Using a WCET Analysis Tool in Real-Time Systems Education

Samuel Petersson*, Andreas Ermedahl*, Anders Pettersson*, Daniel Sundmark*, and Niklas Holsti#

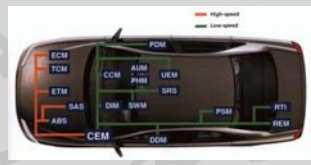
*Mälardalen Real-Time Research Center (MRTC)
#Tidorum Ltd

MRTC
MÄLARDALEN REAL-TIME RESEARCH CENTRE

Status of WCET analysis

- WCET analysis is now mature enough to be used in real industrial settings
- Examples:
  - Avionics software
  - Software controlling in-vehicle communication networks
  - Real-time operating system code
  - Space applications

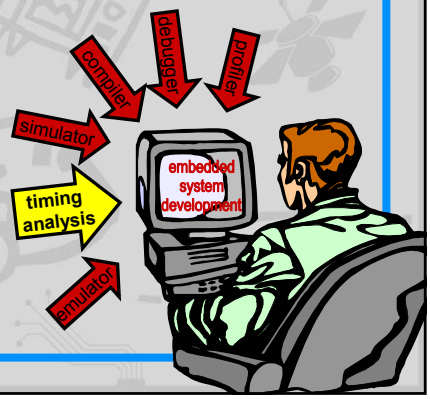
- Timing analysis research has developed into companies
  - Tidorum (static analysis)
  - AbsInt (static analysis)
  - Rapita Systems (measurement/static analysis)



MRTC
MÄLARDALEN REAL-TIME RESEARCH CENTRE

WCET analysis in practise

- WCET analysis tools have a potential to be a standard part of the embedded system developer's tool chest
- The problem: Too few developers are yet aware of WCET analysis tools



MRTC
MÄLARDALEN REAL-TIME RESEARCH CENTRE

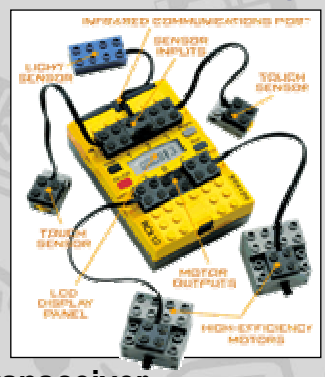
WCET analysis in education

- Embedded system developers need to be educated on the benefits of WCET analysis tools
- The solution: Make WCET analysis tools a standard part of the education of these developers

MRTC
MÄLARDALEN REAL-TIME RESEARCH CENTRE

Lego Mindstorms

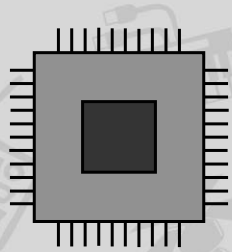
- An off-the-shelf kit of Lego bricks for building and controlling Lego robots
- Including the fundamental necessities of an embedded real-time system:
  - The RCX unit – including a programmable Renesas H8/3292 microprocessor
  - Sensors & actuators – motors, touch- and light sensors, ...
  - Limited I/O – LCD display, IR-transceiver, …
- Used in many real-time courses in academia!



MRTC
MÄLARDALEN REAL-TIME RESEARCH CENTRE

The H8/3292 microprocessor

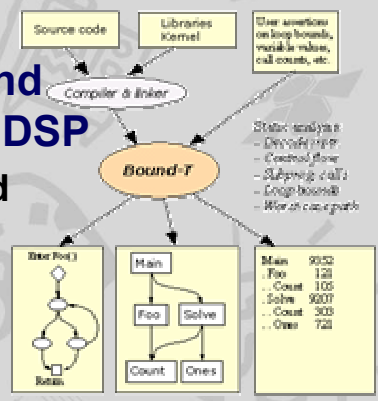
- Features a H8/300 CPU core
  - Single-chip RISC
  - Runs at 16 MHz
- 57 instructions
- 8 addressing modes
- 64 kB address space
  - 16 kB of ROM – containing code for reading sensors, controlling motors, etc
  - 512 bytes of on-chip RAM
  - 16 kB external RAM
- 16 8-bit registers or 8 16-bit registers
- No cache or pipeline



MRTC
MÄLARDALEN REAL-TIME RESEARCH CENTRE

The Bound-T tool

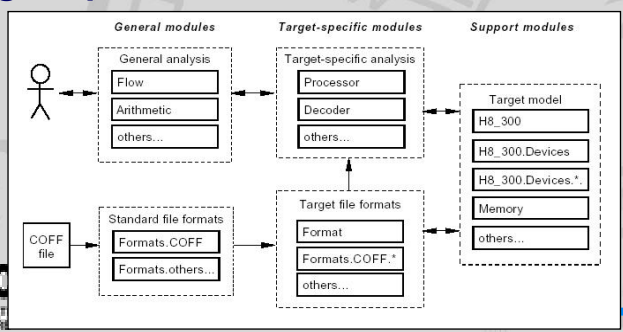
- A commercially available WCET tool
  - Provided by Tidorum Ltd, (Niklas Holsti)
- Supported targets:
  Intel 8051, Sparc V7, and
  Analog Devices 21020 DSP
  - Ports to Atmel AVR and ARM7 under way
- Works directly upon the binary executable



MRTC
MÄLARDALEN REAL-TIME RESEARCH CENTRE

Some Bound-T details

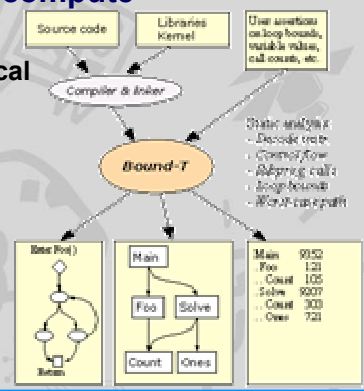
- The Bound-T tool is written in Ada
- Clear division into general- and target-specific modules
- To port Bound-T to a new processor only target-specific modules need to be added



MRTC
MÄLARDALEN REAL-T
RESEARCH CENTRE

More Bound-T details

- Decodes instructions, construct CFGs, and call-graph directly from the executable
- Presburger analysis is used to find loop bounds, resolve dynamic jumps and to compute stack usage bounds
  - Requires description of arithmetical effects of decoded instructions
- IPET is used to calculate the WCET bound(s)
  - Requires timing on the nodes and/or edges in the CFGs
  - One WCET per function and/or a WCET for the whole program



MRTC
MÄLARDALEN REAL-TIME RESEARCH CENTRE

Porting Bound-T to H8/300

- Work performed by one MSc student (Samuel Petersson)
  - Supervised by Ermedahl, Holsti and Lisper
  - Took about 5 months
- Four main steps performed:
  1. Decode executable into (abstract) instructions
  2. Derive timing for instructions
  3. Give arithmetical effect of instructions
  4. Add representation of decoded instructions to the Bound-T program model (CFGs + CG)

MRTC
MÄLARDALEN REAL-TIME RESEARCH CENTRE

Step 1: Binary decoding

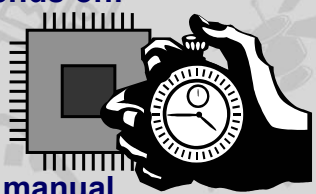
- Input is one or two 16-bit binary words
  - Provided by Bound-T's COFF reader
- Instruction type, addressing mode, and operands needs to be identified
  - Example: 7903 0006 ⇒ mov.w #6, r3
- Considerable job, since 57 instructions with eight different addressing modes
  - No instruction allow all addressing modes

Addressing mode	Mnem.	Operands	Instruction code				No. of states
			1st byte	2nd byte	3rd byte	4th byte	
Immediate	MOV.W	#xx:16, Rd	7 9	0 0 rd	IMM		4
Register indirect	MOV.W	@RS, Rd	6 9	0 rs 0 rd			4
Register indirect with displacement	MOV.W	@(d:16,Rs),Rd	6 F	0 rs 0 rd	disp.		6
Register indirect with post-increment	MOV.W	@Rs+, Rd	6 D	0 rs 0 rd			6
Absolute address	MOV.W	@aa:16, Rd	6 B	0 0 rd	abs.		6

MRTC
MÄLARDALEN REAL-TIME RESEARCH CENTRE

Step 2: Instruction timing

- Processor manual gives time in *execution states*
  - An execution state ≈ clock cycle = 62,5 µs
  - In between 2 to 20 executions states per instruction
  - No caches or pipelines
- The actual execution time depends on:
  - Instruction length
  - Addressing mode
  - Data width
  - Memory areas accessed
- Most required information can be fetched from the processor manual
  - Some depends on the run-time state
- Result as timing on entities (nodes an edges) in Bound-T's CFGs
  - Used in IPET calculation



MRTC
MÄLARDALEN REAL-TIME RESEARCH CENTRE

Troublesome instructions

- EEPMOV = MOVe data to EEPROM
  - Moves block of data in R5 to R6, length in R4L
  - Execution time of instruction depends on value in R4L
- MOVFPE and MOVTPE
  - Synchronizes with the peripheral clock
  - The peripheral clock has a variable access time
  - Worst access time assumed (usually an overestimation)
- Memory configuration change during run-time
  - Dynamically changed by setting special mode pins
  - Might have huge effect on the timing of instructions
  - Assumed that the programmer does not use this feature

MRTC
MÄLARDALEN REAL-TIME RESEARCH CENTRE

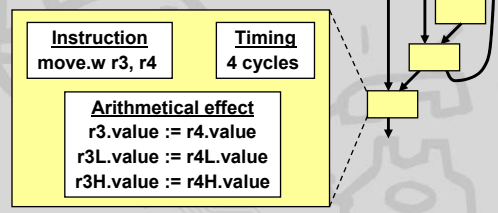
Step 3: Arithmetical effect

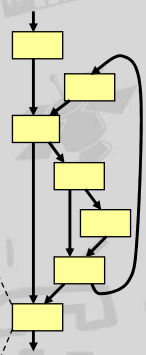
- Description on how executed instructions update different hardware resources
  - Such as registers and memory locations
  - The ”semantics” of the instructions
- Example: move.w r3, r4
  - Updates the 16-bit r3 register with the value in the r4 register
  - Updates the 8-bit r3H and r3L register values
  - Updates the condition code register, by setting the N, Z and V bits
- Information fetched from the processor manual and the instruction decoding
- Needed by loop bound analysis

MRTC
MÄLARDALEN REAL-TIME RESEARCH CENTRE

Step 4: Constructing CFGs

- Decoded instructions, arithmetical effects and timings are all added to Bound-T's internal program model
  - CFGs and CG are constructed on-the-fly
  - Interface provided by Bound-T
- Remaining WCET calculation steps are handled by non-target specific Bound-T modules
  - WCETs can now be calculated





MRTC
MÄLARDALEN REAL-TIME RESEARCH CENTRE

WCET and System Timing

- To provide system timing guarantees we need WCET of all system components, including tasks, OS routines, interrupts etc.
- Used in e.g. schedulability analysis

Worst-Case Response Time

Period

Worst-Case Execution Time

$$R_i = C_i + \sum_{j \in hp(i)} \lceil R_i / T_j \rceil C_j$$

Provided by the Bound-T WCET tool

MRTC
MÄLARDALEN REAL-TIME RESEARCH CENTRE

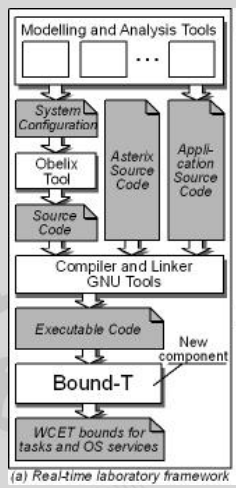
The Asterix & Obelix RT laboratory environment

- A laboratory environment used in real-time courses given at Mälardalens University, Sweden
  - So far 500 students have performed 200 robot projects
- Asterix – a small real-time kernel
- Obelix – a system configuration tool
- Clear separation of functionality and configuration
  - Application might be implemented late, focussing on theoretical aspects of designing robust real-time system
- Suited for schedulability analysis!

MRTC
MÄLARDALEN REAL-TIME RESEARCH CENTRE

Bound-T & the RT laboratory framework

- The framework uses Lego Mindstorms as target platform
- Bound-T will add the following:
  - WCET for student application code
  - WCET for OS calls
  - Illustrative flow-graphs of the code



(a) Real-time laboratory framework

(b) Example configuration

(c) Example task code

MRTC
MÄLARDALEN REAL-TIME RESEARCH CENTRE

System calls in Asterix

- Asterix has a small set of function calls
- Bound-T was used to derive their WCET
  - These WCETs will be given to the students
  - Students must derive WCET of their own tasks

self	Returns tasks own identification number
getSemaphore	Try to take specified semaphore
releaseSemaphore	Releases specified semaphore
raiseSignal	Wakes up all tasks waiting for a signal
getReadPointerWF	Returns a pointer to a buffer where the value to read is.
getWritePointerWF	Returns a pointer to a buffer where the user can write a value.
writeChannel	Writes to a waitfree-channel specified by pointer

MRT
MÄLARDALEN REAL-TIME RESEARCH CENTRE

WCET analysis example

- Some OS-call WCETs were constant:

self:

WCET	34 (cycles)

- Some OS-call WCETs were parametrical:

getSemaphore:

Semaphores	WCET(cycles)
1	900
2	1258
3	1616
4	1974

  - WCET formulas obtained (manually):
    $WCET_{getSemaphore}$: 358 * (#Sems – 1) + 900
  - #Sems can be taken from the Obelix config file

MRTC
MÄLARDALEN REAL-TIME RESEARCH CENTRE

Conclusions

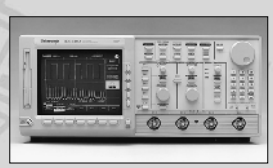
- Porting a WCET-tool to a new target platform require much work
  - Even though a simple processor
- The resulting WCET tool will be used in education
  - Giving WCETs both for student- and OS- code
- Both the Bound-T WCET tool and the RT laboratory framework will be freely available for academia
  - Together they should provide a solid foundation for development of good RT labs
  - Please contact us for details!

MRTC
MÄLARDALEN REAL-TIME RESEARCH CENTRE

MÄLARDALENS HÖGSKOLA

Future work

- Validating the H8/300 Bound-T timing model
  - Against the hardware
- Evaluate the Bound-T tool on students in real-time courses
  - Should provide a lot of valuable feedback
- Investigate if Bound-T can analyze BrickOS
  - An alternative OS for Lego Mindstorms
  - However, not a hard real-time OS



MRTC
MÄLARDALEN REAL-TIME RESEARCH CENTRE

Robot demo & Questions!