Overcoming Non-determinism in Testing Smart Devices: A Case Study

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Abstract. This paper presents a case study in "black-box" assessment of a "smart" device where, based only on the user manuals and the instrument itself, we try to build confidence in smart device reliability. To perform the black-box assessment, we developed a test environment which automates the generation of test data, their execution and interpretation of the results. The assessment was made more complex by the inherent non-determinism of the device. For example, non-determinism can arise due to inaccuracy in an analogue measurement made by the device when two alternative actions are possible depending on the measured value. This non-determinism makes it difficult to predict the output values that are expected from a test sequence of analogue input values. The paper presents two approaches to dealing with this difficulty: (1) based on avoidance of test values that could have multiple responses, (2) based on consideration of all possible interpretations of input data. To support the second approach we use advanced modelling and simulation techniques to predict all the likely interpretations and check whether any of them is observed at the smart device output.

Keywords: testing, non-determinism, smart instruments, safety.

1 Introduction

The justification of smart instruments has become an important topic in the nuclear industry [1]. These instruments have operational and safety benefits as they are more accurate and require less calibration, but since they are programmable devices, there is a potential for software defects within the device, which could result in unpredictable behaviour.

Ideally some independent assessment of the development information and firmware should be performed to gain assurance that the behaviour is predictable. In practice, however, it may not be possible and independent "black-box" testing [2] may be necessary to gain confidence in the device. "Black-box" testing is based solely on publicly available artefacts—typically the user manuals (for operation and maintenance) and the instrument itself.

In this paper we describe the test environment we have developed to automate the process of test data generation, test execution and result checking. This was used to perform a range of automated black-box tests on a commercially available smart device. We found that a key difficulty in automating these tests was the *non-deterministic* response of the smart device to certain input values. We describe the strategies we have used to overcome this problem.

2 Non-determinism in Smart Devices

Smart instruments are physical devices to which we feed the input and read the corresponding output. For the purpose of this section we are assuming that a smart device:

- has an analogue input to measure some plant parameter
- has a configurable alarm, which is set on when the input value exceeds a certain limit
- has a configurable deadband, to avoid "jitter" the alarm is only turned off when the input value drops below the deadband

No matter what test environment we use to analyse such an instrument, non-determinism is unavoidable. It arises from a number of different sources that are inherent to smart devices. In particular:

- smart device accuracy
- smart device sample rates
- smart device response lags

In addition, the test harness can be a further source of uncertainty when checking the correctness of the results.

2.1 Smart Device Accuracy

Inaccuracy in the measured input value leads to a non-deterministic output result when the input value is close to some configured alarm limit as shown in **Fig. 1**.

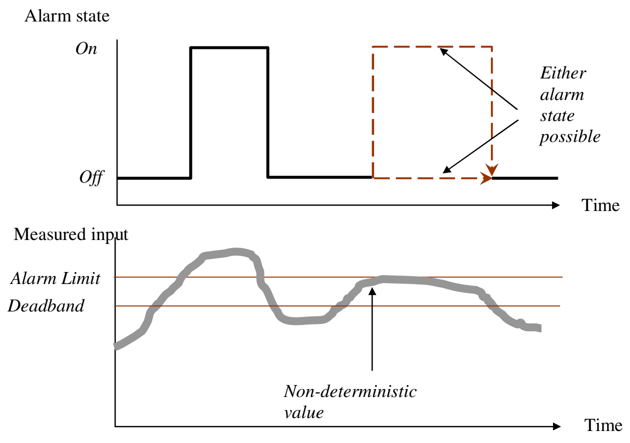


Fig. 1. Non-determinism due to smart device inaccuracy

The smart device measurement inaccuracy is represented by the thick grey line. If the internally measured value could lie on either side of the alarm limit (due to smart device measurement inaccuracy) then two alternative alarm states are possible. The test results only become deterministic when the measured value ensures that only a single alarm state is possible (e.g. when the measured value drops well below the deadband).

2.2 Discrete Sampling Intervals

A similar non-determinism problem arises if smart device measurements are only performed at discrete time points (see **Fig. 2**).

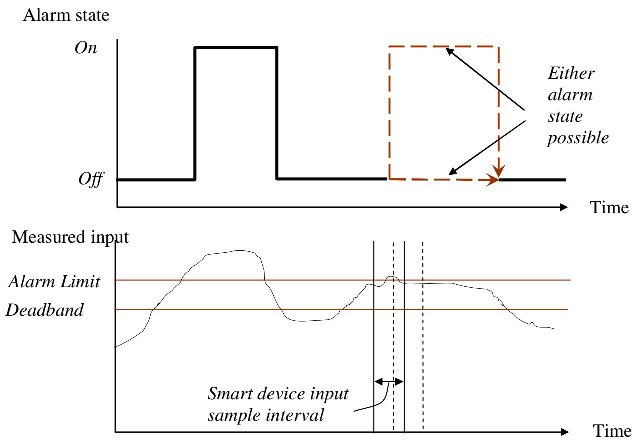

Alarm state
On
Off
Either alarm state possible
Time
Measured input
Alarm Limit
Deadband
Smart device input sample interval
Time

Fig. 2. Non-determinism due to discrete smart device sample intervals

It can be seen that the device will not “see” a short excursion above the alarm limit if the measurement samples straddle the excursion (solid lines) but the device would see the excursion if a sample coincided with the excursion (dashed lines). As we have no way of knowing when the samples occur within the smart device, we cannot determine which alarm state is expected *even if the test equipment and smart device were absolutely accurate*.

2.3 Smart Device Lags

Even if the alarm activation decision is deterministic, there is still uncertainty about *when* the expected response will appear at the smart device output. This is illustrated in **Fig. 3** below.

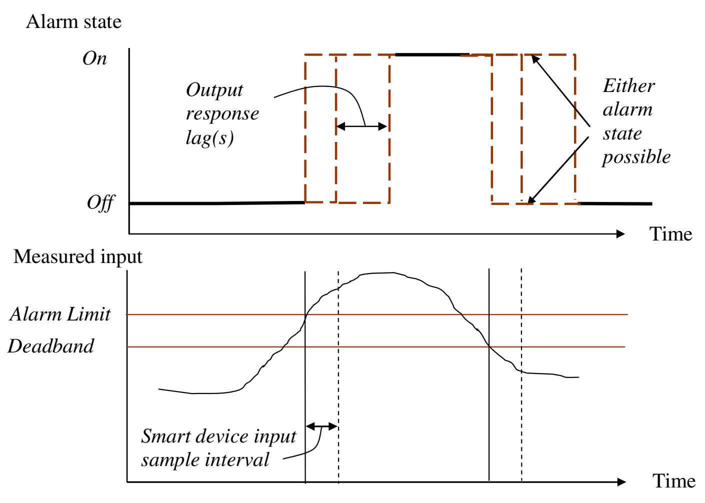


Fig. 3. Non-determinism due to uncertain response times

This arises from:

- uncertainty about when the smart device samples the input
- lags introduced by internal filtering algorithms
- uncertainty about the computation time taken to decide the alarm state
- variation in the time needed to physically switch an alarm relay to another state.

2.4 Non-determinism in the Test Harness

The test harness is also a source of non-determinism due to:

- Finite accuracy. This increases the uncertainty in the measured value as seen by the smart device.
- Lags in the test relays. Special test relays controlled by the PC can simulate events like broken wires or power interruption. It can take a finite time to activate and de-activate a test relay, and this can extend the apparent time taken by the device in responding to the event.

3 Testing Non-deterministic Systems

To test smart instruments we have to address all the types of non-determinism described above. We can do it in the following way:

- smart device accuracy – by taking one of the approaches: (1) avoidance of inputs which are “close” to an alarm limit (i.e. beyond the inaccuracies introduced by the smart device and the test harness) or (2) detailed analysis of all the possible interpretations of the inputs by the device to assess which outputs may be correct

- smart device sample rates – by holding the test value steady for a fixed "settling time" before reading the result
- smart device response lags – by holding the test value steady for a fixed "settling time" before reading the result
- test harness – by allowing for the operation of test relays in the "settling time" (lags in the test relays) and taking the steps mentioned in bullet 1 (finite accuracy)

Avoidance of inputs which are "close" to an alarm limit should, in theory, ensure that the smart device will respond in a deterministic way where each input measurement is interpreted as being definitely above or below the decision point. So we should be able to predict the alarm output values for each.

However this restricts the scope for realistic testing and may make the detection of some bugs impossible, e.g. a device may enter erroneous state after receiving a value which is interpreted as equal to the decision point. If we wish to simulate typical plant operation we should allow *any* realistic sequence of input values, including

- continuously changing values
- inputs close to the alarm limit

If this is allowed, then analysis of the smart device outputs becomes much more difficult. The test result checker has to:

- identify when input values can result in different responses (given the uncertainties in accuracy and timing in the smart device)
- maintain different execution threads for the different input interpretations
- accept a set of output results that agree with any current thread.

This mechanism is illustrated in **Fig. 4**. If the actual result does not correspond with a given thread, the thread is discarded. If all the threads are removed this way, the result checker indicates a potential error.

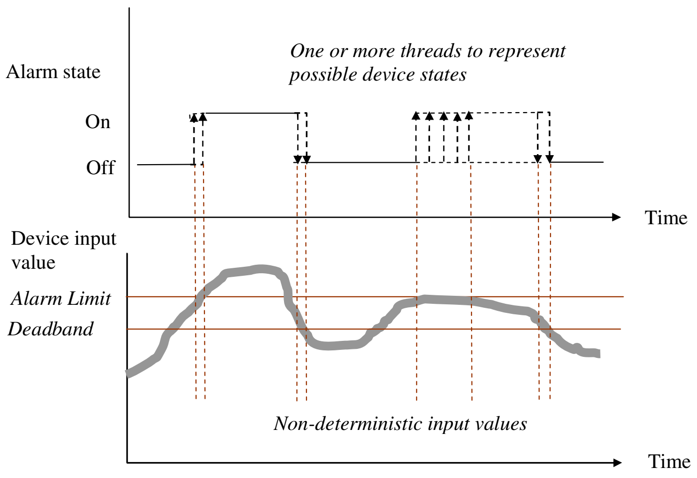

Alarm state
One or more threads to represent possible device states
On
Off
Time
Device input value
Alarm Limit
Deadband
Non-deterministic input values
Time

Fig. 4. Handling non-deterministic test results

The figure shows a simplified version of the problem. Smart sensors often set an alarm after a configurable delay (i.e. the input must stay above the limit for at least certain time). If we remain "close" to a decision point for some time, assuming that a delay is set, the number of threads may be thousands or millions rather than the two shown in **Fig. 4**. The complexity of the analysis depends on the frequency with which the device can change interpretation of a constant input being "close" to a decision point. We can influence the complexity of the analysis by changing this assumption and as a result obtaining more or less false positives (Section 6 gives an example).

4 Black-Box Testing Case Study

The smart device chosen for this study is a smart sensor alarm unit that can measure a plant parameter and raise an alarm if a programmable limit is violated. The smart sensor used in this study can monitor a wide range of plant measurements (via thermocouple, resistance, or 4-20mA input signals). The device controls four relay outputs to annunciate different alarm states.

The smart device can be configured to:

- use different plant input sensors
- trigger an alarm on high or low measured values
- avoid alarm "jitter" by specifying latching, alarm delays and deadbands
- detect rapid rates of change
- raise an alarm if internal errors are detected

The device also has LED status indicators which reflect the current state of each alarm relay. There is a push-button input that can be used to manually reset alarms that are configured to latch to the "on" state. The device can be configured via front panel pushbuttons and a display screen. It can also be programmed via configuration software running on a PC connected to the device by a serial interface.

5 Test Harness

We implemented a test harness to support functional test definition, execution and analysis of the results. The harness is composed of three parts (as shown in **Fig. 5**).

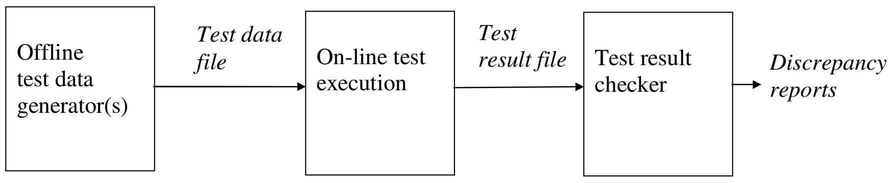


Fig. 5. Test harness elements

The harness comprises:

- An off-line test data generator. This produces test cases according to some strategy. The results are stored in a test data file.
- An on-line test execution system, which reads the test data file, applies the test to the smart device and records the result.
- An off-line result checker, which takes the test data file, computes the expected results and compares this against the result generated by the smart device.

We chose to use off-line test generation and checking because this gives us additional flexibility. If there are errors in the checker, the test result file is still valid, so we only need to fix the checker.

5.1 Test Data Generator

We developed an application for test data generation. The application generates tests using two different strategies:

- Statistical tests. This is an approximation of plant transients where the input increases to some limit with random fluctuations. An example of a transient is depicted in **Fig. 6**.

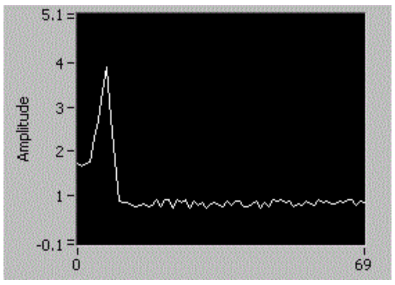


Fig. 6. Simulated transient test sequence

- Random tests. These are designed to maximise changes in the alarm outputs. An example is depicted in **Fig. 7**.

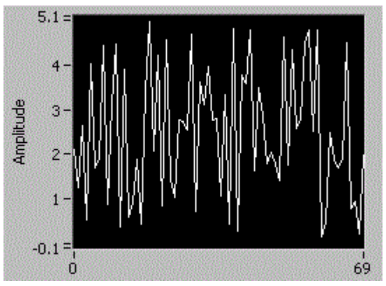


Fig. 7. Random test sequence

5.2 On-Line Test Execution System

The on-line test execution system comprised:

- a PC with analogue and digital interfaces connected to the smart device
- a LabVIEW program to read the data file with test cases to the smart device and record the results

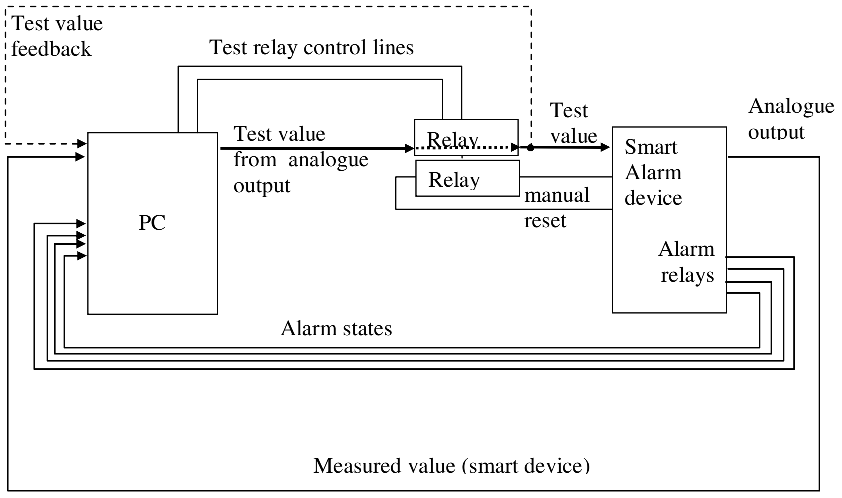


Fig. 8. Test harness schematic

The test environment (shown in **Fig. 8**) includes control of test relays to simulate broken wire conditions, and the operation of a manual reset button. We were also reading the output of the smart sensor to compare it with the test input and understand if differences observed can influence interpretation of the results. We tried to read back the test signal generated by the analogue interface by feeding it back to an analogue input so that it could be read by the PC. This however, affected the accuracy of the other analogue interfaces. Therefore, after doing some experiments we decided to remove this connection.

The test execution system is composed of:

- a personal computer, which runs a LabVIEW application controlling test execution and another application for configuring the smart sensor
- a card with relays extending the PC interface (InLog PCX-4288)
- a data acquisition device extending the PC interface (National Instruments USB-6008/6009)
- a smart sensor undergoing tests
- an analogue lab board providing voltage source for testing the state of the smart sensor

In this configuration, the test signal error was about ±10mV (around 0.2% of the full scale value).

The hardware was controlled by two Microsoft Windows application written in LabVIEW [3]. We developed:

- a manually operated test-bench application
- an automated test execution application

The test-bench application was used to check out the hardware of our test execution system. It has a knob to adjust the input, diagrams, indicator lamps presenting the state of the alarms, and switches to simulate "broken wire" and pressing the reset button of the smart sensor. It also has four charts which display a diagram with the output from the alarms.

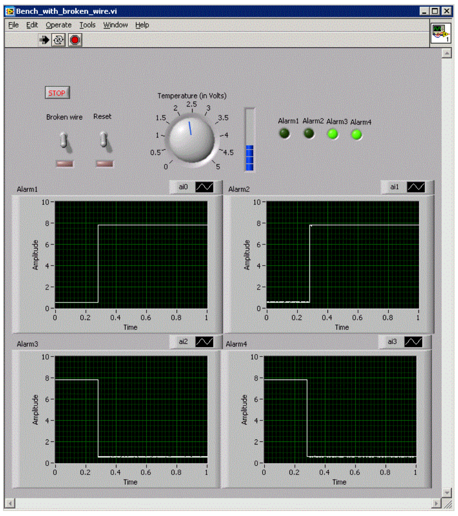


Fig. 9. Test-bench application (GUI)

The test execution application performs a set of pre-defined tests stored in a file created by the application for test data generation. The application has the following functionality:

- It reads input from a data file (i.e. the voltage for the analogue input of the smart sensor, the state of the reset button and the state of the "broken wire" relay).
- It provides input in a loop to the device acquisition card and sets the state of relays.
- It reads output (i.e. the state of the analogue output and the state of the alarms) in a loop and writes it together with the corresponding input to a file.

The model of the application is given in **Fig. 10**.

Execution of one test takes 2s or 6s depending on whether a reset is part of the test. We found that we needed 2s for simulating the input because with shorter delays (e.g. 1s) behaviour of the smart sensor was unpredictable, i.e. many errors were recorded which could not be reproduced with the delay of 2s. We needed an additional 4s for simulating the reset button because the relay card we used is slow and with

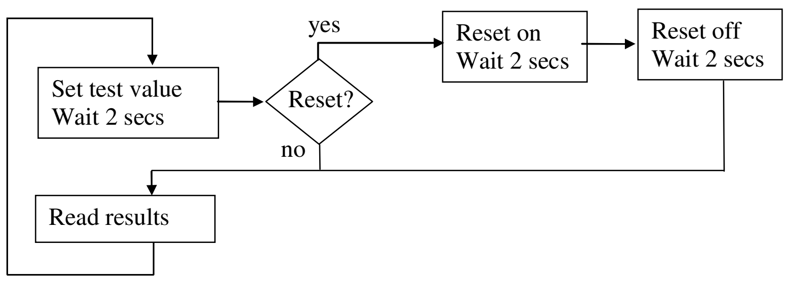


Fig. 10. Test execution application model

shorter delays it would be hard to be sure that the reset operation was simulated properly. A timing accuracy of 2s is acceptable for the device we have been analysing, but we plan to perform a more accurate response time analysis in subsequent research.

Apart from these two applications, we used another one developed by the manufacturer of the smart sensor in order to configure the smart device via a PC and read the state of the process variable of the device.

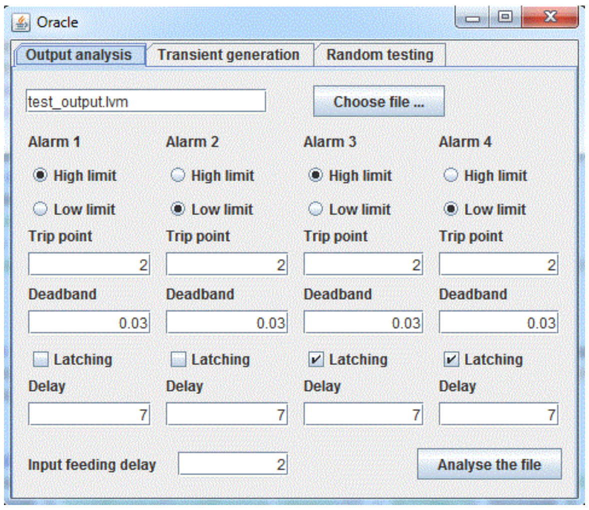
5.3 Test Analysis

We implemented an off-line test results checker (an oracle) as an application. The result checking process is identical no matter which test data generation procedure is used. It takes the test result file comprising a sequence of smart sensor inputs and outputs and then checks if they agree with the internal model of the device built into the application. The model is a finite state machine defined based on the behaviour specified in the user manual. As the documentation is not precise, the model must try to take the weakest assumptions possible, i.e. permit all behaviours which do not conflict with the manufacturer's documentation. If the outputs of the oracle and the actual result disagree, the checker generates a list of potential errors.

The result checker is highly configurable. It specifies the configuration of each alarm relay (e.g. type, limit, deadband, latch mode, and relay delay). Its interface is shown in **Fig. 11**.

Given the input data, smart device configuration and delay data, the oracle can compute the result and compare it with the actual result. This is not as straightforward as it may first appear, as discrepancies can be generated if the expected result is not unique. Section 2 discusses the possible sources of non-deterministic results. The result checker has to identify all the possible interpretations of the inputs, and based on this data calculate all the possible states of the modelled device. If any of the threads has output values that match the test result, the result is accepted. If none of the states resulting from the inputs corresponds to the test result, a discrepancy is identified.

Our non-deterministic model initially assumed that the test value measured by the smart device is unchanged between test input changes. However, by monitoring the smart device display, we established that the measured value does in fact differ on successive internal measurements made by the device. This inherent variability due to


Oracle

Output analysis | Transient generation | Random testing

test_output.lvm — Choose file ...

	Alarm 1	Alarm 2	Alarm 3	Alarm 4
Limit	[✓ High limit] Low limit	High limit [✓ Low limit]	[✓ High limit] Low limit	High limit [✓ Low limit]
Trip point	2	2	2	2
Deadband	0.03	0.03	0.03	0.03
Latching	☐	☐	✓	✓
Delay	7	7	7	7

Input feeding delay: 2

Analyse the file

Fig. 11. Result checker interface

periodic internal sampling had to be included in the non-deterministic result checking model by computing new threads at each potential sample point (using a configurable sample rate).

6 Testing and Test Results

We applied three test strategies to derive test cases for the device:

- Statistical testing. We generated and executed 4600 simulated plant transient test sequences. For realistic plant transients, this should give 99% confidence in 10^{-3} failures per demand if no discrepancies are detected by the result checker. Execution of one set of transients takes 8 days of continuous execution by the testing harness.
- Random testing. We generated and executed 10 000 random tests. Execution of the tests took 6 hours.
- Negative testing. We tested the device with:
  - out of range inputs (20% above and below the accepted range)
  - valid, equivalent inputs and checking for variation in the output
  - testing functional independence (i.e. where changes in the device configuration influence unrelated functionality)
  - random testing (this time addressing independence and consistency of the behaviour of alarms)
  - testing based on transients (this time addressing independence and consistency of the behaviour of alarms)

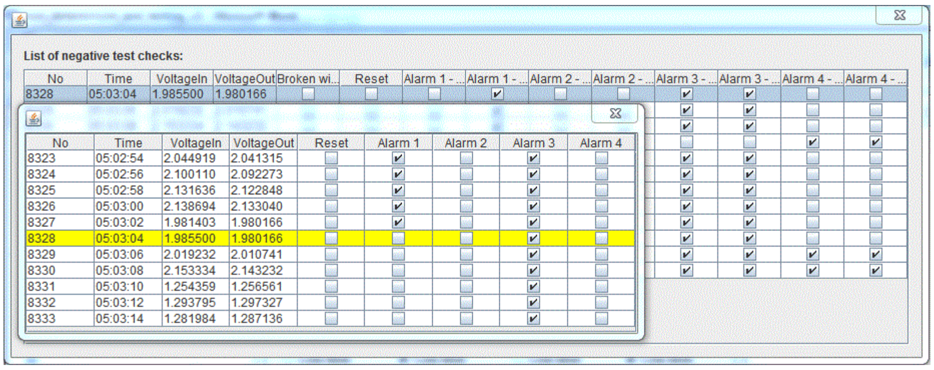
Execution of the tests led to identification of a few potential discrepancies. Statistics about the detection rates for each of the strategies are presented in Table 1.

Table 1. Discrepancy detection rates

Test strategy	Number of discrepancies for a sampling rate			
	non	**1/sec**	**2/sec**	**30/sec**
Statistical testing	25	13	10	10
Random testing	0	0	0	0
Negative testing	1	1	1	1

The table shows the number of discrepancies detected for each of the strategies in the function of the assumed device sampling rate. We can see that the number of discrepancies detected falls when we assume that the device may change interpretation of a constant input. The number of discrepancies becomes constant once the sampling rate is increased to 2/sec, which may correspond to the actual sampling rate of the device.

For each of the discrepancies detected we were able to identify the corresponding inputs and outputs and present them in the context of adjacent inputs and outputs using our analysis tool. An example is shown in **Fig. 12**.


List of negative test checks:

No	Time	VoltageIn	VoltageOut	Broken wi...	Reset	Alarm 1 - ...	Alarm 1 - ...	Alarm 2 - ...	Alarm 2 - ...	Alarm 3 - ...	Alarm 3 - ...	Alarm 4 - ...	Alarm 4 - ...
8328	05:03:04	1.985500	1.980166	☐	☐	☐	✓	☐	☐	✓	✓	☐	☐
										✓	✓	☐	☐
										✓	✓	☐	☐
										☐	☐	✓	✓
										✓	✓	☐	☐
										✓	✓	☐	☐
										✓	✓	☐	☐
										✓	✓	☐	☐
										✓	✓	☐	☐
										✓	✓	☐	☐
										✓	✓	✓	✓
										✓	✓	✓	✓

No	Time	VoltageIn	VoltageOut	Reset	Alarm 1	Alarm 2	Alarm 3	Alarm 4
8323	05:02:54	2.044919	2.041315	☐	✓	☐	✓	☐
8324	05:02:56	2.100110	2.092273	☐	✓	☐	✓	☐
8325	05:02:58	2.131636	2.122848	☐	✓	☐	✓	☐
8326	05:03:00	2.138694	2.133040	☐	✓	☐	✓	☐
8327	05:03:02	1.981403	1.980166	☐	✓	☐	✓	☐
8328	05:03:04	1.985500	1.980166	☐	☐	☐	✓	☐
8329	05:03:06	2.019232	2.010741	☐	☐	☐	✓	☐
8330	05:03:08	2.153334	2.143232	☐	☐	☐	✓	☐
8331	05:03:10	1.254359	1.256561	☐	☐	☐	✓	☐
8332	05:03:12	1.293795	1.297327	☐	☐	☐	✓	☐
8333	05:03:14	1.281984	1.287136	☐	☐	☐	✓	☐

Fig. 12. Discrepancy analysis

Analysis of the identified discrepancies revealed that all of the discrepancies occurred at values close to the configured alarm limits. These discrepancies can be explained if we change some the assumptions made about the behaviour of the device. Some of the potential explanations are given below:

- We had assumed that all alarms use the same interpretation of the process variable. The data captured seems to suggest however that each of the alarms may interpret the input independently, e.g. an input value close to the limit may be interpreted by one of the alarms as being above and by another as being below the limit.
- Our test automation system assumes 2 seconds is sufficient time to wait for a stable response, however, for a small fraction of inputs, it seems this delay is insufficient.
- We might have assumed too small a range around a decision point where the interpretation of inputs is considered to be non-deterministic.

7 Discussion

From our case study it is clear that black-box testing is a non-trivial task. The number of discrepancies detected is very dependent on the accuracy of the model checker and its coverage of all sources of non-determinism in the expected result. We have independent evidence for believing that the smart device does in fact implement its alarm logic correctly, so the residual discrepancies are likely to be due to other sources of non-determinism that have not been included in the model checker.

Clearly we can continue to refine the model checker of smart device behaviour to reduce the discrepancies even further, but we need to consider whether this is a realistic approach. Effectively, we are inventing a smart device design that can explain the observed discrepancies, but in a black-box context, we can never be sure the inferred design is actually valid.

What we really need is a result checker that does not need to know about internal details (such as the sampling rate of the device) but is based solely on the published behaviour. One possible avenue that we intend to explore is the idea of defining a set of "invariant behaviours" derived from the public documentation, e.g.:

```
Test_input >> alarm_lim → Alarm=ON
Test_input << alarm_lim_deadband → Alarm=OFF
```

Note that the >> operator is used to denote "definitely greater given the published inaccuracy, and the condition has remained true for the smart device's published maximum response time".

If we do this, we have to accept that there are points in the test sequence where none of the invariants will apply and the model-checker simply has to ignore the results generated—discrepancies can only be checked when the invariant condition is active. There could also be difficulties with this approach because it assumes test points where the answer is unique, i.e. the possible states of the smart device converge to a single state. This may not always be true. For example:

- An alarm is configured to latch permanently if the limit is exceeded
- The test sequence rises up to the limit then falls

In this case there are two possible responses so the smart device states will diverge for any subsequent test values that stay below the alarm limit. A more complex expression of expected behaviour over time would be needed like invariants expressed in some form of timed temporal logic [4]. We hope to investigate the feasibility of this approach in further research.

8 Conclusions

The paper presents a case study in which a test harness for a smart device was developed and used to execute a set of black-box test cases defined using several test strategies.

We showed that non-determinism of the smart device response makes the testing significantly more difficult. We have sought to address this problem by designing the result checker to explicitly allow for non-determinism. When a potentially non-deterministic test condition is detected, the result checker creates different "threads" representing alternative potential states of the device. Normally the threads recombine at a later point in time, when the input leaves the area "close" to limits because the threads will converge to an identical internal state. For example, after a certain amount of time above a trip limit, all threads will be in the alarm state.

This strategy has proved to be quite successful, but there are still some residual discrepancies that we suspect are false positives. These could probably be removed by increasing the complexity of the non-deterministic model of the device, but it is difficult to justify the model given that the device is a black-box.

In the next stage of research we plan to investigate less strict forms of model checking where we ignore all test cases where there is any uncertainty about the expected results.

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