RV for Ultra-Critical Systems

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3 themes and a case-study

- RV for ultra-critical systems
  - Distributed systems
  - Hard real-time systems
  - Monitor hardware and software faults
- Using functional languages for monitor generation

  embedded domain-specific languages (eDSL)
- Low-cost, high assurance
- Case-study: aircraft guidance systems

Runtime verification is needed!

How do you know your embedded software won't fail?

- Certification (e.g., DO-178B) is largely process-oriented
- Testing exercises a small fraction of the state-space
- It's probably not formally verified
  - Even if so, just a small subsystem
  - And making simplifying assumptions

I'll argue: need the ability to detect/respond at runtime

Software reliability is still a problem (even in ultra-critical systems)

2005-2008:

- Malaysia Airlines Flight 124 (Boeing 777)

  “Software anomaly”

- Qantas Airlines Flight 72 (Airbus A330)

  Transient fault in the inertial reference unit

- Space Shuttle STS-124 aborted launch

  Bad assumptions about distributed fault-tolerance

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Monitoring constraints

Runtime monitoring for real-time embedded systems should satisfy the **FaCTS**:

- **F**unctionality: don’t change the target’s behavior

  No false positives!

- **C**ertifiability: don't require re-certification, or make it easy

  Don't go changing sources.

- **T**iming: don’t interfere with the target’s timing
- **S**WaP: don’t exhaust size, weight, power reserves

How do we monitor a system without violating these constraints?

Our answer

- Synthesize monitors
  - From high-level specs, generate purely functional C99

    Lustre-like stream language → Purely functional Misra-like C
  - Hard real-time: easy to compute WCET
    - Scheduler to give fine-grained timing control
    - No RTOS needed
- *Time-triggered monitoring*:
  - Sample program variables periodically
  - Keep histories as needed
  - ***Not*** addressing control-flow

Sample Copilot specification

If the majority of the three engine temperature probes has exceeded 250 degrees, then the cooler is engaged and remains engaged until the temperature of the majority of the probes drop to 250 degrees or less. Otherwise, trigger an immediate shutdown of the engine.

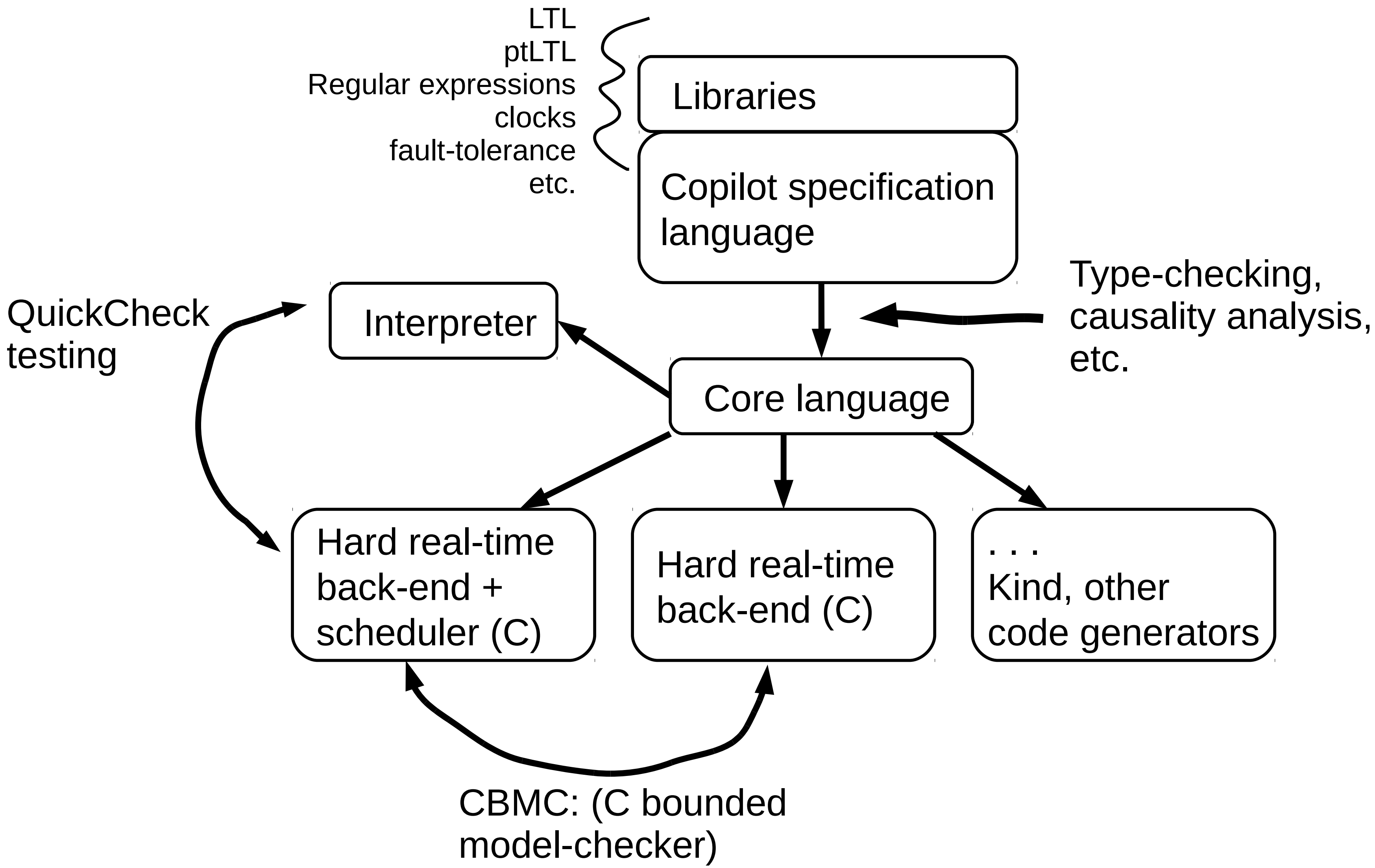
```
engineMonitor = do
  trigger "shutoff" (not ok) [arg maj]

  where

  vals     = map externW8 ["tmp_probe_0", "tmp_probe_1", "tmp_probe_2"]
  exceed   = map (< 250) vals
  maj      = majority exceed
  checkMaj = aMajority exceed maj
  ok       = alwaysBeen ((maj && checkMaj) ==> extern "cooler")
```

Key: library functions trigger macros

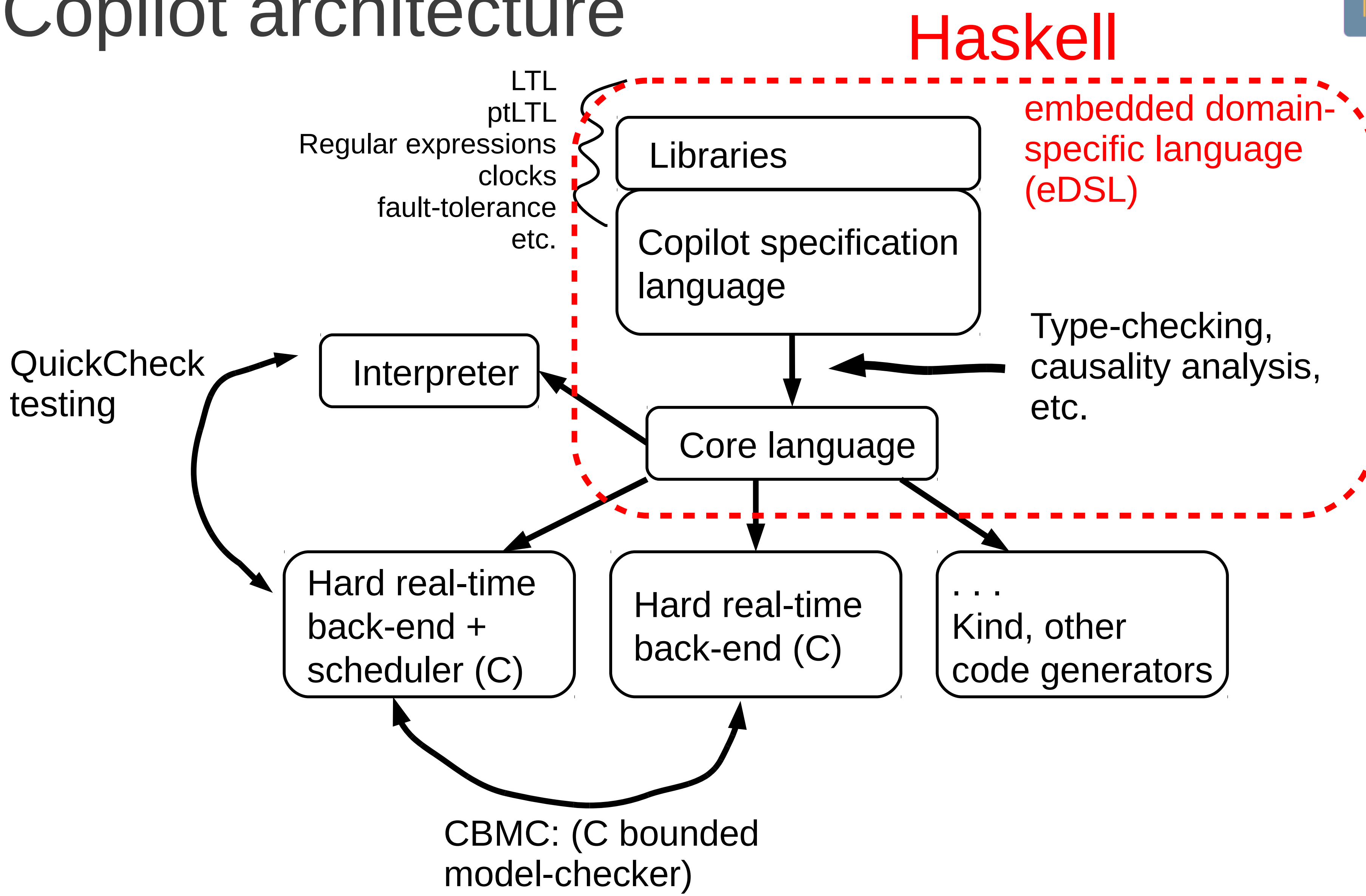
Copilot Interpreter

```
evalExpr_ e0 exts locs strms = case e0 of
  Const _ x              -> x `seq` repeat x
  Drop t i id            -> strictList $
    let Just xs = lookup id strms >>= fromDynF t
    in  P.drop (fromIntegral i) xs
  Local t1 _  name e1 e2 -> strictList $
    let xs    = evalExpr_ e1 exts locs strms
        locs' = (name, toDynF t1 xs) : locs
    in  evalExpr_ e2 exts locs' strms
  Var t name             -> strictList $
    let Just xs = lookup name locs >>= fromDynF t in xs
  ExternVar t name       -> strictList $ evalExtern t name exts
  Op1 op e1              -> strictList $ repeat (evalOp1 op)
                                 <*> evalExpr_ e1 exts locs strms
  Op2 op e1 e2           -> strictList $ repeat (evalOp2 op)
                                 <*> evalExpr_ e1 exts locs strms
                                 <*> evalExpr_ e2 exts locs strms
  Op3 op e1 e2 e3        -> strictList $ repeat (evalOp3 op)
                                 <*> evalExpr_ e1 exts locs strms
                                 <*> evalExpr_ e2 exts locs strms
                                 <*> evalExpr_ e3 exts locs strms
```

Copilot architecture



Copilot architecture



Flight Tests

Pitot tube failures

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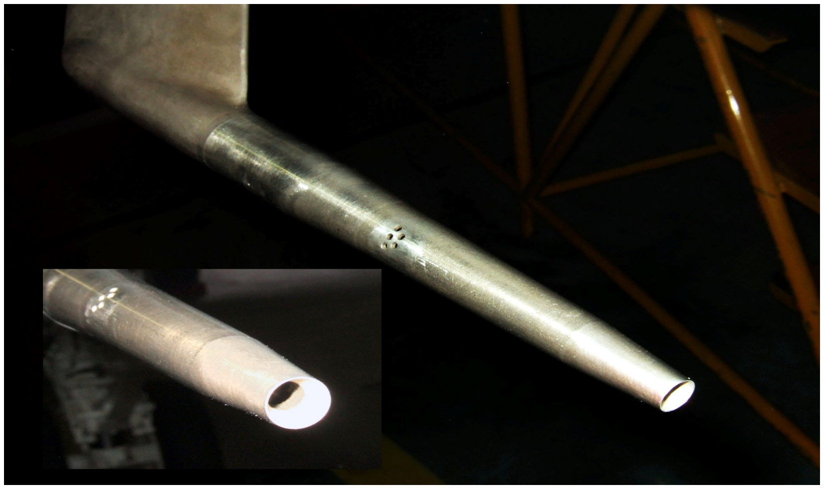

WIKIPEDIA
The Free Encyclopedia

Main page

Article | Discussion

Air Data Inertial Reference Unit

From Wikipedia, the free encyclopedia

An **Air Data Inertial Reference Unit** (ADIRU) is a key compon

Failures and directives

FAA Airworthiness directive 2000-07-27

On May 3, 2000, the FAA issued airworthiness directive 2000-07-27, addres
Boeing 737, 757, Airbus A319, A320, A321, A330, and A340 models.[2][10][

Airworthiness directive 2003-26-03

On 27 January 2004 the FAA issued airworthiness directive 2003-26-03 (lat

Alitalia A-320

On 25 June 2005, an Alitalia Airbus A320-200 registered as I-BIKE departe
failed, leaving only one operable. In the subsequent confusion the third was

Malaysia Airlines Flight 124

On 1 August 2005 a serious incident involving Malaysia Airlines Flight 124,
aircraft acting on false indications.[14] In that incident the incorrect data imp
with the stall warning activated. The pilots recovered the aircraft with the au

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Monday, February 7, 2011

More Pitot Tube Incidents Revealed

New reports of Pitot tube malfunctions on Airbus jetliners during seve
additional safety concerns about their reliab

Reliability of the air pressure sensors made by both Thales and Goodr
particular prominence after the 2009 crash of an Air France
Rio de Janeiro to Paris that claimed 228 victims. Pitot Tubes

AVIATIONWEEK.COM

Lessons Of Air France 447 Start To Emerge

35+ years of failures

Failures cited in

- Northwest Orient Airlines Flight 6231 (1974)---3 killed

    Increased climb/speed until uncontrollable stall

- Birgenair Flight 301, Boeing 757 (1996)---189 killed

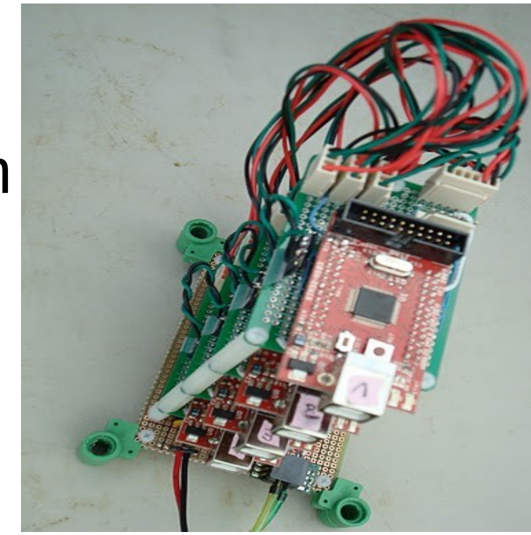
    One of three pitot tubes blocked; faulty air speed indicator

- Aeroperú Flight 603, Boeing 757 (1996)---70 killed

    Tape left on the static port(!) gave erratic data

- Líneas Aèreas Flight 2553, Douglas DC-9 (1997)---74 killed
    - Freezing caused spurious low reading, compounded with a failed alarm system
    - Speed increased beyond the plane's capabilities
- Air France Flight 447, Airbus A330 (2009)---228 killed
    - Airspeed "unclear" to pilots
    - Still under investigation
- ...

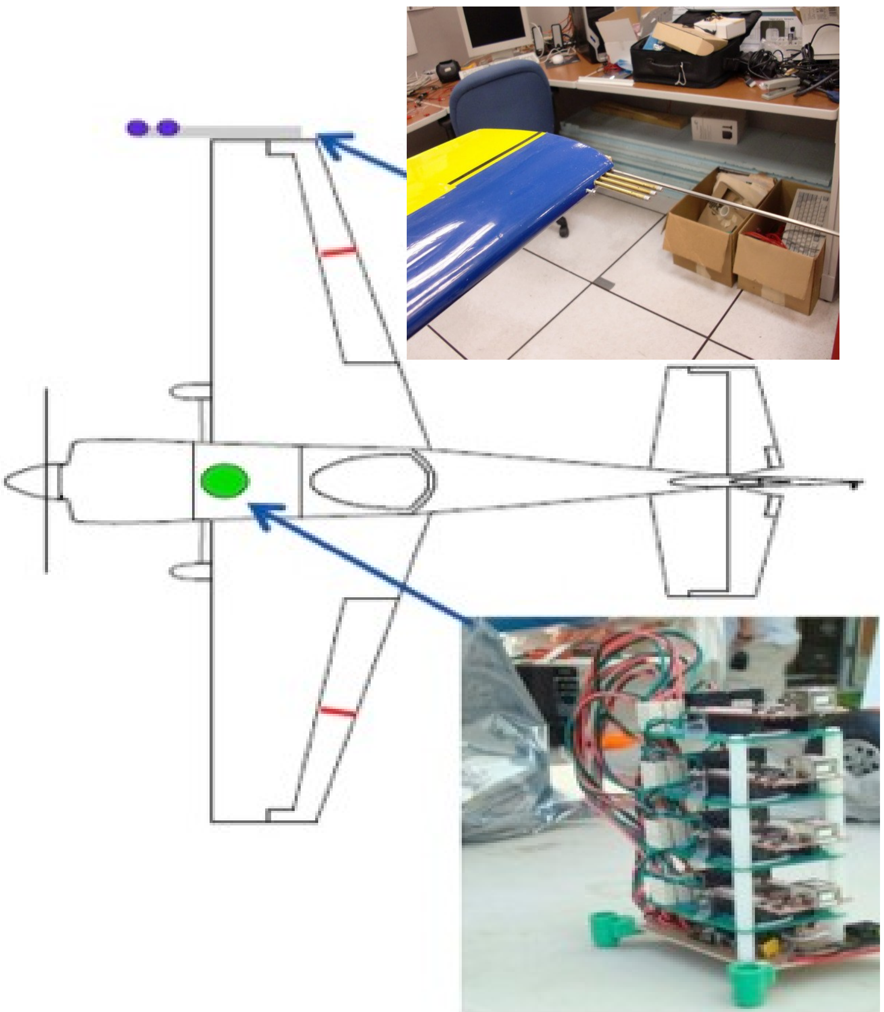
Experiment goals



- Monitors to check a distributed airspeed system
- Monitors also distributed & real-time

  “Bolt-on” fault-tolerance
- While satisfy timing, certifiability, SWaP goals
- Inject both physical and software faults

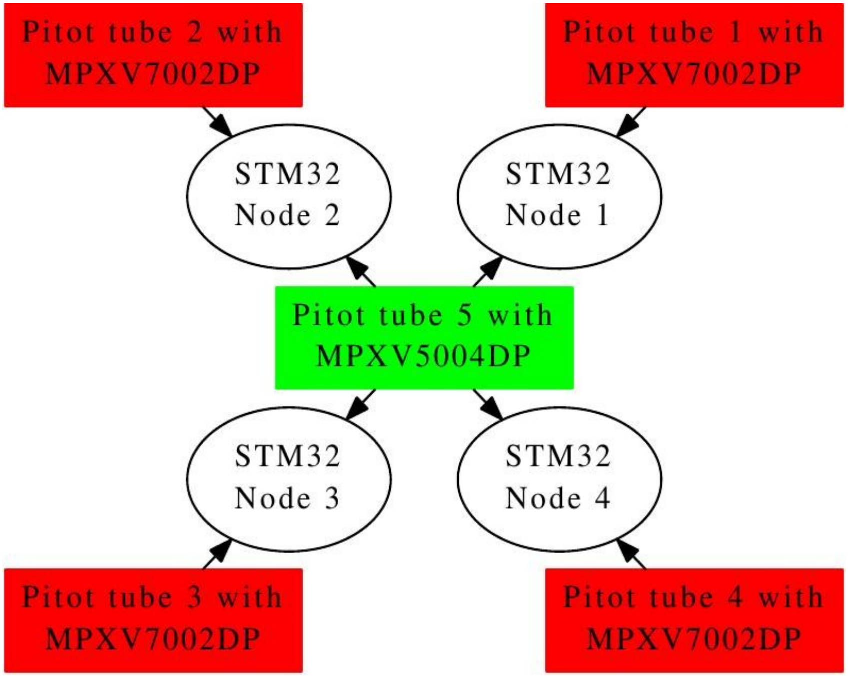
Aircraft configuration
Edge 540T



Monitoring experiments

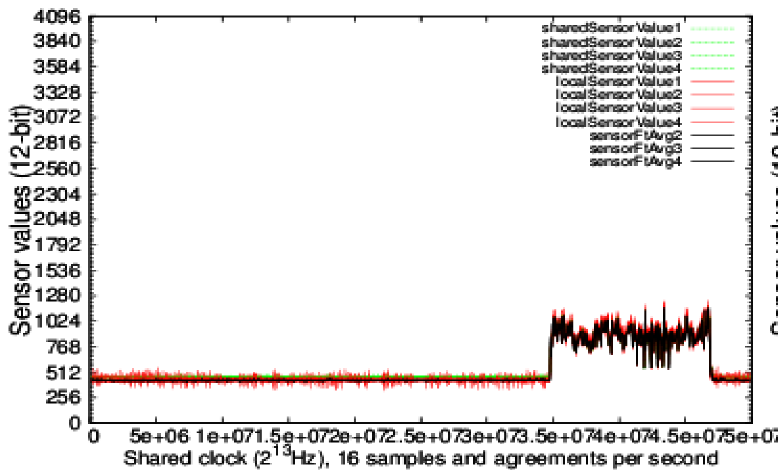
- Monitors communicate with one another over dedicated serial lines in real-time
- Properties
  - *Agreement*: return a fault-tolerant average of sensor values
    - Used to diagnose local faults
    - Diagnoses faults in the monitors **or** the sensor systems
  - Unrealistic sensor data

    Senors values change “too fast”
- Upshot: decomposable fault-tolerance

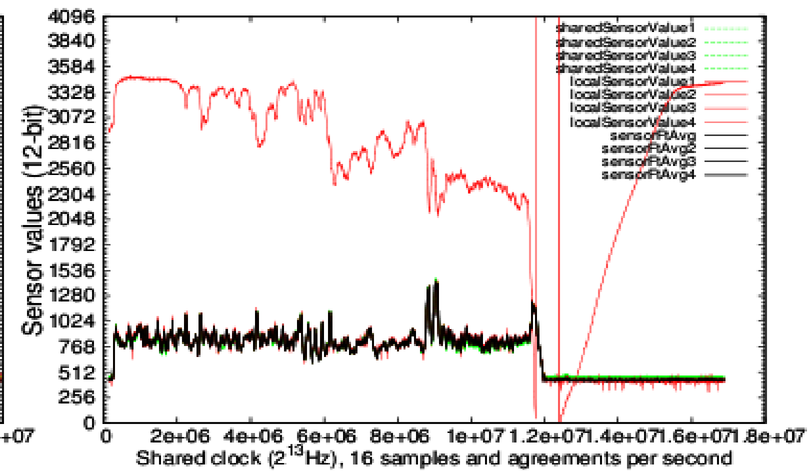


Monitoring results

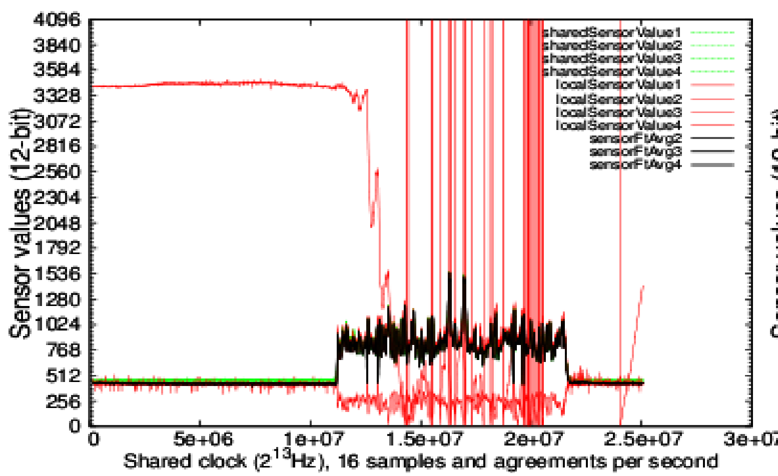
One Byzantine-faulty processor, plus



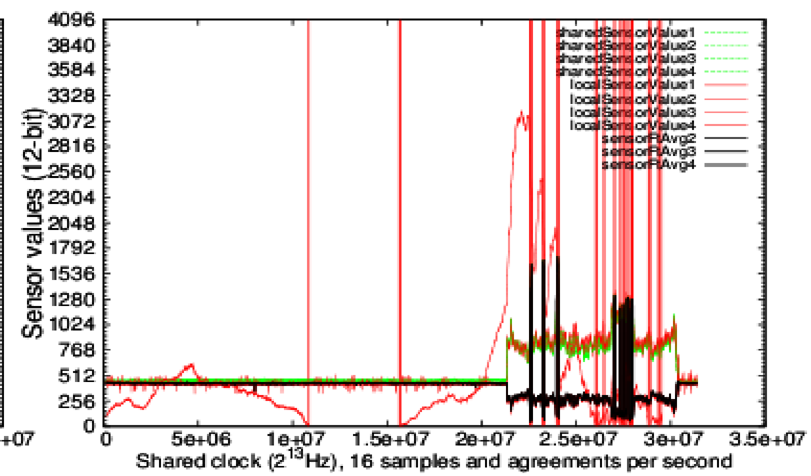
(c) All tubes unmodified



(d) One tube stuck



(e) Two tubes stuck



(f) Three tubes stuck

Future work

- Another case-study on autopilot communication system
- Tools for scheduling monitors
  - Used timer interrupts
  - And scheduler to decompose monitor's tasks (variable sampling, computation, etc.)
- Efficient compilation for eDSLs
- Automated mapping from real-time history to value history

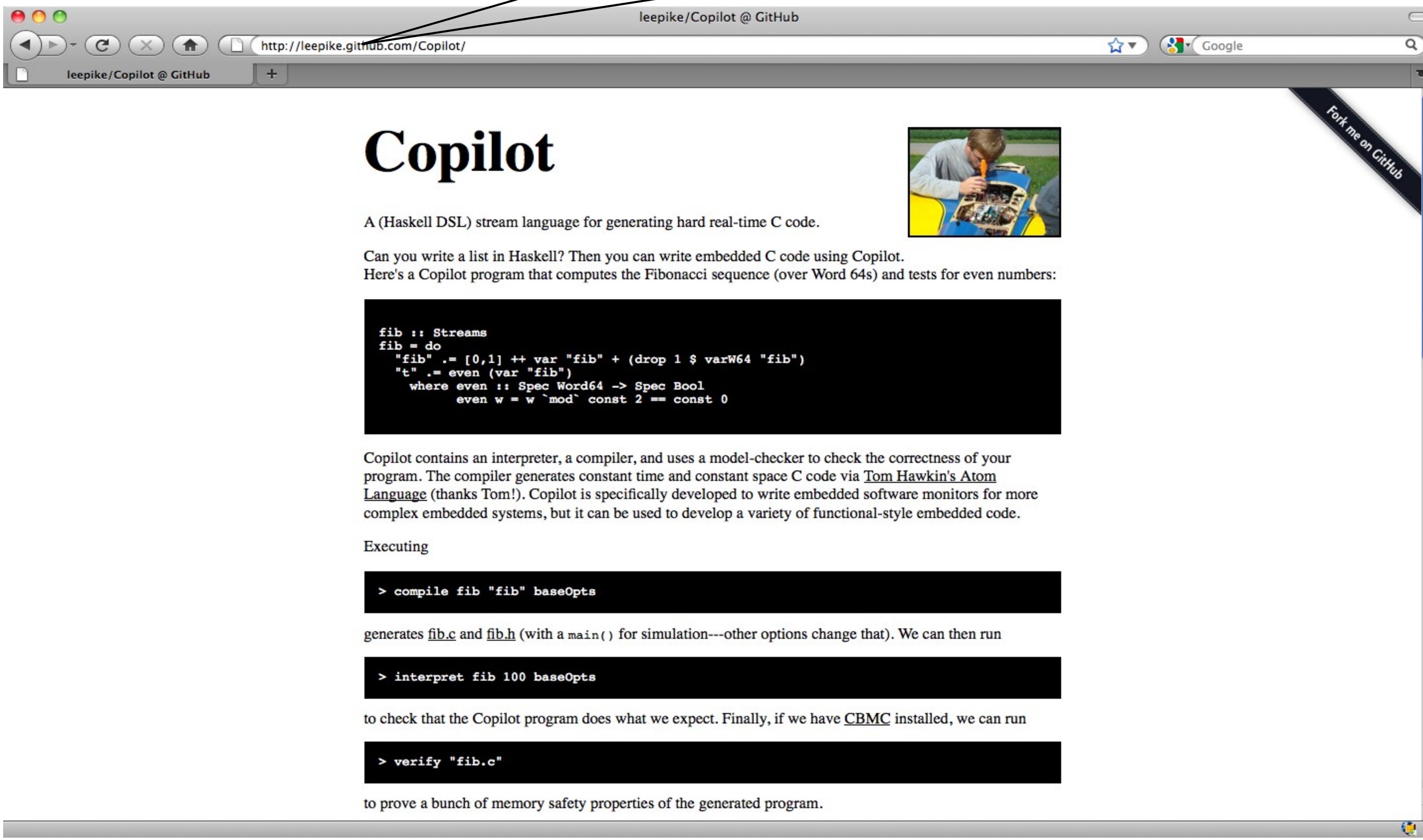
E.g., state in monitor that the Δ in *v* over 1sec. → monitor maintains a history buffer of x values.

Summary

- RV works and is needed for ultra-critical systems!
  - Distributed systems
  - Real-time systems
- Using functional languages for monitor generation

  eDSLs: “the benefits of functional languages applied to real-time embedded systems”
- Low-cost, high assurance

http://leepike.github.com/Copilot/



leepike/Copilot @ GitHub

http://leepike.github.com/Copilot/

Copilot

A (Haskell DSL) stream language for generating hard real-time C code.

Can you write a list in Haskell? Then you can write embedded C code using Copilot.
Here's a Copilot program that computes the Fibonacci sequence (over Word 64s) and tests for even numbers:

```
fib :: Streams
fib = do
  "fib" .= [0,1] ++ var "fib" + (drop 1 $ varW64 "fib")
  "t" .= even (var "fib")
    where even :: Spec Word64 -> Spec Bool
          even w = w `mod` const 2 == const 0
```

Copilot contains an interpreter, a compiler, and uses a model-checker to check the correctness of your program. The compiler generates constant time and constant space C code via Tom Hawkin's Atom Language (thanks Tom!). Copilot is specifically developed to write embedded software monitors for more complex embedded systems, but it can be used to develop a variety of functional-style embedded code.

Executing

```
> compile fib "fib" baseOpts
```

generates fib.c and fib.h (with a `main()` for simulation---other options change that). We can then run

```
> interpret fib 100 baseOpts
```

to check that the Copilot program does what we expect. Finally, if we have CBMC installed, we can run

```
> verify "fib.c"
```

to prove a bunch of memory safety properties of the generated program.

Differences From Lustre

- eDSL approach
- Polymorphic (embedded in Haskell)
- Simpler clock calculus—no projection operator
- BSD3
- V&V tools

Cheap assurance

Who watches the watchmen?

- Types are free proofs—use a typed language
- Reuse existing compiler infrastructure
- Automated random testing

    Ensure interpreter == compiler, millions of times

- Test coverage (line, branch, functional call) using *gcov*
- Automated back-end equivalence proofs (CBMC)

And it's all cheap & easy.

The power of eDSLs

- Some problems for conventional compilers go away
  - New language features are host-language macros
  - Don't need scripting languages
- E.g., compiling distributed monitors is just another host-language function:

```
compile program node
  (setCode (Just header)) baseOpts
```

```
distCompile program node headers =
  compile (program node) node
    (setCode (Just (headers node))) baseOpts
```