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Building Consensus: Foundations of Monitoring Ultra-Reliable Systems

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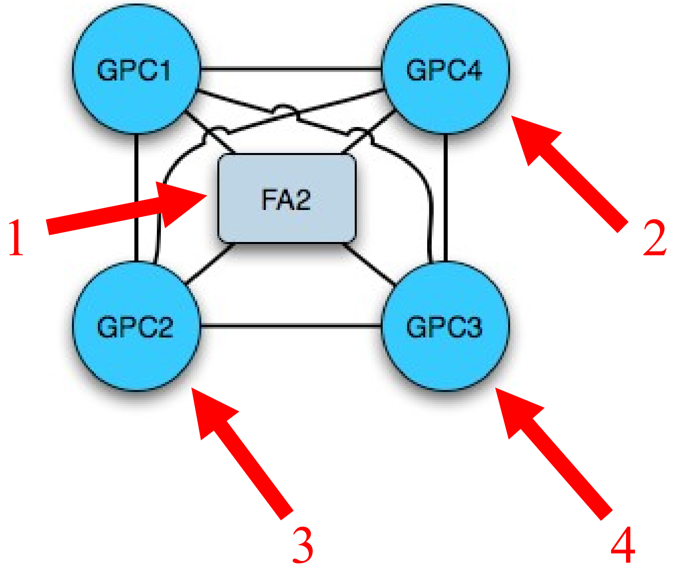
The Problem: Motivation

Space Shuttle

- In 2008, a pre-launch failure of STS-124 was reported in the Space Shuttle's data processing system.
- Components:
  - **FA 2**: the flight-aft mux/demux card
  - **GPC *n***: general-purpose computers *n*
- The incident:
  1. A diode fails on FA 2.
  2. GPC 4 receives bad data from FA 2; in the data comparisons with GPC 1-3, it is voted out.
  3. Then similarly for GPC 2.
  4. GPC 3 also determined to be faulty.
  5. With only one GPC remaining, the system was powered-down.
- Described as a "non-universal I/O error"



Characterizing the Systems

The systems we focus on must be ultra-reliable, and so demand catastrophic-failure rates of ≥ 10^{-9} per hour of operation.

- They're fault-tolerant, meaning they
- have replicated hardware & distributed architectures
- and have fault-management SW,
- and are hard real-time.

Previous Efforts

Previous research on monitors mostly focuses on systems lacking one or more characteristics of ultra-reliable systems.

- Much focus on *inline* monitors for software, particularly Java programs, e.g.,
  - Run-time Monitoring and Checking (MaC) – Insup Lee et al.
  - Monitoring-Oriented Programming (MOP) – Rosu et al.
- Efforts to compile specifications to efficient inline monitors.
- Specification-logics aim to capture properties about program traces.

Previous Efforts

A few efforts have touched on aspects of safety-critical embedded systems. Representative efforts include:

- MOP extensions to monitor distributed programs using a past-time modal logic.[1]
- BusMOP: synthesizing high-level specs onto FPGAs for zero-overhead bus monitoring.[2]
- Logics for monitoring real-time systems (particularly distributed Java programs).[3]

[1] [Sen, Vardhan, Agha, Rosu. Efficient Decentralized Monitoring of Safety in Distributed Systems, *ICSE*'04.]

[2] [Pellizzoni, Meredith, Caccamo, Rosu. *Hardware Runtime Monitoring for Dependable COTS-based Real-Time Embedded Systems*, *RTSS*'08.]

[3] [Mok and Liu. Efficient Run-Time Monitoring of Timing Constraints. *RTAS*'97.]

Research Agenda

- Our research aims at monitoring for faults. Specifically, we want to know when a fault is systematic or beyond the system's fault model.
- We focus on monitor synthesis for checking consensus in distributed hard real-time systems.
- So what's new?
  - Our approach marries runtime monitoring with fault detection.
  - We propose that HW & SW cannot be separated when considering reliability.
  - We focus on simple consensus properties.

Outline

1. ~~Context setting: previous work~~
2. Consensus properties
3. Monitor requirements
4. Conclusions

Consensus Properties

- We propose to monitor for consensus in distributed systems.
- What faults can be couched in terms of consensus?
    1. Fault-model violations
    2. Point-to-point error-checking
    3. Timing violations

Consensus Properties: Consensus

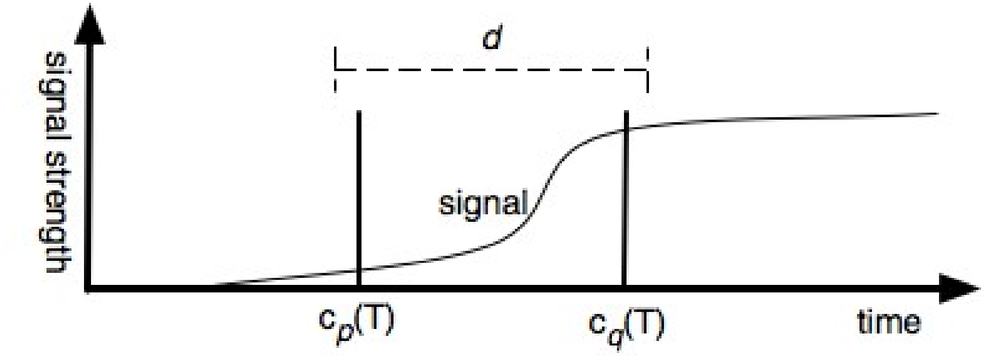
Monitoring fault-model violations

- A maximum fault assumption (MFA) states the maximum number of each kind of fault a system designed to withstand.
- An MFA along with the fault-arrival rate gives you its hypothesized reliability.
- Too often hypothesized reliability < actual reliability:
  - Design errors (i.e., systematic faults) cause the actual MFA to be a subset of the hypothesized MFA.
  - Designers underestimate the MFA required to achieve the desired reliability. The Shuttle incident arguably resulted from an underestimated MFA.

Consensus Properties: Consensus

- A monitor can observe consensus (or the lack thereof) between distributed components.
- This principally means observing classes of asymmetric or Byzantine faults (including omissive faults).
- It appears that Byzantine faults are also the most “malicious” and least accounted-for faults.
- Example: non-universal I/O error in the Shuttle!
- Monitors are bound by the “laws” of distributed-system observation (given real-time clocks). This means there's some probability of false-positives and false-negatives.

  Example:



Consensus Properties: CRCs

Monitoring point-to-point error-checking

- Point-to-point error-checking provides evidence to a receiver that a message got corrupted in transit.
- Cyclic redundant checks (CRCs) are standard practice for catching point-to-point communication errors in embedded systems.
- They can catch both burst errors and random bit-errors.

Consensus Properties: CRCs

- Reliability figures for distributed embedded systems depend on the error-checking reliability of CRCs...
- But reliability figures may be overly-optimistic:

> “...The use of CRCs as a mechanism to provide ultra-dependable system operation (10^{-9} failures/hour) is questionable in many cases. The main problem is that network inter-stages can exhibit arbitrary faults, accidentally forging valid CRC check sequences.”[1]

[1] [Paulitsch, Morris, Hall, Driscoll, Koopman, & Latronico. *Coverage and the Use of Cyclic Redundancy Codes in Ultra-Dependable Systems*, DSN’05.]

Consensus Properties: CRCs

For example, consider the case of “Schrödoinger’s CRCs”:[1]

	11-Bit Message	USB-5
Receiver A	1 1 1 1 1 1 0 1 1 0 1	1 0 0 0 1
Transmitter	1 1 1 1 1 1 0 1 1 0 ½	1 ½ 0 ½ 1
Receiver B	1 1 1 1 1 1 0 1 1 0 0	1 1 0 1 1

- (USB-5 has a Hamming Distance of 3 for 11-bit data.)
- No good data exists on the real-world probability of Schrödoinger’s CRCs.
- Probably more likely than commonly believed.

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[1] [Driscoll, Hall, Sivencrona, & Zumsteg. Byzantine Fault Tolerance, from Theory to Reality, SAFECOMP’03.]

Consensus Properties: Timing

Violated timing assumptions

Hard realtime systems have timeliness guarantees, provided system timing assumptions hold.

- The timing assumptions are constraints on clock drift, skew, message delays, resynchronization, etc.
- Constraints cannot be monitored directly.
- (A monitor has no more access to real-time than the what's monitored.)

Consensus Properties: Timing

- Constraints talk about real-time (i.e., wall-clock time).
- For example: here's a *clock drift-rate* constraint:

$$\lfloor (1-\rho)\cdot(t_1 - t_2) \rfloor \leq C(t_1) - C(t_2) \leq \lceil (1+\rho)\cdot(t_1 - t_2) \rceil$$

- But violations of constraints will manifest themselves as systematic faults (i.e., greater than the expected fault-arrival rates).
- And faults are likely to be slightly-out-of-spec timing errors.
- Challenge: determining when a fault is frequent enough to be a systematic fault.
- Techniques for probabilistic runtime checking in soft real-time systems are applicable.[1]

[1] [Sammapun, Lee, Sokolsky, Regeher. Statistical runtime checking of probabilistic properties, RTV'07.]

Architectural Considerations

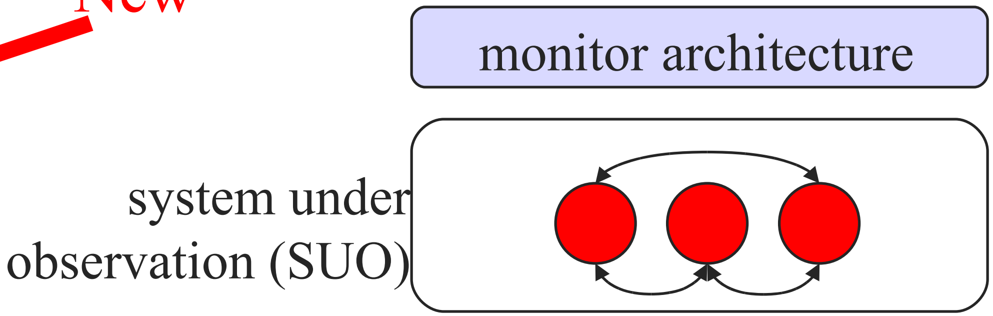
- What are monitors:
  - Inputs are local state projections.
  - Data are fault-arrive probabilities and state-collection times.
  - State is occurrence frequencies.
  - Outputs are consensus violations.
- Where does the the monitor “go”?
  - Two architectural approaches:
    - Distributed: monitors at the distributed nodes, and interchange “consensus data”.
    - Central: nodes send “consensus data” to a central monitor.
  - Resulting in various reliability/cost tradeoffs.
  - Want to be able to synthesize multiple architectures.

Monitor Architecture Requirements

- What general requirements are there for **monitor architectures?**

- We propose three requirements covering
  - *Functionality*
  - *Schedulability*
  - *Reliability*

New



Monitor Architecture Requirements

- *Functionality*: the monitor does not change the functionality of the *system under observation* (SUO), unless the SUO violates its specification.
  - Unintentional: safe-guards must be in place to ensure that monitor faults do not affect the SUO's functionality.
  - Intentional: the monitor must signal a reset, etc. to the SUO only if the SUO has (probably) violated its specification.
- *Schedulability*: the monitor architecture does not cause the SUO to violate its hard real-time guarantees.
- *Reliability*: the reliability of the SUO in the context of the monitor architecture is greater or equal to the reliability of the SUO alone.

  A monitor might reduce the SUO's reliability for some class of faults of (improbable) faults and yet increase the system's overall reliability.

Synthesis

- In other monitoring work, the synthesis challenge is
  - Synthesizing efficient monitors from expressive high-level specifications.
  - Inlining the monitors into the system.
- In ours, the challenge is to
  - Synthesize multiple architectures and ensure noninterference with the observed system.
  - Synthesize reliability data (to probabilistically distinguish systematic and random faults).
  - Synthesize temporal constraints on monitoring.

Anticipated Developer Workflow

In our context, the system designer

- Instruments processes to make "consensus data" available to the monitor (e.g., memory access).
- Provides random fault-arrival probabilities.
- Defines a monitor architecture.
- Play a game:
  - Do you assume consistency at this point in the algorithm/architecture?
  - Then assert consensus.
- Orthogonal to any fault-tolerance in the system.

Conclusions: Comments on the Approach

As compared to other monitoring frameworks...

Benefits:

- Thesis: consensus violations characterize a simple but broad class of faults.
  - Consensus violations characterize recent failures.
  - Consensus is hard and the assumptions are often wrong.
  - Many SW faults are about coordination and fault-tolerance rather than the core GN&C algorithms.
- Takes a unifying view of HW and SW.
  - Reliability is a function of (1) systematic and (2) random faults.
  - Thus, we take a system-level viewpoint of monitoring.

Conclusions: Comments on the Approach

As compared to other monitoring frameworks...

Challenges:

- In ad-hoc systems, which state-projections should be in agreement at which times?
- Synthesizing monitoring architectures.
- Are false-positive/negative observations acceptable (for ultra-reliable systems)?
- Is the δ-increase in reliability sufficient to warrant monitoring?

Conclusions: Summary

- Ultra-reliable systems may benefit from runtime monitoring, but new approaches are needed.
- Important classes of faults can be couched in terms of consensus.
- The synthesis problem for these monitors include architectural integration and including hypothesized fault-arrival rates.
- Our hope is that “cheap and easy” consensus monitors encourage better design practices.

Conclusions

More details:

- Extended abstract accepted in the *Software Health Management Workshop* (SHM'09).
- Submitted: paper on our real-time test-bed and automated-test framework.
- In preparation: technical report survey & foundations of monitoring real-time distributed systems.
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