Macrodebugging: Global Views of Distributed Program Execution

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The 7th ACM Conference on Embedded Networked Sensor Systems (SenSys 2009)
Macroprogramming

- A single macroprogram → Several microprograms
- No support for debugging
- MacroLab
  - A macroprogramming framework that offers a vector programming abstraction similar to Matlab for Cyber-Physical Systems (CPSs).
MDB

- Like GDB
- "Macrodebugging" on a single machine
- Steps through a macroprogram in a sequential order
- Implemented for MacroLab
Example of MacroLab program

- **Lines 1-4**
  - **Initializes**
    - The `motes` vector of node IDs
    - The `magSensors` vector of magnetometer sensors
    - The `magVals` macrovector of magnetometer readings
    - `neighborMag`, n x n neighbor reflection vector

- **Line 7**
  - Reads from all magnetometer values

- **Line 8**
  - Creates an active vector with the IDs of all nodes that have at least 3 neighbors with values > THRESH

```plaintext
1   motes = RTS.getMotes('type', 'tmote')
2   magSensors = SensorVector(motes, 'magnetometer')
3   magVals = Macrovector(motes)
4   neighborMag = neighborReflection(motes, magVals)
5   THRESH = 500
6   every(1000)
7   magVals = magSensors.sense()
8   active = find(sum(neighborMag > THRESH, 2) > 3)
9   maxNeighbor = max(neighborMag, 2)
10  leaders = find($\ldots$
11      maxNeighbor(active) == magVal(active))
12  focusCameras(leaders);
13  end
```
Example of MacroLab program (cont.)

- **Line 9**
  - Creates a `maxNeighbor` vector with the highest sensor value in `neighborMag`

- **Line 10-11**
  - Creates a `leaders` vector with the IDs of those nodes having the highest sensor value in an active neighborhood

- **Line 12**
  - Focus all available cameras on the leader nodes

```python
1  motes = RTS.getMotes('type ', 'tmote ')
2  magSensors =
3      SensorVector(motes, 'magnetometer ')
4  magVals = Macrovector(motes)
5  neighborMag = neighborReflection(motes, magVals)
6  THRESH = 500
7  every(1000)
8      magVals = magSensors.sense ()
9      active = find(sum(neighborMag >THRESH , 2)
10         > 3)
11  maxNeighbor = max(neighborMag , 2)
12  leaders = find($\ldots$
13      maxNeighbor(active) == magVal(active))
14  focusCameras(leaders);
15  end
```
Example of MacroLab program (cont.)

- All nodes will execute the program asynchronously and independently.

Magnetometer values automatically get reflected to neighboring nodes and populate the caches of `neighborMag` vector.
Three types of macroprogramming bugs

- **Logical Error**
  - $active = \text{find}(\text{sum}(\text{magVals} > \text{THRESH}) , 2) > 3$

- **Configuration Error**
  - Line 6, 1000ms might be too big

- **Synchronization Error**
  - Message loss, data races, asynchronous execution
 MDB UI – Logically synchronous views

- Commands
  - lbreak(l)
    - Place a breakpoint at line l
  - lcont
    - Move forward to the next breakpoint
  - lstep[(l)]
    - Increment to the next line (or step l lines)

- Limitation
  - Views of distributed state may include values that correspond to different points in time

```java
while (magVals < 10 )
    magVals = magSensor.sense()
end
if magVals > 3000
    magSensor.calibrate()
end
Display(magVals)
```
MDB UI – Temporally synchronous views

- **Commands**
  - $t_{jump}(t)$
    - Change the state of the system to time $t$ μs
  - $t_{step}[(t)]$
    - Change the state of the system to next logged time (or current time + $t$)

- **Limitation**
  - The user must be able to specify the exact times of interest
MDB UI – Historical Search

- Access the history of a macrovector by adding a new dimension to it
  - magVals(5, 1000)
- Standard Matlab operators can be applied to macrovectors
  - find(numel(leaders(:, :)) > 1)

MDB UI – Hypothetical Changes

- **Base timeline (bt)**
  - The original execution trace that was collected during program execution

- **Alternative timeline (at)**
  - Generated by applying hypothetical changes to the base timeline
  - \[ at = \text{alt}(’\text{magVals} = 0’, 7, \text{bt}) \]

- **Four hypothetical changes**
 MDB UI – Hypothetical Barrier

- Barrier
  - A point in the source code that all nodes must reach before any node can proceed
- hb = alt(’barrier()’, 12, bt)
- message re-ordering

(a) Hypothetical Barrier
MDB UI – Hypothetical Time Delay

- Produces the distributed state that would have been produced if a time delay of $\Delta t$ were inserted at a particular point in the macrocode
- $dt = \text{alt(’deltat(10)’,12, bt)}$
- message re-ordering

MDB first creates a logically synchronous view on line12
MDB UI – Hypothetical Cache Coherence

- Shows the hypothetical distributed state if all caches were coherent at a given time
- \( cv = \text{alt('coherent()', 12, bt) } \)
- message re-ordering

(c) Hypothetical Cache Coherence
Shows the hypothetical state that would result if cache expiration were used at a given line of code, without a particular expiration time

\[ \text{ev} = \text{alt('expire(100000)', 12, bt)} \]

- \( \text{ev} \) stores the last values written to each element of the macrovector in the time interval
- \( \text{ev} = \text{NaN} \) if an element had no value written to it within the time interval
MDB Execution Traces

- **Post-mortem debugger**
  - Allow the user to inspect program execution after the logs are retrieved

- **Data traces**
  - Log entry
    - program counter, variable location, etc.

- **RAM → external flash**
  - Advantage
    - Reduces contention for the CPU
  - Disadvantage
    - Log entries in the RAM buffer may be lost if the node crashes
Distributed Timekeeping

- Causal consistency
  - Any event E that cause event E’ must have smaller timestamp than E

- Lamport algorithm
  - Any events on the sender have an earlier timestamp than events they might cause on the receiver
  - Used off-line after the logs are collected

- One Message every two minutes
Data vs. Event Logging

- Data logging
  - Number of logging statement

- Event logging
  - Number of interrupts

- Testbed
  - 21 Tmote Sky nodes with photoresistor sensors
RAM overhead

- MDB has modest RAM requirements
- MDB needs to store a maximum of 304 bytes of data
Flash overhead

- The applications store less than 300 Bps to the flash
- Tmote Sky has 1MB of external flash
- Approximately,
  - 9 hour logs for Surge

<table>
<thead>
<tr>
<th>Application</th>
<th>Flash (Bps)</th>
<th>Wraparound (hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Surge</td>
<td>31</td>
<td>9</td>
</tr>
<tr>
<td>Accoustic</td>
<td>187</td>
<td>2</td>
</tr>
<tr>
<td>OTA</td>
<td>288</td>
<td>1</td>
</tr>
</tbody>
</table>
CPU overhead

- Count the logging instructions executed during a particular run
- Run the applications on Cooja simulator
  - 1 node for Surge
  - 5 nodes for Accoustic
  - 10 nodes for OTA
- Logging code executes for less than 0.5% of the total execution time
Energy Consumption

- Test application
  - OTA
- When Low-power listening (LPL) is enabled
  - With MDB
    - Consumes 30% more energy comparing to no-MDB
  - With MDB-lite
    - Consumes 0.9% more energy comparing to no-MDB
Q&A