Hard Real-Time Test Tools – Concepts and Implementation

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In this presentation, ...

- ... we describe concepts and techniques for automated testing of hard real-time systems
  - Test specification formalisms describing rules for automated
    - Discrete and time-continuous test data generation
    - Test evaluation ("test oracles")
  - Hardware and operating system support for testing in hard real-time

Background and Related Work

- Theoretical foundations of the modelling techniques used have been elaborated by
  - T. A. Henzinger (Hybrid Automata)
  - Authors' research teams at TZI and Verified Systems (algorithms for automatic test data generation and test evaluation)
  - Brinksma, Cardell-Oliver, Tretmans, Nielsen et. al. (alternative approaches to test automation)
  - E. Bryant (ordered binary decision diagrams)
- Real-time concepts are based on / inspired by results of
  - T. A. Henzinger (GIOTTO real-time programming language)
  - H. Kopetz (Time-Triggered Architecture for real-time systems)
  - Authors' research teams at TZI and Verified Systems (Linux real-time kernel extensions, user thread scheduling, unified communication concept)
  - ARINC 653 Standard for avionics operating system API

Background and Related Work

- All concepts described here have been implemented in Verified's test automation tool RT-Tester
- Applications are currently performed for SW integration testing – HW/SW integration testing – system testing of
  - Aircraft controllers for the Airbus families:
    - A318-SDF Smoke Detection Facility
    - A318/A340-500/600 CIDS Cabin Communication System
    - A380 IMA Modules – controllers with Integrated Modular Avionics architecture
  - Train control and interlocking components (Siemens)
- RT-Tester automation tool has been qualified for testing specific A/C controllers according to RTCA DO-178B

Recall: Hard Real-Time Testing ...

- ... Investigates the behaviour of the system under test (SUT) with respect to correctness of
  - Discrete data transformations
  - Evolution of continuous observables over time – speed, temperature, thrust, …
  - Sequencing of inputs and outputs
  - Synchronisation
  - Timing of SUT outputs with respect to deadlines – earliest/latest points in time for expected outputs

A Glimpse at Theory: Test Specification Formalisms for Hard Real-Time Systems

- Question: How much expressive power is required for “suitable” hard real-time systems test specification formalisms?
- Answer from theoretical research (Hybrid Automata): Formalisms need to express facts about
  - States and events
  - Cooperating parallel system components
  - Initial conditions – invariants – flow conditions
  - Trigger conditions for state transitions
  - Actions

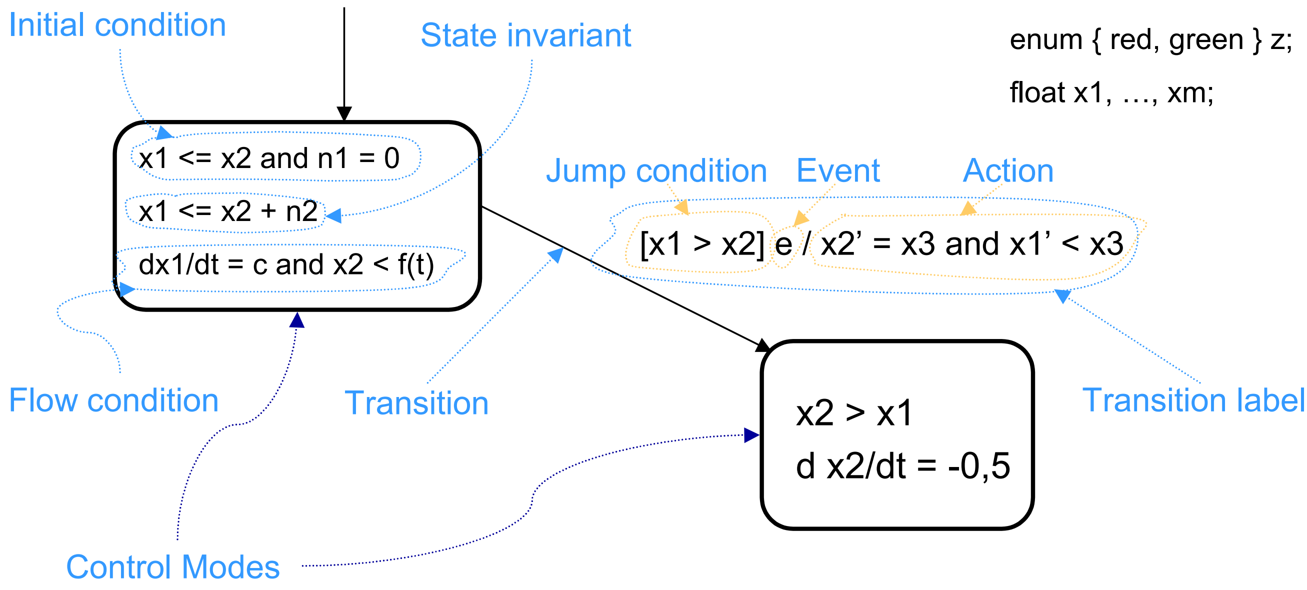
Hybrid Automaton (one sequential component)

State Variables

int n1, … , nk;

enum { red, green } z;

float x1, …, xm;



Hybrid Automata

- Control Modes: Principal states describing the operational modes of the (sub-)system
- State Variables: discrete variables (int, enum, …) and continuous variables (float, complex,…)
- State Space = control modes + state variables
- Transitions: change between control modes
- Labels: transition specification
  - Jump condition: must hold for variables
  - Event: input signal which triggers transition if jump condition holds
  - Action: list of output signals and predicate specifying how variables are changed when transition occurs – may be deterministic (x’ = 5) or nondeterministic (x’ < y)

Hybrid Automata (continued)

- Control modes and variables may be changed when transitions take place
- Continuous variables change over time according to the flow condition specified for actual control mode
- System may stay in control mode as long as the associated state invariant holds
- System may take transition as soon as jump condition holds and (optional) input event occurs
- This concept allows to specify deadlines for system reactions via invariants and jump conditions

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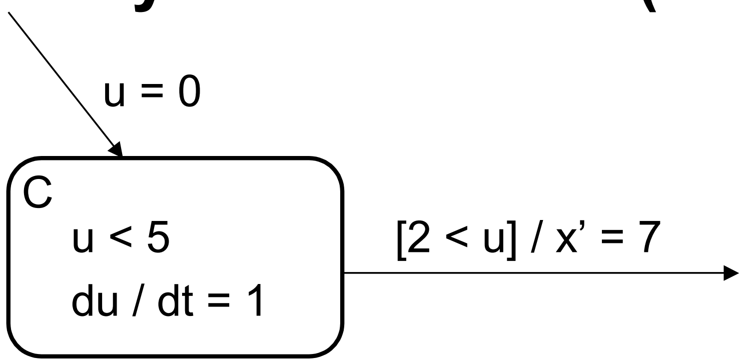
Hybrid Automata (continued)



After entering control mode C, system will leave this mode within time interval (deadline) [2,5) time units, setting x to 7.

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Adapting Theory to Real-Time Testing Practice: A List of Problems

For practical hard real-time testing, the following problems have to be solved:

- Interface abstraction:
  - How should SUT interface data be abstracted in test specifications ?
  - How is SUT interface data mapped to abstract specification data and vice versa ?
- Communication concept:
  - How should parallel test system components interact with each other and with SUT ?

Adapting Theory to Real-Time Testing Practice: A List of Problems

- Parallel execution: How can
  - Stimulation of test-specific SUT reactions
  - Simulation of environment components
  - Checking of SUT reactions

  be performed in parallel and in real-time ?
- Generation of input data: How should SUT input ports be stimulated in real-time, in order to
  - Trigger specific SUT reactions (transitions)
  - Establish invariant conditions in specific SUT states
  - Establish flow conditions on continuous SUT inputs ?

Adapting Theory to Real-Time Testing Practice: A List of Problems

- Checking of output data: How can we check SUT outputs against
  - State transitions describing the expected SUT behaviour
  - State invariants and
  - Flow conditions which should be enforced by SUT

  - preferably on-the-fly ?

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Adapting Theory to RT-Testing Practice: Solutions

- Interface Abstraction
  - Interface Modules are used as adapters between test specifications and SUT interfaces (SW or HW interfaces)
  - Events and state variables are refined to the concrete SUT input interfaces and associated data
  - SUT outputs are abstracted to the events and variable values used on test specification level.

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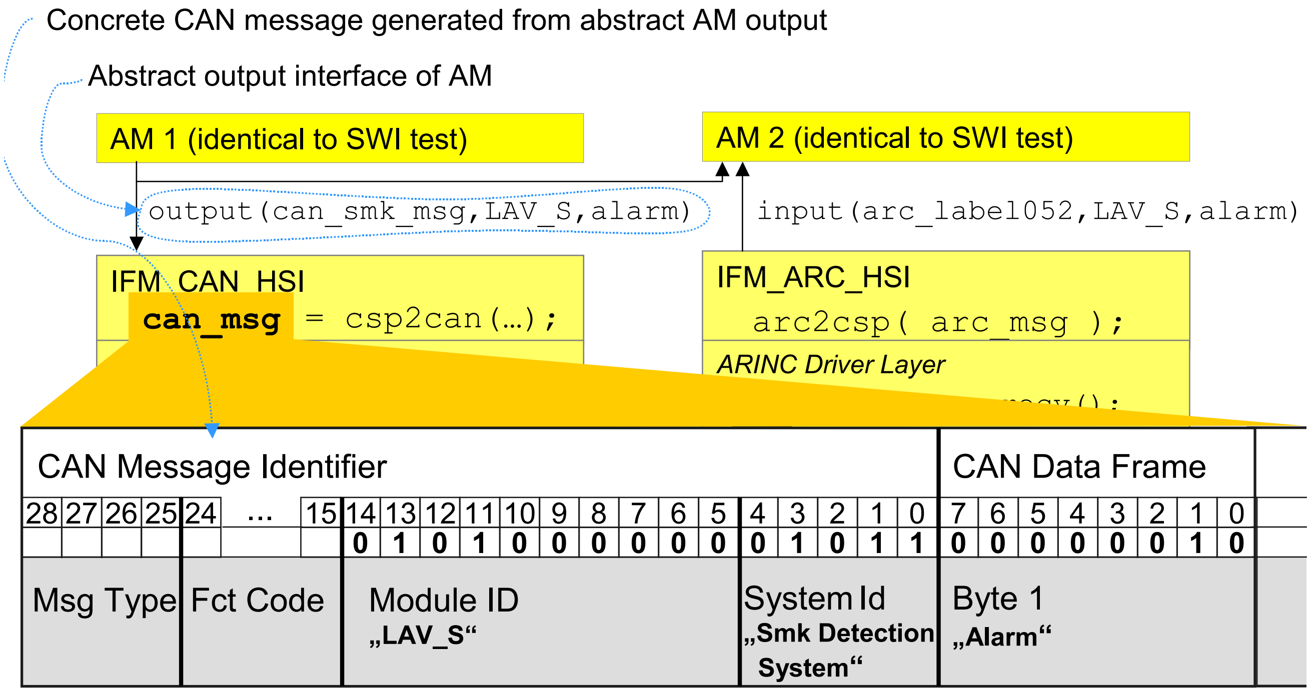
Example: Interface Abstraction



Adapting Theory to RT-Testing Practice: Solutions

- Communication concept
  - On abstract level, all interfaces are identified as ports
    - Sampling ports offer operations
      - Read and keep current data value in port
      - Write new value to port

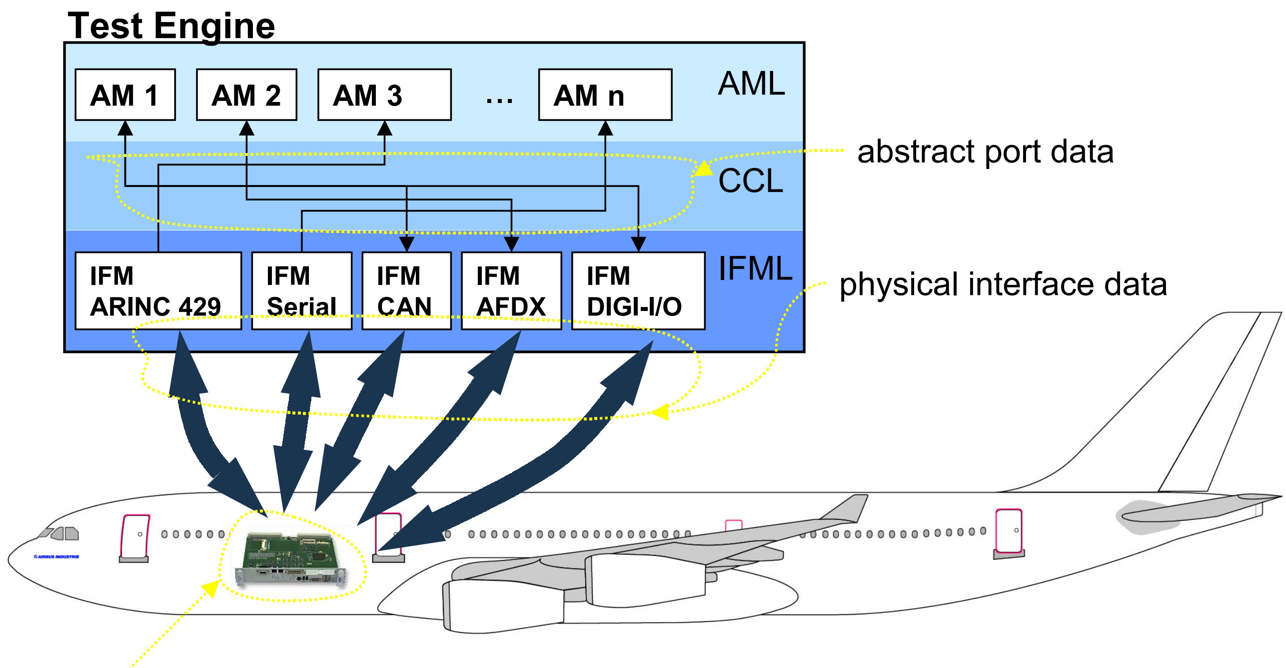
      Used for communication of sensor/actuator data and state variables
    - Queuing ports are FIFO buffers with operations
      - Append to end of queue
      - Read and delete first element of queue
      - Read and keep first element of queue

      Used for communication of messages and events

Adapting Theory to RT-Testing Practice: Solutions

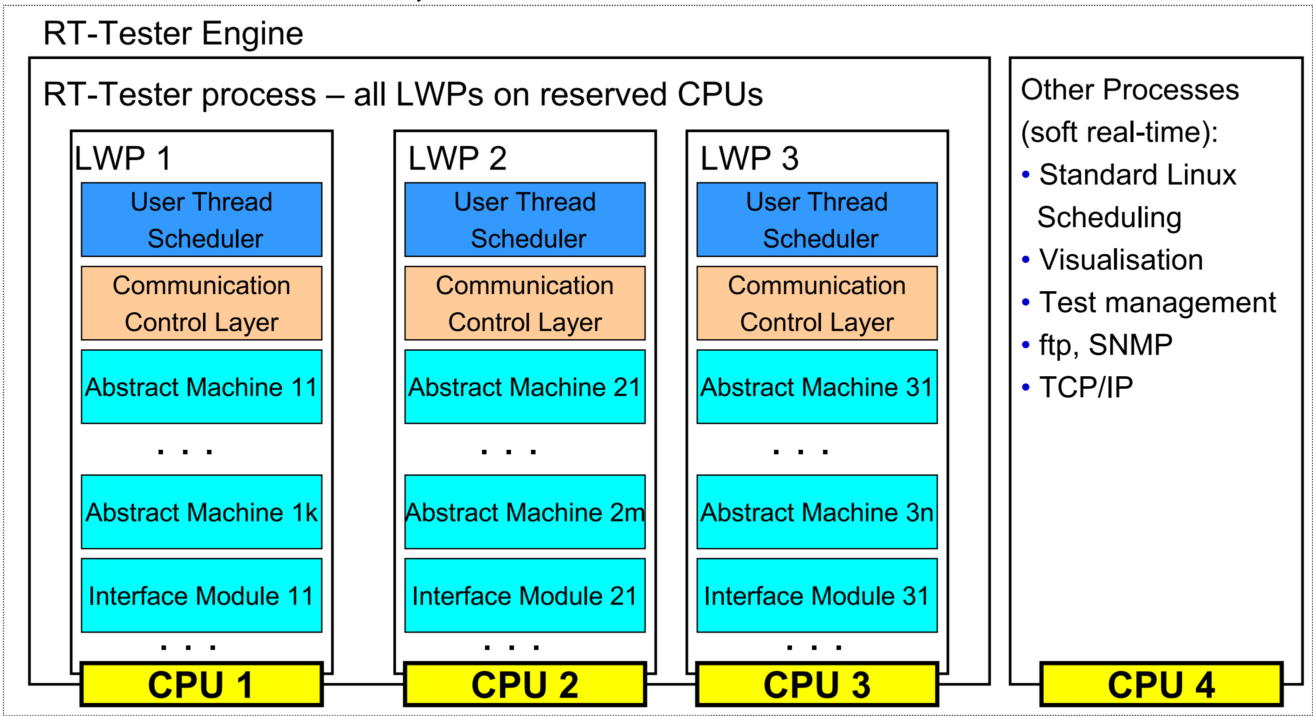
- Parallel execution:
  - Parallel components are allocated as Abstract Machines on dedicated Light Weight Processes (LWPs)
  - Light weight processes in multi-processor environments may use CPUs exclusively
  - User thread scheduling of Abstract Machines on LWPs without participation of the operating system kernel
  - Port communication mechanism is implemented by Communication Control Layer

RT-Tester Organisational Model for Testing A/C Controllers



System Under Test : A318-SDF, A318/A340 CIDS, A380 IMA Module

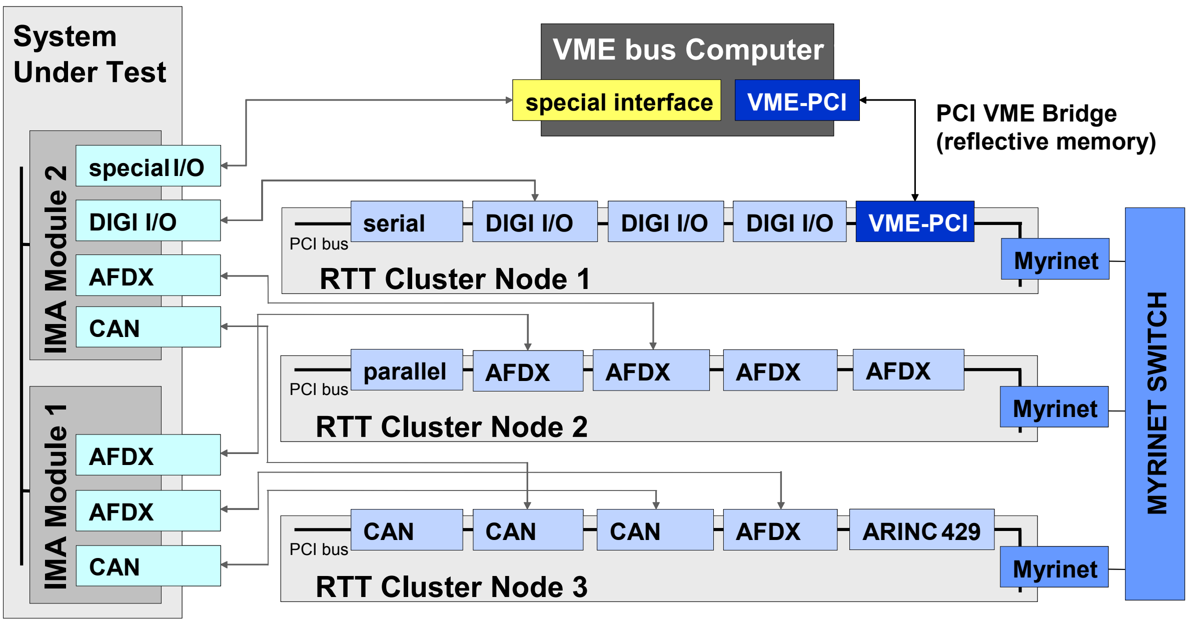
Solutions … LWPs, Abstract Machines and Interface Modules



Adapting Theory to RT-Testing Practice: Solutions

- Parallel execution (continued):
  - Explicit mapping from I/O interrupts to CPUs
  - High resolution real-time clock and timers
  - Avoid PCI bus and memory bus bottlenecks by means of test engine cluster consisting of 2 or more PCs
  - Communication between cluster nodes via high-speed message passing (DMA) over Myrinet link
  - Accuracy better than 100microsec without using specialised hardware

Test Engine Cluster Configuration for A380 IMA Testing



Adapting Theory to RT-Testing Practice: Solutions

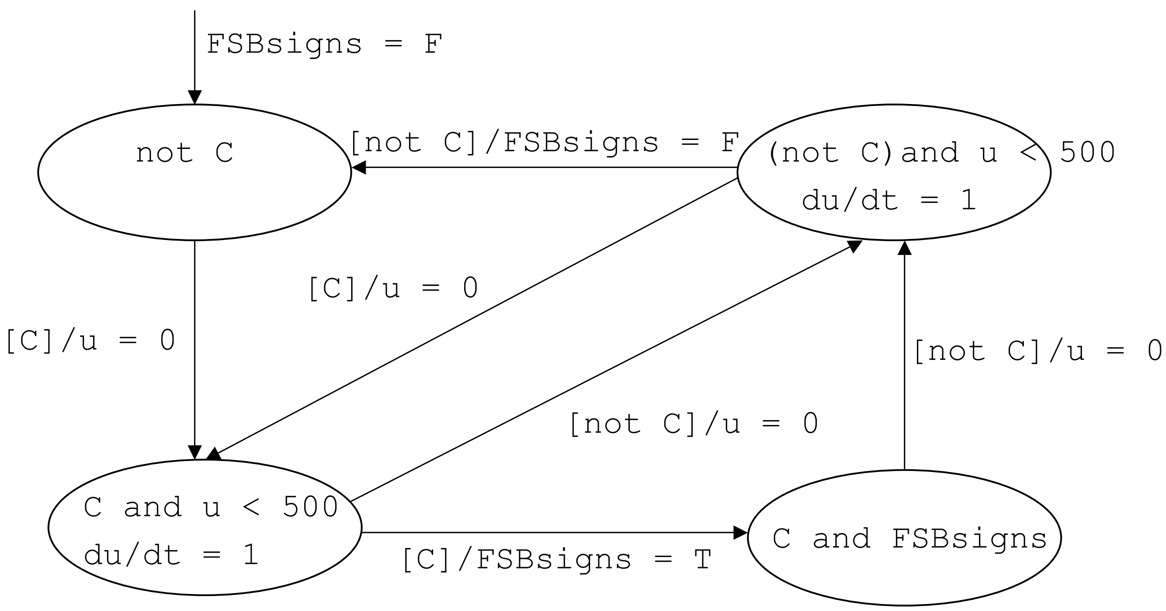
- Generation of input data – example: Control of Fasten Seat Belts Signs – switch FSB signs on (`FSBsigns = true`) within 500msec if
  - Cockpit switch `FSBswOn` has been activated or
  - Cabin pressure is low (`CPC1on or CPC2on`) and automatic FSB switching has been configured (`CONF_FSB_CPC`)for this situation
  - Landing gears are down and locked (`LDGdownLck`) and automatic FSB switching has been configured (`CONF_FSB_LDG`)

Adapting Theory to RT-Testing Practice: Solutions

- Generation of input data – example:
  Logical condition C for “FSB SIGNS ON”:
  - C ≡

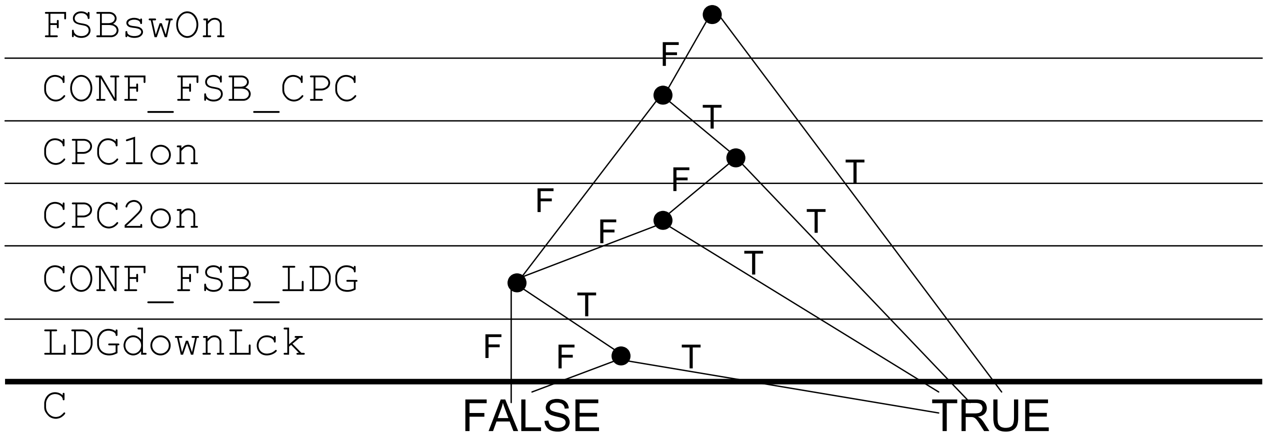
```
FSBswOn or
  (CONF_FSB_CPC and (CPC1on or
CPC2on))or
  (CONF_FSB_LDG and LDGdownLck)
```


Example – continued: specification of FSB controller



Example – continued: Input Generation for Condition C

- Automatic generation with Ordered Binary Decision Diagrams (OBDD): Every path of OBDD defines combination of input values to make C true or false



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Example – continued: Input Generation for Condition C

- Test system simulates SUT transitions between control modes in parallel to SUT execution
- In each control mode, test system generates input data vector, so that
  - Every possible transition will be taken
  - Every possible data combination for making conditions true or false is generated from OBDD
  - If too many combinations exist, heuristics are applied to generate “relevant” combinations – users may specify such combinations to optimise data generation process

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Conclusion

- Hybrid Automata have suitable expressive power for testing real-time systems with both discrete and time-continuous interfaces (sensors, actuators)
- For using Hybrid Automata in the context of testing,
  - A hard real-time testing environment has been developed based on
    - Port communication
    - Network of cooperating Abstract Machines (AM) performing test control, simulation and checking and
    - Interface Modules (IFM) for mapping data between AM and SUT interfaces
    - Specialised user thread scheduling for AM and IFM on reserved CPUs – hard real-time extension of Linux kernel
    - Test engine cluster platform based on multi processor PC linked via Myrinet

Conclusion

- For using Hybrid Automata in the context of testing (continued),
  - Test data generation algorithms have been developed based on
    - Graph traversal in real-time for coverage of control modes
    - User-specified selection of discrete input data to SUT or
    - Automatic selection of input data based on binary decision diagrams
    - Stepwise Δt-integration of flow conditions – solutions of differential equation may be imported from Matlab or similar tools

Conclusion

- For using Hybrid Automata in the context of testing (continued),
  - Algorithms for automatic evaluation of SUT responses ("Test Oracles") have been developed based on
    - Graph traversal algorithms for checking SUT outputs against expected transitions between control modes
    - Pre-compiled correctness conditions for checking invariants and jump conditions
    - Comparison of time-continuous SUT outputs on actuator interfaces against reference functions derived from flow conditions