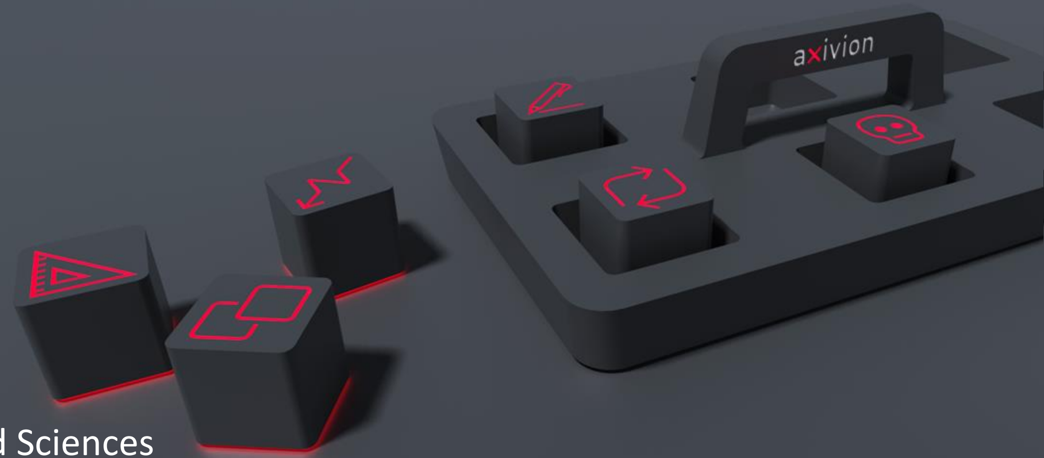
A Verified Low-Level Implementation of the Adaptive Exterior Light and Speed Control System



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This one is a little different than what we usually have at ABZ.

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Differences to Other Case Studies

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- We did not follow a (fully?) formal approach to the case study
- Instead:
    - Implemented ELS and SCS in low-level C
    - Used test-driven development
    - After some implementation, used model checking (on C!) for verification
- Attempted an approach closer to industry
    - No offense here!
    - Understand differences to help industrial uptake of FM
    - Provide a baseline to argue about advantages of FM in other case study realizations

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Why Baselining?

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- Some time ago, we read
  - Seven Myths of Formal Methods – Hall
  - Seven More Myths of Formal Methods – Bowen & Hinchey
- Both discuss myths regarding the costs of using FM and disprove them
- Yet, case studies implementing a system both formally and non-formally are
  - Done only seldomly
  - Often done either by teams of FM experts or non-experts
  - Tend to the extremes: all formal or not formal at all

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- Test-driven development
  - For functional requirements
  - Realized using cmockery & ctest
- Restricted language Misra C
  - To avoid common pitfalls
  - Enforced by static analysis, to some extent dataflow and pointer analyses
- Model checking
  - For functional requirements
  - Directly on the C code
  - Realized using CBMC

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- Development and style guidelines for C
- Introduced by the Motor Industry Software Reliability Association
- Improve safety and security by avoiding common pitfalls
- To some extend automatically checkable, others undecidable

No verification of functional requirements here!

MISRA C:2012

Guidelines for the use of the C language in critical systems

March 2013

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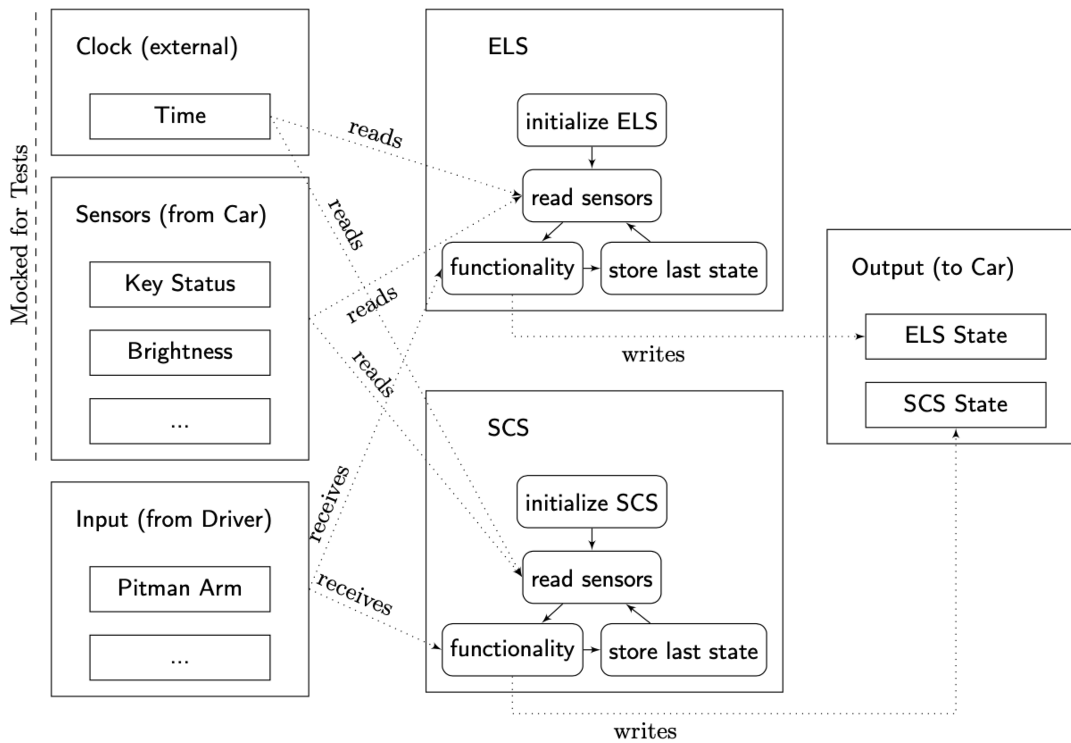

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```
1  // ignition: key inserted + ignition on
2  sensor = update_sensors(sensor, sensorTime, 1000);
3  sensor = update_sensors(sensor, sensorBrightnessSensor, 500);
4  sensor = update_sensors(sensor, sensorKeyState, KeyInIgnitionOnPosition);
5  sensor = update_sensors(sensor, sensorEngineOn, 1);
6
7  mock_and_execute(sensor_states);
8
9  sensor = update_sensors(sensor, sensorTime, 2000);
10 pitman_vertical(pa_Downward5);
11 mock_and_execute(sensor_states);
12
13 assert_partial_state(blinkLeft, 100, blinkRight, 0);
14 pitman_vertical(pa_ud_Neutral);
15 sensor = update_sensors(sensor, sensorTime, 2000);
16 mock_and_execute(sensor);
17
18 pitman_vertical(pa_Upward7);
19
20 progress_time_partial(2000, 2499, blinkLeft, 100, blinkRight, 0);
21 progress_time_partial(2500, 2999, blinkLeft, 0, blinkRight, 0);
22
23 int i;
24 for (i = 3; i < 6; i++) {
25     progress_time_partial(i * 1000,       i * 1000 + 499,
26                           blinkLeft, 0, blinkRight, 100);
27     progress_time_partial(i * 1000 + 500, i * 1000 + 999,
28                           blinkLeft, 0, blinkRight, 0);
29 }
```

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- Requirement: Whenever the low or high beam headlights are activated, the tail lights are activated, too.
- Translate into invariant
- Place assertion in C code, will be checked at runtime and during model checking

```
assert(implies(state.lowBeamLeft > 0,
               state.tailLampLeft > 0 &&
               state.tailLampRight > 0));
```

Model Checking using CBMC – Additional Assumptions

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- CBMC unrolls transition system
- Needs to know cardinalities of enumerations, domain of variables, etc.
- Some are automatically detected, some depend on implementation (e.g. size of integers)
- Can be passed to CBMC so support it
- Again, this is a macro transparent to the C compiler

```
keyState ks = get_key_status();
__CPROVER_assume(ks == NoKeyInserted
              || ks == KeyInserted
              || ks == KeyInIgnitionOnPosition);
```

Model Checking - Example - CBMC Output

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```
State 59 file light/light-impl.c line 242 function light_do_step thread 0
----------------------------------------------------
 ks=/*enum*/NoKeyInserted (00000000000000000000000000000000)

State 63 file light/light-impl.c line 242 function light_do_step thread 0
----------------------------------------------------
 ks=/*enum*/KeyInIgnitionOnPosition (00000000000000000000000000000010)

State 65 file light/light-impl.c line 244 function light_do_step thread 0
----------------------------------------------------
 engine_on=FALSE (00000000)

State 69 file light/light-impl.c line 244 function light_do_step thread 0
----------------------------------------------------
 engine_on=TRUE (00000001)
```

Model Checking – CBMC - Remarks

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- CBMC found counterexamples, e.g., to the requirement ELS-22
- Output was barely readable, i.e., 52 state transitions represent two high level states after the initialization
- As a result, we wrote our own state graph visualization tool
- A simple C-style assertion would often have tripped the test case, CBMC adds thoroughness

Model Checking - Example – Ad-hoc Visualization

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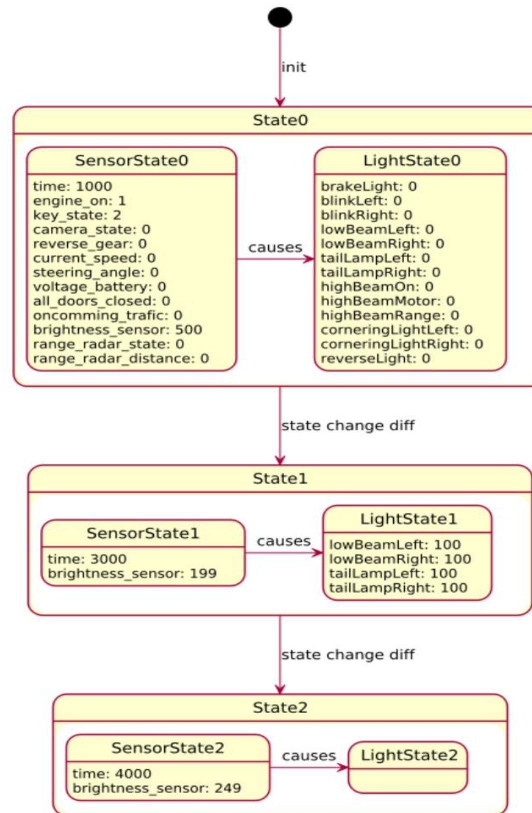

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- Would like to follow up with an actual comparison of the different case studies
    - Discuss advantages and disadvantages of using FM
    - General lessons learned
- Idea: Make invariants from a formal model survive code generators and end up invariants in C code
    - Verify implementation again on actual system / in actual context
    - Spot errors in code generators

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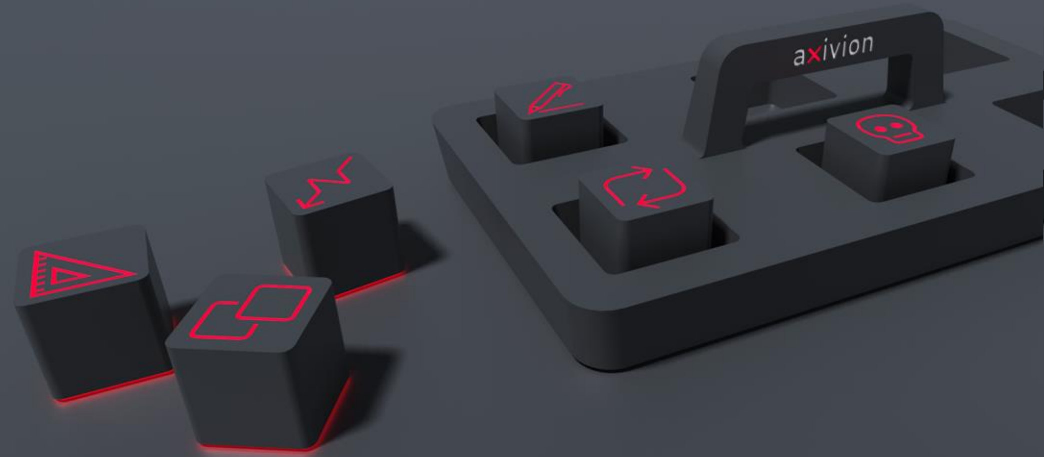
- We have
  - Implemented a low-level version of the case study
  - Used a language common in industry and broadly available infrastructure and techniques
  - Tried to stayed close to what might have happend in industry
  - Provided a baseline to compare more formal approaches to
- We suspect
  - More rigorous approaches will show advantages and disadvantages

Thank you for your attention!



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