Automated Proof with Caduceus: Recent Industrial Experience

Dan Sheridan (djs@adelard.com)

About this talk

- This is a **fuzzy** talk, not a **maths** talk.
- I want to tell you about using an automated verification tool on a real piece of industrial code.
- I can't show you code or annotations because of the NDAs that make this work possible.
- Hopefully there will still be something interesting for the automated verification community!

Contents

EAST and FEAST

- **CINIF**, the Control and Instrumentation Nuclear Industry Forum funds applied research on behalf of the nuclear operating companies
- “**Experience with Advanced Static Analysis**” was funded by CINIF in 2001 to focus on analysing off-the-shelf computer systems in nuclear control applications
- It became “**Further Experience with Advanced Static Analysis**” in 2002. (After that we ran out of clever ideas for names)
- We looked at the effectiveness and cost of various techniques (from Lint up to Hoare logic-style proof) and their compatibility with safety cases

Smart sensors

- Little embedded computer systems: replacements for analogue level alarms and transmitters, with a bit more intelligence.

Why smart sensors?

- Lots of reasons for spending lots of effort on smart sensors:
  - Pure analogue sensors are **disappearing**
  - There is increasing **demand** for them from the stations
  - They are very **simple**, from an algorithmic point of view – they don't do very much, except linear arithmetic, table lookups, and I/O
  - They are typically written **without an OS**, removing much of the potential complexity
- The next step up, from a C&I point of view, is PLCs – fully programmable, real-time OS, ...

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Industry situation

- The nuclear industry is a small customer, so doesn't have much leverage with the manufacturers. *If we want formality, we have to do it ourselves.*
- Surprising interest from one supplier: in FEAST we have worked with three devices (one assembler and two C) and the supplier has even taken on board our comments.
  - FEAST4, 5 and 6 focus on the latest of these devices

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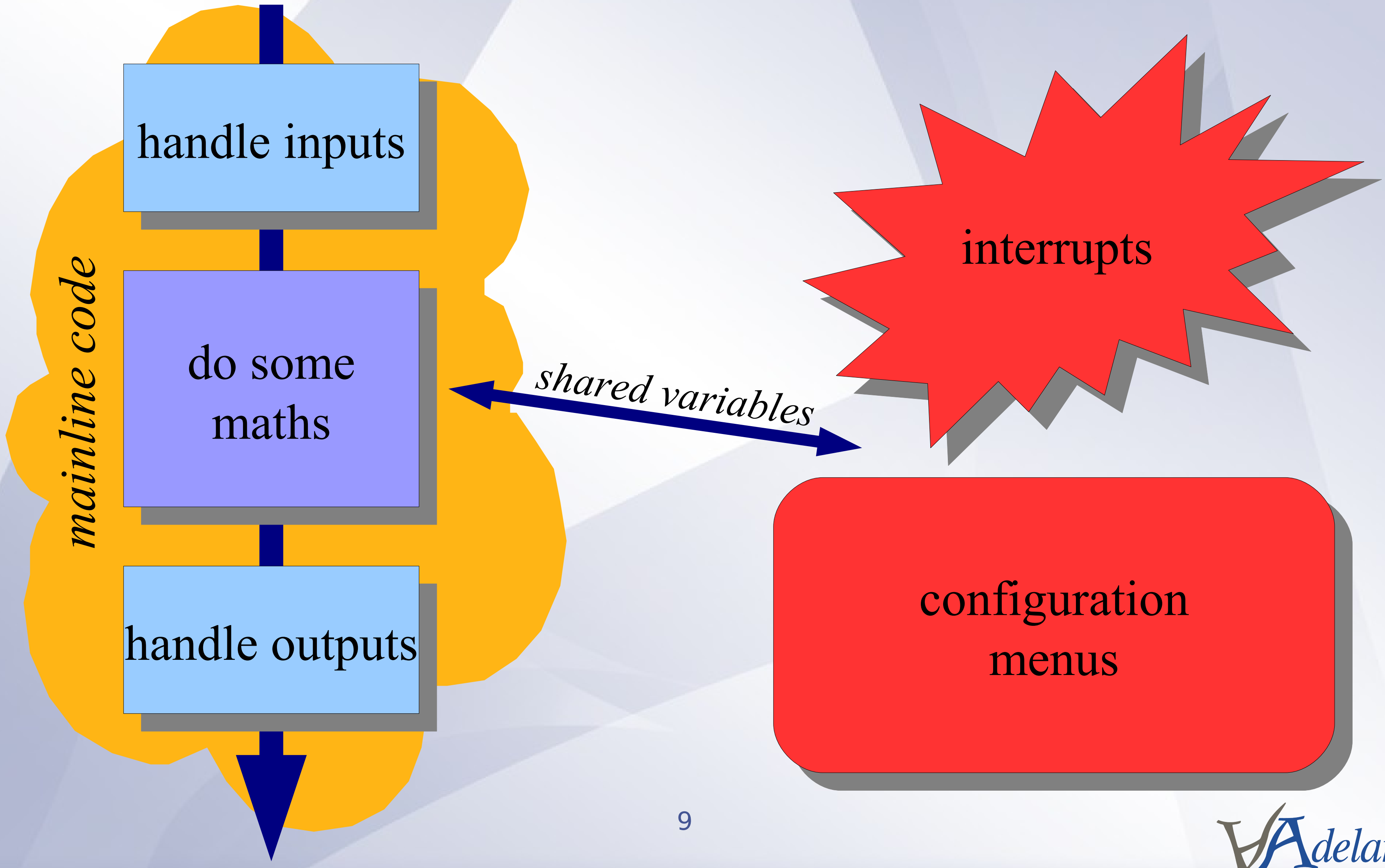
Rough block diagram



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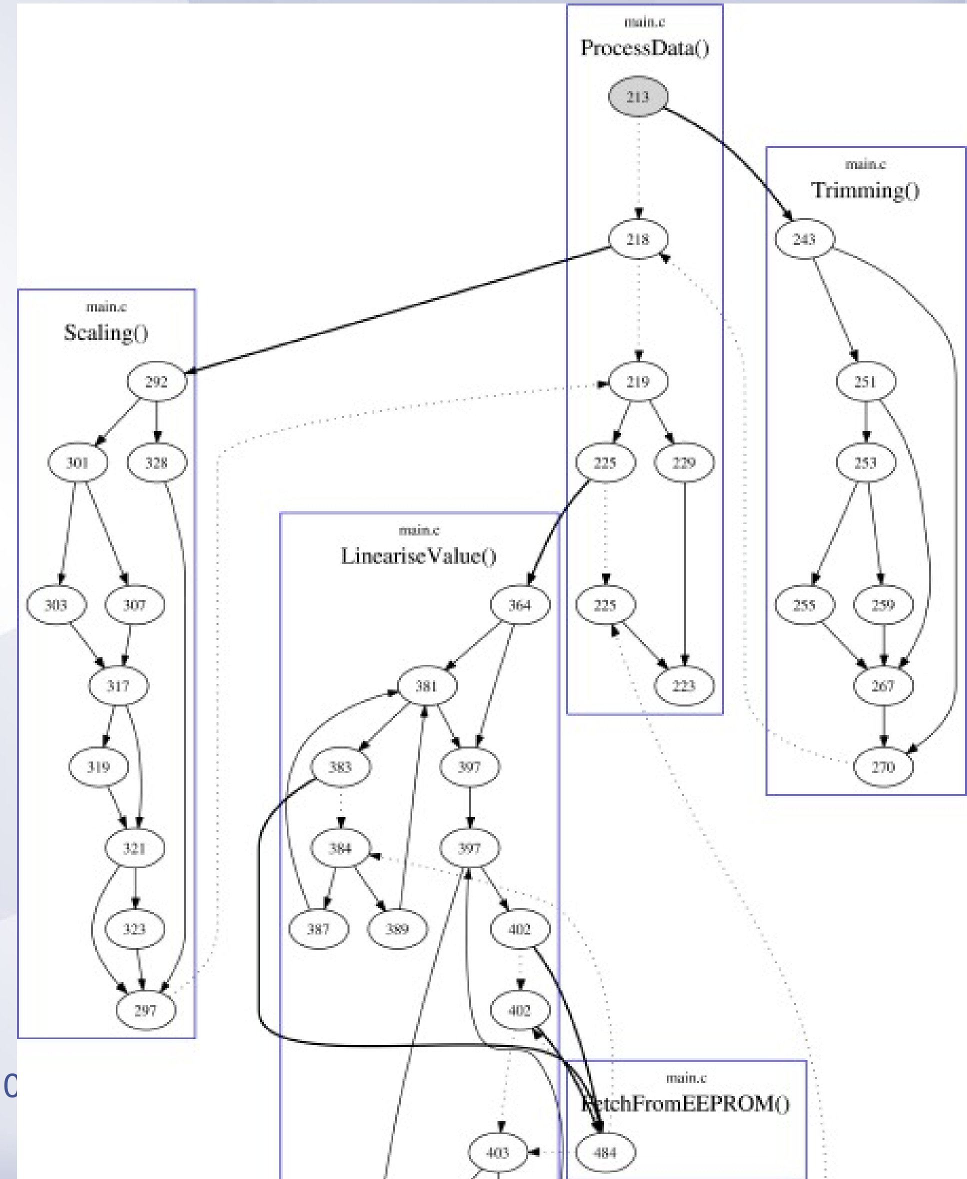
The FEAST4 manual proof

- Out of **10,000** lines of code, we focused on **200** that do the main transformation of the process variable (the bulk of the code is concerned with the serial interface and the menu system).
- In FEAST5 we explored the problem of arguing that the rest of the code doesn't invalidate the proofs.



Why was it hard?

- Documentation shortcomings
  - At least we had some!
  - It didn't really agree with itself, and it wasn't written with verification in mind
- Constructing specifications
  - We had to make up a formal spec – based on the documentation, the code, the comments, and what we thought it was supposed to do
- Presenting the work
  - Enough information to be repeatable
- We estimate
  - 2 days to write the specs, 1 day of analysis, and 5 days of presentation

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  - The good
  - The bad
- Some **conclusions**

Mechanising the proofs

- Why?
  - Less (or differently) error-prone than manual proof
  - More scalable than manual proof
  - Repeatable, once annotations have been developed
- Advantages of Caduceus/Why tools
  - Ability to use SMT decision procedures
  - Diverse backends
  - Operate directly on C (unlike Malpas, the current tool of choice in the nuclear industry)

A process for using Caduceus

- Is this obvious? One of the nice things about Caduceus is that it enables a rapid **edit/prove/debug** cycle.
- For each function:
  - Run Caduceus on the source to find out what it's going to choke on:
    - —Unions, strings, and unsafe pointer manipulation
  - Try a precondition and a postcondition for each case in the specification
    - —Discover unexpected proof failures (more on this later) as well as incorrect specs
  - Put the specs back together to make a “one-click” proof

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Language barriers

- Caduceus handles most of C, but leaves out some constructs (especially **union**, **strings**, **unsafe pointers**).
  - We want to avoid changing the code, though.
  - Must be careful with anything we do to it to push it through the tools – is it really still the same code?
- Interesting overlap with **Safer C** recommendations explored in FEAST4, though – we've already tried to avoid some of these issues.

Old habits die hard

```
#include <stdio.h>;
#include <math.h>;

const char *Ver = "1.1";
```

- We don't need complex headers, but programmers often throw them in out of habit
- The only use of strings in this signal processing software – ignore it

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Memory accesses

```
addr = (float*)(x+(int)y);
return *addr;
```

- Lucky in this case – access is to a table in EEPROM. Essentially an array lookup because b[x+y] is equivalent to *(&b+x+y)

Unions

```
union FloatToByte {
    float F;
    long L;
};
```

- Not the classic use of unions (to produce sum types); this is a **type-hack**. Used to check whether the EEPROM has been initialised – we want to read floats, but check whether the bit pattern is all 1s.
  - Fixed by replacing the union with a float only, and dropping the initialisation check. Unsafe?
- There are other union datatypes in the header files – but the types aren't used in the interesting code, so we commented them out.

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Experience of applying Caduceus

- **Success** in that we found a mismatch between the spec and the code, missed in the manual proof – neatly illustrates the advantage of the approach
  - The mistake wasn't a big deal, though – it's to do with the value of the process variable in the divide-by-zero case, which is later discarded.
- **Cost-effective** – the distribution of time was slightly different from manual proof, but more scalable:
  - Creating spec: 2 days
  - Preparing for Caduceus: 3 days
  - Executing Caudceus: 3 days

The divide-by-zero problem

```
float example(float w, x, y) {
  if (x-y = 0)
     /* Raise an error */
  else
     return w/(x-y);
}
```

- Clearly, no divide-by-zero can occur (although there is danger of overflow...)
- Caduceus adds precondition $x - y \neq 0.0$
- but the conditional provides $x - y \neq RealOfInt(0)$
- and our specification initially isolated the cases with $x \neq y$

Divide-by-zero and solvers

- What do solvers think of $x - y \neq 0.0$, $x - y \neq RealOfInt(0)$ and $x \neq y$?
- CVC3 (in SMTLIB mode) cannot relate any of these
- Yices (SMTLIB) barfs on `w/(x-y)`
- CVC3 (in CVC-lite mode) treats integers as a subset of the reals, so has no trouble

Caduceus: the good

- Operates on **nearly unmodified C** – it's easy to argue that the proofs carry across to the real code
- **Easy to use** – the GUI is brilliant, and allows us easy access to lots of solvers
- **Solver diversity** – brings both confidence (when the solvers agree) and strength (when some solvers succeed and some don't)

Caduceus: the bad

- The GUI could be more supportive: it's possible to figure out which path through the code is being considered by the structure of the proof; the GUI could support this to help find spec problems.
- The frontend should ignore stuff that's not used – e.g., rather than die on unions, only die when they are instantiated.
- It would be nice to be able to specify multiple pre/post-condition pairs, rather than having to do the case split manually.
- The real output of the solvers is hidden in the terminal window and the debug option. More parsing?

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Conclusions: my views

- The multiple-solver situation is reminiscent of BlackBox (planning-as-SAT system). Will a **zchaff** of the SMT world emerge and make it all pointless?
- In the course of the FEAST projects, we've also looked at partial evaluation and flow graph generation (using Sparse); an all-in-one tool would be nice. **Frama-C**?
- I hate not being able to provide more detail on this work – hopefully we'll be able to eventually release something anonymised or abstracted.

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