radio Transceiver
Flash Memory
Structure: Control Layer

- Receives
  - software requests
  - hardware requests (IRQs)

- Emits notifications

- Manages the Peripheral Devices
Structure: Control Layer

- Receives
  - *software requests*
  - *hardware requests* (IRQs)
- Emits *notifications*
- Manages the Peripheral Devices

Event Management Part

- Handle *request queues*
Structure: Control Layer

- Receives
  - software requests
  - hardware requests (IRQs)
- Emits notifications
- Manages the Peripheral Devices

Event Management Part

- Handle request queues
- Executes the Reactive Part

Reactive Part

- Device Drivers Machines
  - Reactive Kernel
- Resource Operational Code
Principles of the Solution

(Para-)Virtualization Concept

▶ Interception and Control of Software Operations
▶ *Global* Resource Control ⇒ Centralized Knowledge
▶ May Forbid (or Enforce) Operations
Principles of the Solution (cont’d)

(Para-)Virtualization Concept

▶ Interception and Control of Software Operations
▶ Global Resource Control ⇒ Centralized Knowledge
▶ May Forbid (or Enforce) Operations

Key Elements (Boolean Mealy Machines)

▶ Resource Automata
  ▶ Inputs: Software Requests...
  ▶ Outputs: Low-Level Code, Notifications...
▶ Controller
Example of Uncontrollable Automaton

Timer

disable . enable / timer_restart()

disable / timer_stop()

disable . enable . irq_timer_expired / timer_expired

timer_init()
Example of Controllable Automaton

Timer

disable . enable . ok_t / ack_t, timer_restart()
disable . ok_t / ack_t, timer_stop()
disable . enable . irq_{timer_expired} / timer_expired

timer_init() → Disabled
enable . ok_t / ack_t, timer_start()

Disabled → Counting

disable . ok_t / ack_t, timer_stop()
Exclusion of Energy-greedy States: Example

Radio Transceiver || ADC

Diagram showing the states and transitions for the radio transceiver and ADC, including:
- Calibrate
- Sleep
- Idle
- Tx
- Rx
- Rx_Packet
- Off
- On

Transitions and events include:
- `irq_end_of_calibration`
- `calibrate()`, `ok`
- `ackr`, `sleep()`
- `enter_rx()`, `okr`, `ackr`, `enter_rx()`
- `enter_tx()`, `okr`, `ackr`, `enter_tx()`
- `irq_end_of_packet`, `packet_received`
- `irq_fifo_threshold`, `refill_tx_buffer()`
- `irq_on_packet`, `exit_rx()`, `okr`, `ackr`, `exit_rx()`
- `irq_end_of_packet`, `irq_fifo_threshold`
- `empty_rx_buffer()`
- `adc_init()`, `adc_on()`, `ok_a`, `ack_a`
- `adc_off()`, `ok_a`, `ack_a`
Exclusion of Energy-greedy States: Example

Radio Transceiver || ADC || Controller
Principles of the Solution (cont’d)

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- *Global* Resource Control \(\Rightarrow\) Centralized Knowledge
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Key Elements (Boolean Mealy Machines)

- Resource Automata
  - Inputs: Software Requests...
  - Outputs: Low-Level Code, Notifications...
- Controller
Principles of the Solution (cont’d)

(Para-)Virtualization Concept

► Interception and Control of Software Operations
► Global Resource Control ⇒ Centralized Knowledge
► May Forbid (or Enforce) Operations

Key Elements (Boolean Mealy Machines)

► Resource Automata
  ► Inputs: Software Requests & Approval Signals
  ► Outputs: Low-Level Code, Notifications & Acknowledgments
► Controller
  ► Inputs: Software & Hardware Requests
  ► Outputs: Approval Signals

Enforcing Global Properties  ~  Designing the Controller
How to: Selecting the Best MCU Low-Power Mode

Operating Modes

2.3 Operating Modes

The MSP430 family is designed for ultralow-power applications and uses different operating modes shown in Figure 2−10. The operating modes take into account three different needs:

- Ultralow-power
- Speed and data throughput
- Minimization of individual peripheral current consumption

The MSP430 typical current consumption is shown in Figure 2−9.

![Operating Modes Diagram](image)

The low-power modes 0−4 are configured with the CPUOFF, OSCOFF, SCG0, and SCG1 bits in the status register. The advantage of including the CPUOFF, OSCOFF, SCG0, and SCG1 mode-control bits in the status register is that the present operating mode is saved onto the stack during an interrupt service routine. Program flow returns to the previous operating mode if the saved SR value is not altered during the interrupt service routine. Program flow can be returned to a different operating mode by manipulating the saved SR value on the stack inside of the interrupt service routine. The mode-control bits and the stack can be accessed with any instruction.

When setting any of the mode-control bits, the selected operating mode takes effect immediately. Peripherals operating with any disabled clock are disabled until the clock becomes active. The peripherals may also be disabled with their individual control register settings. All I/O port pins and RAM/registers are unchanged. Wake up is possible through all enabled interrupts.
How to: Selecting the Best MCU Low-Power Mode

- Reducing Energy Consumption
- ...as usual...
How to: Selecting the Best MCU Low-Power Mode

- Reducing Energy Consumption
  - ... as usual...

- Wake-up time
  - Latency property
How to: Selecting the Best MCU Low-Power Mode

- Reducing Energy Consumption
  - ...as usual...
- Wake-up time
  - Latency property
- To be sure to wake up!
  - Potential IRQs?
How to: Other Possibilities

- Mutual Exclusion of Accesses to Shared Resources
  - Safety Property
How to: Other Possibilities

- Mutual Exclusion of Accesses to Shared Resources
  - Safety Property

- Controlling Guest Tasks / Resources
  - Modification of the Guest Scheduler
  - Allowing Direct Access to the Resources
How to: Other Possibilities

- Mutual Exclusion of Accesses to Shared Resources
  - Safety Property

- Controlling Guest Tasks / Resources
  - Modification of the Guest Scheduler
  - Allowing Direct Access to the Resources

- Booking Controller
  - Slightly more complex (to use)... fits in the model however
Outline

- Context
- Preliminary Remarks
- Proposal
- Implementation
- Summary
Implementation

Proof of Concept

- Rough Implementation
- Resource Automata and Controller encoded in Lustre
- Multithreaded, Contiki
- Targetting Wsn430 Platform

Comparative to Solutions using Decentralized Control

Extra Memory Footprint: 1.5 to 2.5 KB

Timing Overhead: One Reaction ≈ 1,600 CPU cycles
Implementation

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Practicable?

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Summary

Global Resource Control

- Synchronous Programming... in Wireless Sensor Networks!
Summary

Global Resource Control

- Synchronous Programming... in Wireless Sensor Networks!
- Many Possible Extensions ~ Powerful
Summary

Global Resource Control

▶ Synchronous Programming... in Wireless Sensor Networks!
▶ Many Possible Extensions ～ Powerful
▶ Para-Virtualization Concept ～ Flexible Framework
Summary

Global Resource Control

- Synchronous Programming... in Wireless Sensor Networks!
- Many Possible Extensions
  \(\leadsto\) Powerful
- Para-Virtualization Concept
  \(\leadsto\) Flexible Framework

Implementation

- Proof of Concept
- Practicable
- Device Drivers Revealed “easier” to Develop
Perspectives

Evaluation

» Efficiency to Reduce Power Consumption?

Soon in the Senslab Testbed...
Perspectives

Evaluation

▸ Efficiency to Reduce Power Consumption?
  Soon in the Senslab Testbed…

Automated Control

▸ Using Controller Synthesis
Perspectives

Evaluation

- Efficiency to Reduce Power Consumption?
  Soon in the Senslab Testbed...

Automated Control

- Using Controller Synthesis

Synchronous Approach

- “More-Lustre” Solutions?
- Monitoring
- Other Domains (Real-Time...)
Thank you

Questions?
Outline

- Example Execution
Example Execution

- **Guest tasks execution**
  - `lpm()`
  - `on()` `enter` `lpm()`
  - `irq` `tx` `done`
  - `adc`
  - `off()` `enter` `lpm()`
  - `tx()`
  - `tick.run` `step()`
  - `adc` `off` `adc` `on`
  - `enter` `tx` `adc`
  - `off` `adc` `on`
  - `on` `sw` `adc` `on`
  - `on` `sw` `enter tx`
  - `on` `sw` `adc` `off`
  - `end pf tx`

- **CL**
  - `Free`
  - `Off`
  - `Idle`
  - `enter lpm()`
  - `adc on()`
  - `timer expired`
  - `ack_a`
  - `timer expired`
  - `ack_r`
  - `timer expired`
  - `timer expired`
  - `timer expired`
  - `timer expired`
  - `timer expired`

- **Network**
  - `Tensing`
  - `Networking`

- **Radio**
  - `Idle`
  - `Off`
  - `On`
  - `Tx`

- **ADC**
  - `Off`
  - `On`
  - `Idle`

- **Cmd**
  - `Free`
  - `Idle`

- **Networking**
  - `Idle`
  - `Off`
  - `Free`