Comparing and Validating Measurements of Dependability Attributes

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Introduction

- Fault injection is becoming widely used in the development of safety-related systems.
  - The upcoming ISO 26262 lists fault injection as highly recommended for ASIL C and D.
- Numerous fault injection tools and techniques exist today.
- These techniques and tools all have their pros and cons.
- Many factors can affect the results of fault injection experiments.

Open issues

- *Can results be reproduced using different fault injection techniques?*
- *What are the sources of uncertainties?*

Contributions

We evaluate the metrological compatibility of measurement results obtained by three diverse fault injection techniques.

- Identify sources of uncertainty.
- Investigate if results obtained by the three fault injection techniques can be compared.
- Validate the correctness of the implementation of each technique.

Metrology – Basic concepts

- Fault injection tools can be seen as measurement instruments.
  - Discussed by Bondavalli and Vadursi in DSN 2007.
- The measurand is the quantity intended to be measured.
- Measurement results in general consist of
  - A measured value
  - A measurement uncertainty
- Uncertainty expresses doubt about the validity of a measurement result.
  - Characterizes the dispersion of values that could be attributed to a measurand.
- Measurement results are metrological compatible if they refer to the same measurand.

Sources of uncertainty in fault injection

Measurement results are affected by

- Initialization uncertainty
  - Non-initialized memory values in a computer system
- Spatial and temporal intrusiveness
  - Changes made to the target system needed for the experimental evaluation.
- Assumptions in the measurement procedure
  - Unforeseen external events, or internal events affecting the target system, *e.g.*, caused by design flaws in the hardware or software.
- Instrumental uncertainty
  - The tools used for the measurements are not always validated.
- ...

Investigation of uncertainties

Objectives

- Identify sources of uncertainty in our experimental setup
- Validate the implementations of three diverse techniques

The same set of faults was injected using:

- Test port-based injection
- Instrumentation-based injection
- Exception-based injection

Experiments were conducted with two target systems.

- A brake-by-wire controller running on a MPC565 microcontroller.
- SECERN – A real-time kernel running on a MPC5554 microcontroller.

The GOOFI-2 fault injection tool

The previous version of GOOFI provides:

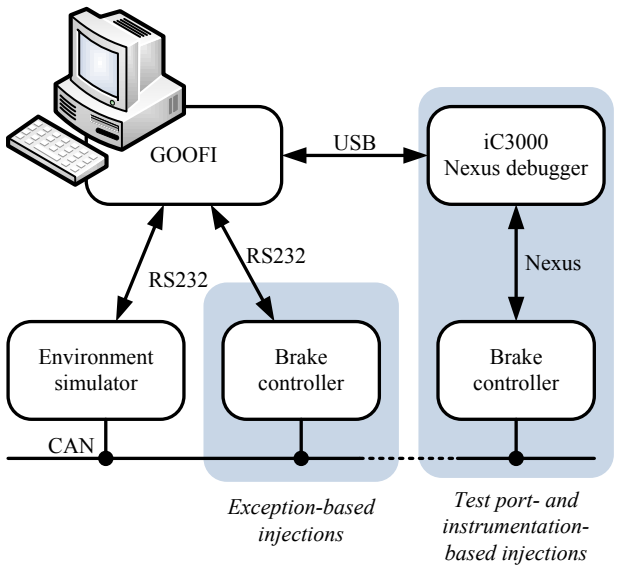
- **Test port-based injection**
  - Uses a Nexus-compliant debugger to injects faults.
  - No spatial intrusiveness, but high temporal intrusiveness.

The current version adds support for two well-known techniques:

- **Instrumentation-based injection**
  - Software-implemented technique that instruments the executable file with a fault injection routine.
  - Low temporal intrusiveness, but also low observability
- **Exception-based injection**
  - Injects faults using exception routines that are activated by hardware exceptions.
  - Low temporal intrusiveness, but high spatial intrusiveness.

Brake-by-wire controller

- Designed specifically for future brake-by-wire systems.
- Software-implemented mechanisms for detection and recovery of transient hardware faults.
- Injected the exact same faults using all three techniques.
  - Single bit-flip errors in general purpose registers and the data memory (1000 injections each).



Results – Brake-by-wire controller

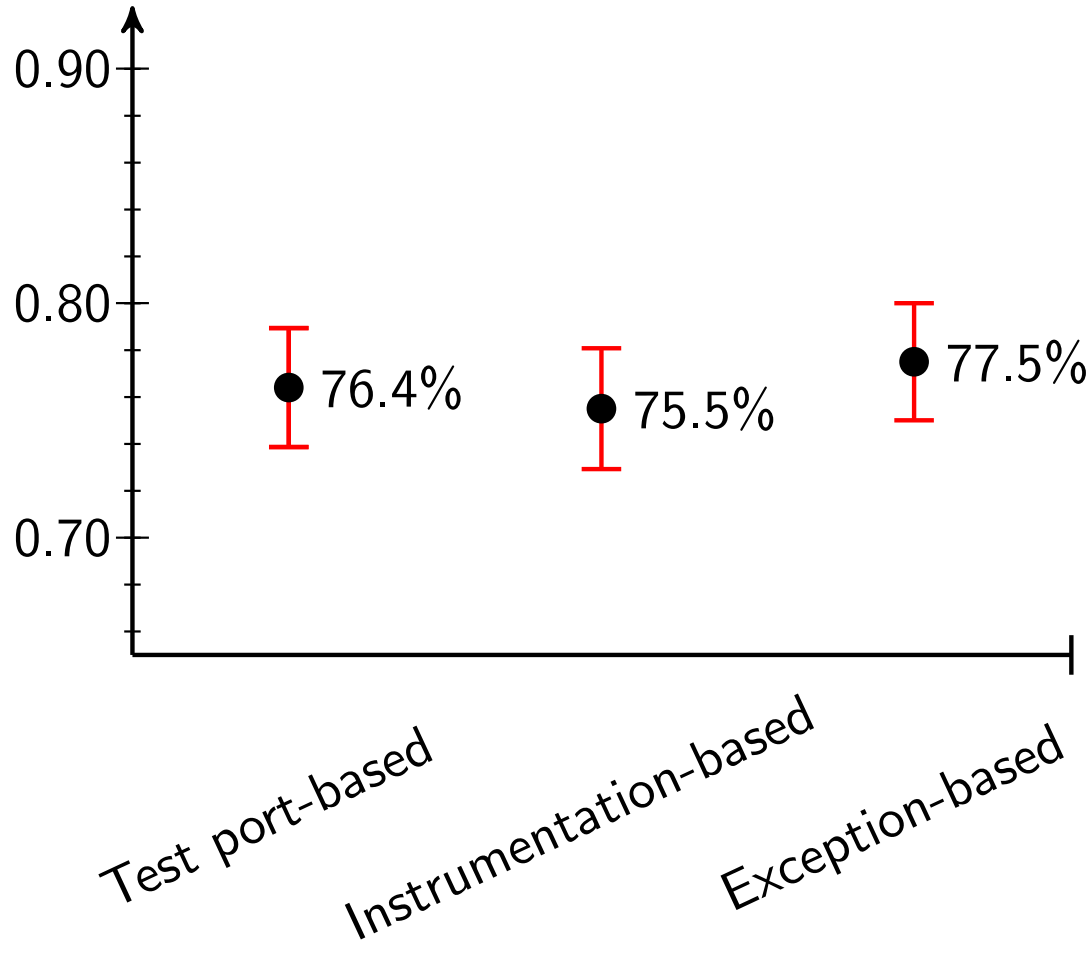
- All three techniques produced identical results for errors injected in memory.
- Faults injected in general purpose registers had different outcomes in several cases.

Test port/instrumentation-based:	99% experiments matched
Test port/exception-based:	93% experiments matched
Exception/instrumentation-based:	92% experiments matched

Results – Brake-by-wire controller

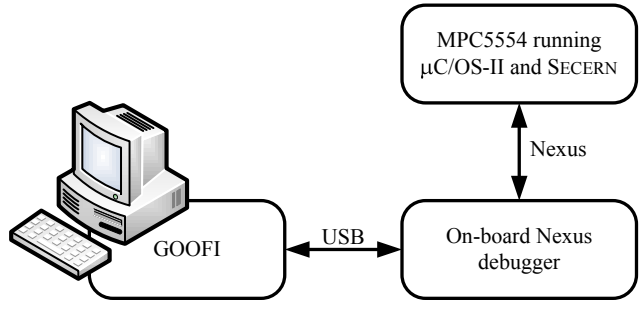
Errors injected into registers (GPRs)

Proportion of incorrect outputs and the 95% confidence interval



SECERN

- Extension to the μC/OS-II real-time kernel that provides robust partitioning.
  - Ensures that a faulty task cannot affect the kernel or other tasks using, *e.g.*, memory protection.
- A task's accessible memory is initialized at startup.
  $\Rightarrow$ Initialization uncertainty is minimal.
- Injections of single bit-flip errors using the test port-based and the instrumentation-based technique.
  - The fault set included 1000 injections in general purpose registers and 1000 injections in the data memory.



Results – SECERN

- The two techniques obtained identical results, except for a single fault.
- This fault was injected into an unused register.
  - Instrumentation-based injection caused a task to be removed.
  - Test port-based injection did not have any impact.
- We could not reproduce this behavior by repeated injections of the specific fault.
  - Subsequent injections were all classified as having no impact.

Identified sources of uncertainty

- Brake-by-wire controller
  - *Initialization uncertainty* caused differences in the outcome of many individual experiments for all three techniques.
  - The high *spatial intrusiveness* of the exception-based technique caused additional differences in the obtained results.
- SECERN
  - The different outcome for the single fault was attributed to *assumptions in the measurement procedure*.

Tool validation

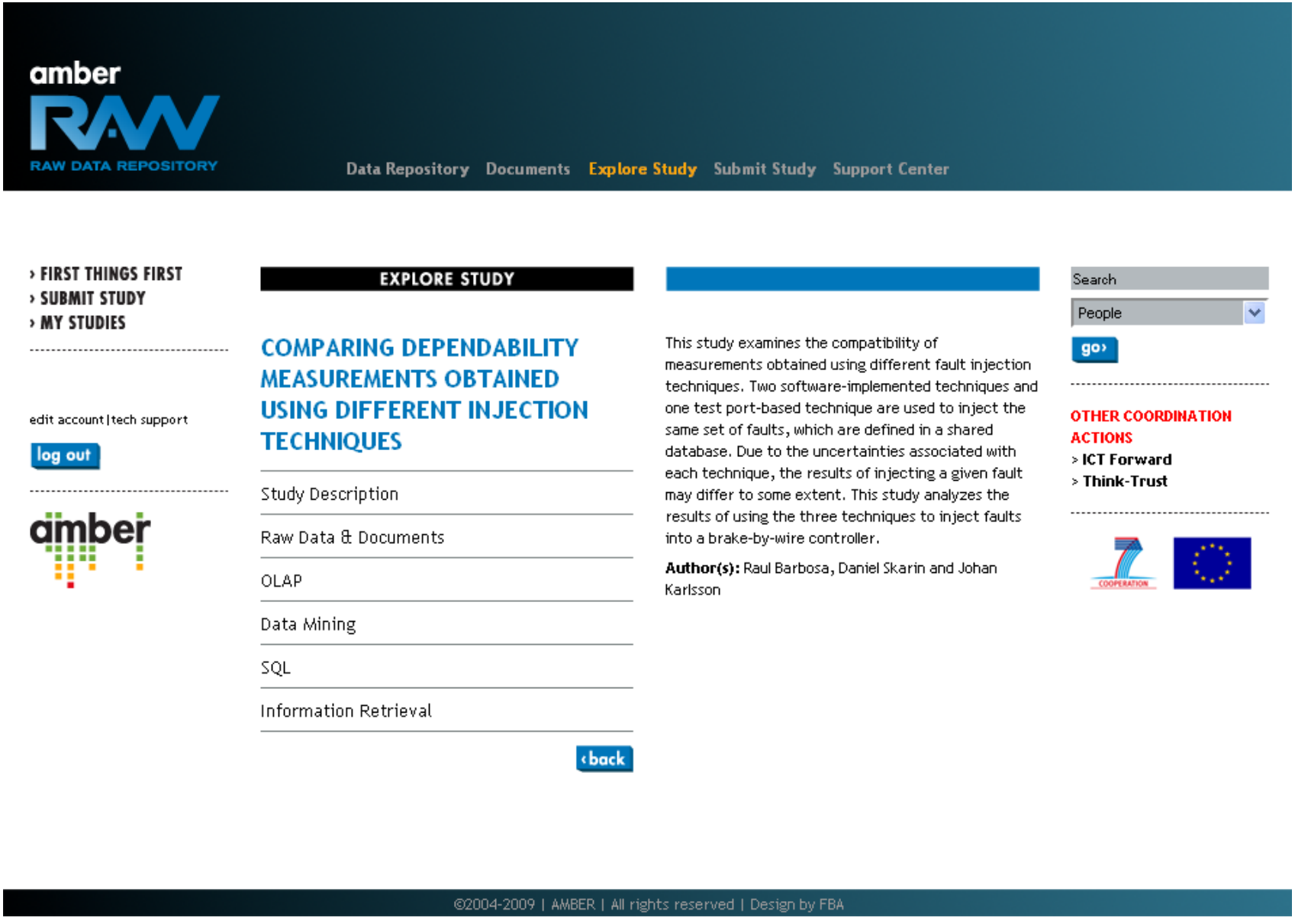
- The three techniques produced similar average results over a large number of experiments.
- The cases in which the outcomes differed were not caused by bugs in the tool, but rather by measurement uncertainties.
- We can therefore be confident that the instrumental uncertainty is minimal.
- If we also consider the temporal aspect, the techniques may produce different results due to variations in their temporal intrusiveness.

Conclusions

- We identified three sources of uncertainty affecting our three fault injection techniques
- The outcome of many individual experiments was affected by these uncertainties.
- These uncertainties were related to injections in general purpose registers.
  - The proportion of individual experiments with different outcome varied from 1% to 8%.
- Despite these uncertainties, the results obtained from the different fault injections techniques were similar.
- Our results show that the three techniques obtain metrologically compatible results.

Future work

- Quantify the identified uncertainties.
- Investigate how results for a given system in a specific environment can be be extrapolated.
- Study how the number of experiments affects fault forecasting estimations and fault removal effectiveness.

Fault injection results available on-line

http://www.amber-project.eu