Integrating Formal Program Verification with Testing

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Workshop on Theorem Proving in Certification
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Outline

Project Hi-Lite

Application to Nose Gear Velocity

Tool Qualification
Unit proofs vs. unit tests

unit tests are costly to develop and maintain

use instead unit proof:

1. express LLRs as function contracts
2. interpret code+contracts in Hoare logics
3. use Dijkstra’s WP calculus to generate VCs
4. prove VCs with automatic prover

unit proof used industrially:

- SPARK toolset (SPARK code): data/information flows, run-time errors
- Frama-C platform (C code): contracts and run-time errors

DO-178C supports replacing unit tests with unit proofs
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How do we define contracts?

usual approach: first-order logic + program locations
  ▶ problem! avoid inconsistencies
      solution? generation of models
  ▶ problem! detect incorrect contracts
      solution? generation of counterexamples

our approach: pure Boolean expressions (no writes)
  ▶ avoid inconsistencies? forbid axioms
  ▶ detect incorrect contracts? test/execute
  ▶ possible effects? analyze and reject
  ▶ possible run-time errors? generate VCs and prove
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How do we deal with unprovable code?

usual approach:

1. restrict language to potentially provable subset
2. use multiple automatic provers
3. write proof script in proof assistant
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The three pillars of formal methods in DO-178C

Unambiguous formal semantics

match compiler choices of sizes & alignments for target
prevent compiler-dependent behavior:

▶ functions (not procedures) cannot have side-effects
▶ expressions cannot have side-effects
▶ arithmetic expressions are parenthesized if needed

Sound formal analysis

deductive verification à la Hoare

Justified assumptions for proofs

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formal verification of $P$ assumes:

- precondition of $P$
- postcondition of subprograms called
- both user-defined and implicit ones

assumptions made for proof should be verified by testing

2 cases:

- tested $T$ calls proved $P$
  $\rightarrow$ check precondition of $P$ at run-time
- proved $P$ calls tested $T$
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- ...during test of $T$!
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2. effects: generated (restrictions on complete program)

3. strong typing:
   - strongly typed language (Ada)
   - forbid unsafe language features (pointer conversion)
   - proof: generate VCs
   - test: compiler inserts checks

4. non-aliasing:
   - limit proof to subset with references (no pointers)
   - global static analysis for non-aliasing with globals
   - proof: semantic verification for parameter non-aliasing
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Tool Qualification
two different types of data:
- external counters with modulo semantics
- non-negative values for time/distance/velocity

coded in C example as unsigned causing 4 kinds of errors in code:

1. useless wraparound code
2. wrong wraparound: 65534 - (prevTime - thisTime)
3. inconsistent pattern: if (prevCount < thisCount)
4. copy-paste error: currTime or thisTime for t3?

in Ada, modulo integer (semantics) ≠ non-negative (constraint)
two dimensions: distance and time
three combinations: velocity, acceleration, jerk
many units: distance (cm, m, inch), time (ms, s), velocity (km/h)

vulnerability in code:
\[
\text{static init whcf = } \ldots \times 254) / 7) \times 22) / 100;
\]
equivalent to
\[
\text{static init whcf = } \ldots \times 254) \times 22) / 7) / 100;
\]
only up to \text{WHEEL_DIAMETER} = 51

errors in code:
1. wrong conversion: missing /100 for maxMsecs
2. wrong conversion: *500 should be *50 for maxClicks
package SI is new Constrained_Checked_SI (Float);
package U is new SI.Generic_Units;
use SI, U;

Pi : constant := 3.14;
Inch : constant Distance := 2.14*centi*Meter;
WHEEL : constant Distance := 26.0*Inch;
WHCF : constant Distance := WHEEL * Pi;

PrevCount : Count := 0;
PrevTime : Time := 0.0*milli*Meter;

raised NG.SI.SI.UNIT_ERROR :
    unconstrained_checked_si.adb:72
    instantiated at constrained_checked_si.ads:204
    instantiated at ng.ads:9
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Compile-time dimensional analysis in GNAT

1 subtype Time is Natural with
2   Dimension (second => 1, others => 0);
3 subtype Distance is Natural with
4   Dimension (meter => 1, others => 0);
5 subtype Count is Natural;
6 subtype Velocity is Natural with
7   Dimension(meter => 1, second => -1, others=>0);
8
9 WHEEL : constant Distance := 26;  -- inches
10 WHCF : constant Distance :=  -- cm
     (((WHEEL * 254) / 7) * 22) / 100;
11
12 PrevCount : Count := 0;
13 PrevTime : Time := 0;  -- ms
update should not occur if no new click
translated as precondition:

```plaintext
procedure ComputeNGVelocity
(CurrTime : in Mod_Time;
 ThisTime : in Mod_Time;
 ThisCount : in Mod_Count;
 Success : out Boolean;
 Result : out Velocity)
with
Pre => ThisTime /= PrevTime
    and then ThisCount /= PrevCount;
```

explicit precondition avoids error in C example:

```plaintext
if (thisTime = prevTime) return;
...
if (thisCount = prevCount) {
...
procedure ComputeNGVelocity (...) is
  T1, T2 : Time;
  D1, D2 : Distance;
begin
  if ThisCount − PrevCount < ThisTime − PrevTime
  then
    Success := False;
    return;
  end if;
  T1 := Time (ThisTime − PrevTime);
  T2 := Time (CurrTime − ThisTime);
  D1 := WHCF * Count (ThisCount − PrevCount);
  D2 := (D1 * T2) / T1;
  Success := True;
  Result := ((D1 + D2) * 3600) / (T1 + T2);
end ComputeNGVelocity;
Formal verification for run-time errors

ng.adb:49:28: range check not proved
ng.adb:50:28: range check not proved
ng.adb:51:18: (info) overflow check proved
ng.adb:51:18: (info) range check proved
ng.adb:52:17: overflow check not proved
ng.adb:52:23: (info) division check proved
ng.adb:52:23: (info) overflow check proved
ng.adb:52:23: range check not proved
ng.adb:55:23: overflow check not proved
ng.adb:55:29: overflow check not proved
ng.adb:55:37: (info) division check proved
ng.adb:55:37: (info) overflow check proved
ng.adb:55:37: (info) range check proved
ng.adb:55:43: (info) overflow check proved
procedure ComputeNGVelocity (...)

with

Pre => ThisTime /= PrevTime

and then ThisCount /= PrevCount,

Post =>

(if Success then

Result = Velocity(

((WHCF × Integer (ThisCount−PrevCount)) +
((WHCF × Integer (ThisCount−PrevCount))

* Integer (CurrTime − ThisTime))

/ Integer (ThisTime − PrevTime))

* 3600)

/ Integer (CurrTime − PrevTime)));
change code from

1  D2 := (D1 * T2) / T1;

to erroneous

1  D2 := (D1 + T2) / T1;

leads to

raised SYSTEMASSERTIONSASSERT_FAILURE:
  failed postcondition from ng.adb:33
Formal verification of contract

ng.adb:24:15: postcondition not proved
ng.adb:27:27: (info) overflow check proved
ng.adb:27:62: overflow check not proved
ng.adb:28:29: (info) overflow check proved
ng.adb:29:22: (info) overflow check proved
ng.adb:30:22: (info) division check proved
ng.adb:30:22: overflow check not proved
ng.adb:30:22: overflow check not proved
ng.adb:31:19: overflow check not proved
ng.adb:32:19: (info) division check proved
ng.adb:32:19: overflow check not proved
procedure UpdateNGVelocity with
    Post =>
    (if EstimatedGroundVelocityIsAvailable then
        EstimatedGroundVelocity =
        (DistanceSinceLastClickBeforeLastUpdate
         * 3600)
        / TimeSinceLastClickBeforeLastUpdate);

function DistanceSince... return Distance is
    (DistanceFromLastClickToLastUpdate
     + DistanceSinceLastUpdate);

function DistanceFrom... return Distance is
    (WHCF * (ThisCount - PrevCount));
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Tool Qualification
1. used for requirement based verification (replaces unit testing) ⇒ TQL-5
2. used for robustness verification (replaces robustness tests) ⇒ TQL-5
3. used for both ⇒ TQL-4 (levels 1 and 2) or TQL-5
4. TQL-4 & TQL-5: Tool Operational Requirements are defined
5. TQL-4: TORs are complete, accurate and consistent
6. TQL-4: tool requirements are developed and verified
Objective B: tools are qualified

- formalism: first-order Hoare logics + run-time checks
- software tools: compiler + translator + VCgen + prover
- assumptions: user-defined contracts + implicit contracts
- all the chain is FLOSS ⇒ facilitates duplication
- soundness argument for each piece
- prover removed from qualification if produces checkable trace
- super qualification: formally proved correct (VCgen, prover)
Objective C: software requirements

1. complete
   ▶ divide contract in cases (behaviors in JML)
   ▶ contract cases cover the precondition

2. consistent
   ▶ contract cases are disjoint
   ▶ consistency can be expressed and checked:
     \[ \forall inputs \in Pre. \exists outputs \in Post. Pre \Rightarrow Post \]

3. unambiguous
   ▶ expression as Boolean predicates

4. verifiable
   ▶ by testing or formal verification
Objective K: source code vs. software requirements

1. compliance
   ▶ contract-based verification (testing or proving)

2. traceability
   ▶ by nature, contracts are attached to function
http://www.open-do.org/projects/hi-lite/