A Combinatorial Approach to Conformance Testing of Personal Healthcare Devices

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Acknowledgement

• Our ProTest Team
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Outline

• What is IEEE 11073 PHD?
• What is Conformance Testing?
• What is T-Way Sequence Testing?
• ProTest: A Prototype Tool (Demo)
• Conclusion and Future Work
IEEE 11073 PHD

• A family of standards that allow personal healthcare devices to interoperate with each other.

• Optimized for the unique characteristics of personal healthcare devices
  – Portable, energy constrained, and limited computing capacity

• Promoted by Continua Health Alliance (http://www.continuaalliance.org/)
  – More than 200 member companies, including IBM, Intel, Cisco, Philips, Samsung, and others.
Agent and Manager

• **Agent**: A device used to obtain measured health data from the user.
  – blood pressure monitors, weighing scales, blood glucose monitors, and others

• **Manager**: Manage and process data collected by one or more agents.
  – personal computers, smart phones, set top boxes

• Manager devices are typically less powered constrained and have more computing capacity.
A Typical Setup

Agents

IEEE 11073 PHD

Managers

Remote Services

- Health Monitoring
- Fitness Advising
- Diet Advising
- Aging Service
• A core component of 11073 that defines rules for data exchange between an agent and a manager.

• Defined at the application layer and can work with different transport protocols
  – Bluetooth, USB, ZigBee, and others.
The Agent State Machine

From 11073 Specification
The Manager State Machine

From 11073 Specification
An Example Scenario

- Association request
- Association response (accepted)
- Confirmed Event Report (weight)
- Acknowledgement (OK)
- Association Release Request
- Association Release Response

- Check system ID and Config ID
- Process event report
- Prepare to release
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Conformance Testing

• In order for agents and managers to interoperate each other, they must implement IEEE 11073 correctly.

• **Conformance testing** is to test agent or manager implementations to ensure that they conform to their protocol specifications.
Testing in General

• Three major steps
  – Test generation, test execution, and test evaluation

• Often impractical to test all possible scenarios
  – What scenarios to test? When to stop?

• The key is to be systematic, i.e., follow a well-defined strategy
  – The notion of coverage is often used to ensure test adequacy

• Testing can easily take more than half of the development budget
  • This is specially so in the medical domain!
Conformance Testing in Focus

- Typically a black-box, model-based approach
  - Does not require access to source code
  - Tests are generated from a model instead of the implementation
- Multiple levels of conformance testing
  - **Message level**: Ensure syntactic and semantic conformance of individual messages
  - **Sequence level**: Ensure conformance for sequences of message exchanges.
Conformance vs Interoperability

- **Conformance testing** typically tests individual implementations against their specifications,
- **Interoperability testing** actually puts multiple implementations together to see if they could interoperate with each other.
- Conformance testing can significantly increase the likelihood of interoperability
State of the Art

- **Automata-Theoretic Methods**: Generate test sequences to guarantee detection of certain types of errors
  - Missing transitions/states, incorrect transitions, output errors, and others
  - Impose certain assumptions and often require a large number of test sequences
  - Examples: W-method, Wp-method, UIO-method, and others
State of the Art (2)

- **Coverage-Based Methods**: Generate test sequences to achieve a coverage goal
  - State cover, transition cover, boundary-interior cover, and others
  - No guarantee on fault detection, but more practical in terms of assumptions and number of test sequences
Our Approach

• A coverage-based method that applies t-way testing to conformance testing of medical devices.

• T-way testing has been shown very effective for general software testing.

• Has the promise to significantly increase the quality of conformance testing while cutting its cost.
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A Bug’s Perspective

• As a whole, the behavior of a system could be affected by many factors.

• However, individual bugs are often affected by only a few factors.
  – A widely-cited NIST study suggests no more than 6 factors for practical applications.

• But, we do not know “what” parameters affect “what” bugs.
The NIST Study

(Kuhn, Wallace, Gallo, 2004)
T-Way Testing

- A t-way test set covers all the t-way combinations, instead of all possible combinations (of all the parameters)
  - No need to know “what” parameters cause “what” faults.
- Extremely effective yet substantially reduces the number of tests
  - 10 5-value parameters (about 10M possible tests):
    - 2-way testing – 49 tests; 3-way testing – 307 tests; 4-way testing – 1865 tests
Consider a system that has three parameters, each having two values 0 and 1.

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Pick **ANY** two parameters, all combinations 00, 01, 10, 11 are covered.
T-Way Sequence Testing

- Expands the domain of t-way testing from test data generation to test sequence generation
- Many programs exhibit sequence-related behavior
  - Web applications, multithreaded programs, network protocols, and others
- **Key Idea:** Instead of testing all possible sequences of all the events, we only test all possible sequence of any set of t events.
T-Way Sequence Coverage

- Every **t-way target sequence** must be covered by at least one test sequence.
- A **t-way target sequence** is a sequence of **t** events that can be executed in the given order.
- A **test sequence** covers a target sequence if the **t** events in the target sequence are executed in the same order.
T-Way Sequence Generation

a. Compute all the t-way target sequence
b. Build a shortest path P to cover a t-way target sequence
c. Extend P to cover as many target sequences as possible
d. Remove all the target sequences that are covered by P
e. Repeat steps b, c, and d until all target sequences are covered
1. All 2-way target sequences:
   - ab, ac, ad, bb, bc, bd, cb, cc, cd
2. Start from S0->S1->S3 (ab), append S4: S0->S1->S3->S4
3. Build test sequence a->b->d
   which covers ab, ad, bd
4. Remaining 6 targets:
   ac, bb, bc, cb, cc, cd
5. Start from S0->S1->S2 (ac), build test sequence
   a->c->b->b->d and covers ac, cb, cd, bb, bd
6. Build a->c->b->c which covers cc
7. All targets are covered.
T-Way vs Transition Cover

• Transition cover requires every transition to be tested once
  – No attempt made to test interactions of events

• Problems due to interaction of events may not be detected by transition cover
  – For example, assume that event a affects event b, and something goes wrong with a.
  – This problem will not be detected if a and b are tested in different sequences.

• T-way testing guarantees detection of such problems!
Long vs Short Sequences

• Longer sequences can reduce the total test length as well as start-up and tear-down cost.
• However, it is often difficult to debug a long sequence if a failure is detected.
• In our approach, the length of a test sequence is restricted by allowing the same event to occur for no more than $t$ times.
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ProTest: A Prototype Tool

• Streamlines the entire testing process, and also integrates with a tool, i.e., LCOV, to collect code coverage
• Supports both transition cover and 2-way sequence testing
• Provides a GUI that allows one to easily operate, visualize and inspect the execution of test sequences
• Written in Java and thus runs on different platforms
The Framework

• Generate a set of test sequences that achieves edge or 2-way coverage based on the state machine model

• For each test sequence, generate test data that are needed to execute the sequence
  – For example, an EVENT REPORT event in a test sequence must be populated with actual report data

• Automatically execute each test sequence and then evaluate the test result
The Framework (2)

Input FSM

Test Sequence Generator

Data Generator

Test Sequences (APDUs)

Test Executor

Expected Responses

Actual Responses

Test Evaluator
Antidote

• An open-source C implementation of 11073-20601’s protocol stack
  – Mainly tested on Linux, and also has a port for Android.
  – Developed by Signove, a Connected Health company in Brazil

• Used by ProTest as the System Under Test
Other x73 Implementations

- **EtherMind** by Mindtree (commercial, ANSI C)

- **OpenHealth** by LibreSoft (open source, Java)
  - Mainly developed for Android
  - [http://openhealth.libresoft.es/node/45](http://openhealth.libresoft.es/node/45)

- **Medical Connectivity Library** by Freescale (free with Freescale processors, ANSI C)
Initial Results

• About 75% of statement coverage in the communications package
  – No attempt to try different message types, some transitions are not implemented

• Detected two bugs of Antidote
  – One confirmed by an Antidote developer, and the other was fixed in the latest, but not released yet, version

• Demonstrated that 2-way sequence testing can detect bugs that cannot be detected by state cover testing.
The Two Real Bugs

• Transition mismatch
  – A transition labeled by event rx_aarq was defined for state checking_config
  – However, in the actual code, three transitions were implemented for three sub-types of event rx_aarq_*, which can never be fired.

• Invalid message construction
  – The length of a message rx_roer was computed incorrectly, which results in a rejection by the encoding module.
A Seeded Bug

• Consider the following event sequence:
  – Agent sends an unknown but acceptable configuration
  – Manager asks for more information and then registers this configuration
  – Agent sends the same configuration again
  – Manager recognizes this configuration as a known configuration

• What if there is a bug such that Manager does not register the configuration correctly?
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Current Status

• Reported our work in a PETRA 2013 paper
  – *A General Conformance Testing Framework for IEEE 11073 PHD’s Communication Model*

• Built a prototype tool that automates the testing process, but only for the Manager side.

• Conducted an initial study on the effectiveness of our approach.
Next Steps

• Extend ProTest to cover the Agent side

• Apply t-way testing to generate message data
  – Currently message data are generated to allow each test sequence to be executed once (i.e., no data coverage is achieved.)

• Develop a framework to allow more complex test evaluation rules
  – For example, the user may add evaluation rules based on their experience
Next Steps (2)

- Conduct empirical studies to evaluate our approach
  - Real-life and seeded faults, comparison with other methods, other open-source implementations
- Generalize ProTest for testing other healthcare protocols
  - Separate protocol-independent part from protocol-specific part
Next Steps (3)

• Develop a comprehensive methodology and toolset for t-way conformance testing of protocols
  – Test data/sequence generation, and testing individual message exchanges as well as sequence of message exchanges
Summary

• Personal health devices play an increasingly important role in the healthcare solutions.
• Initial results indicate that t-way testing can be very effective for testing healthcare protocols.
• Our vision is to develop a comprehensive set of t-way testing methods and tools for conformance testing of healthcare and other protocols.
Questions?