The TacSat3 project is applying Integrated Systems Health Management (ISHM) technologies to an Air Force spacecraft for operational evaluation in space. The experiment will demonstrate the effectiveness and cost of ISHM and vehicle systems management (VSM) technologies through onboard operation for extended periods.

We present two approaches to automatic testcase generation for ISHM:
1) A blackbox approach that views the system as a blackbox, and uses a grammar-based specification of the system's inputs to automatically generate *all* inputs that satisfy the specifications (up to pre-specified limits); these inputs are then used to exercise the system.
2) A whitebox approach that performs analysis and testcase generation directly on a representation of the internal behaviour of the system under test.

The enabling technologies for both these approaches are model checking and symbolic execution, as implemented in the Ames' Java PathFinder (JPF) tool suite.

Model checking is an automated technique for software verification. Unlike simulation and testing which check only some of the system executions and therefore may miss errors, model checking exhaustively explores all possible executions. Symbolic execution evaluates programs with symbolic rather than concrete values and represents variable values as symbolic expressions.

We are applying the blackbox approach to generating input scripts for the Spacecraft Command Language (SCL) from Interface and Control Systems. SCL is an embedded interpreter for controlling spacecraft systems. TacSat3 will be using SCL as the controller for its ISHM systems.

We translated the SCL grammar into a program that outputs scripts conforming to the grammars. Running JPF on this program generates all legal input scripts up to a prespecified size. Script generation can also be targeted to specific parts of the grammar of interest to the developers. These scripts are then fed to the SCL Executive. ICS's in-house coverage tools will be run to measure code coverage. Because the scripts exercise all parts of the grammar, we expect them to provide high code coverage. This blackbox approach is suitable for systems for which we do not have access to the source code.

We are applying whitebox test generation to the Spacecraft Health INference Engine (SHINE) that is part of the ISHM system. In TacSat3, SHINE will execute an on-board knowledge base for fault detection and diagnosis. SHINE converts its knowledge base into optimized C code which runs onboard TacSat3.

SHINE can translate its rules into an intermediate representation (Java) suitable for analysis with JPF. JPF will analyze SHINE's Java output using symbolic execution, producing testcases that can provide either complete or directed coverage of the code.

Automatically generated test suites can provide full code coverage and be quickly regenerated when code changes. Because our tools analyze executable code, they fully cover the delivered code, not just models of the code.

This approach also provides a way to generate tests that exercise specific sections of code under specific preconditions. This capability gives us more focused testing of specific sections of code.

Automatic Testcase Generation for Flight Software

NASA Planetary Spacecraft
Fault Management Workshop
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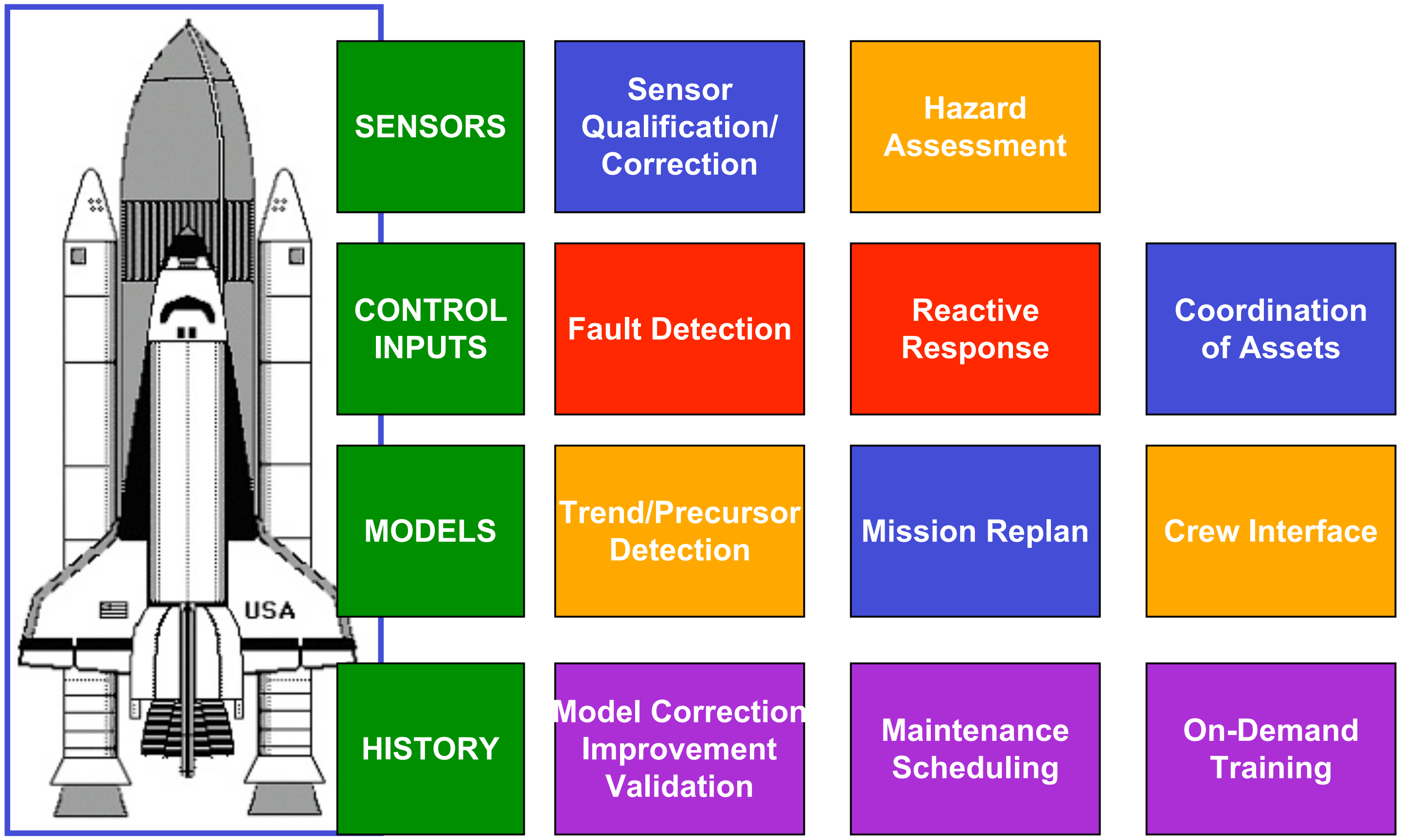
TacSat 3, ISHM, and VSM

- Faults are a fact of life in engineered systems
- NASA needs better ways of handling and recovering from faults
- Fault management is a major driver of complexity in software
- NASA's TacSat 3 VSM project applies Integrated Systems Health Management (ISHM) and Vehicle Systems Management (VSM) technologies to an experimental Air Force satellite
- NASA will test ISHM and VSM onboard TacSat 3 over an extended period

What is ISHM?

- **ISHM: Integrated System Health Management**
  - Capabilities far beyond “Fault Protection”
  - Active control methods to improve safety, reliability, mission capability, sustainability, and ultimate cost
  - Required in an era of increasing system complexity, e.g. Exploration



Goals of the Vehicle Systems Management Experiment

- **Conduct maturation and in-space testing of Vehicle Systems Management technologies**
  - Full-scale validation of model-based, autonomous, and ISHM software
  - Deploy and operate in space environment after launch (TRL 7)
  - Includes closed-loop experiments (full control) after end of primary mission

- **Gain integration and flight experience with TEAMS and SCL**
  - Fault detection and automation technologies TEAMS and SCL baselined for Orion spacecraft
  - Flight experiments crucial for risk-reduction of software technologies

- **Demonstrate new NASA technologies, on-ground and on-board**
  - High-level spacecraft planning
  - ISHM detection, diagnosis, reasoning technologies
  - Advanced V&V approaches to complex software, including TEAMS and SCL

Validating ISHM Components

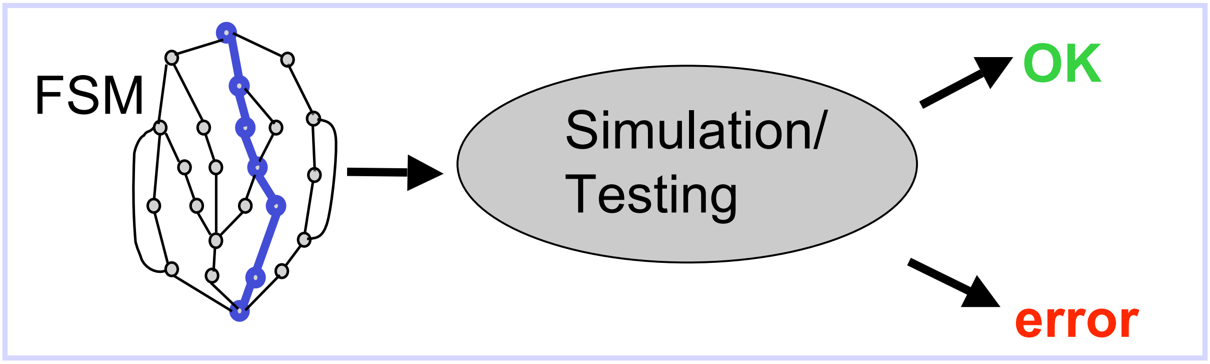
- ISHM by definition deals with *off-nominal* conditions
- Have all the significant failure modes been identified?
- Is a given failure mode well understood?

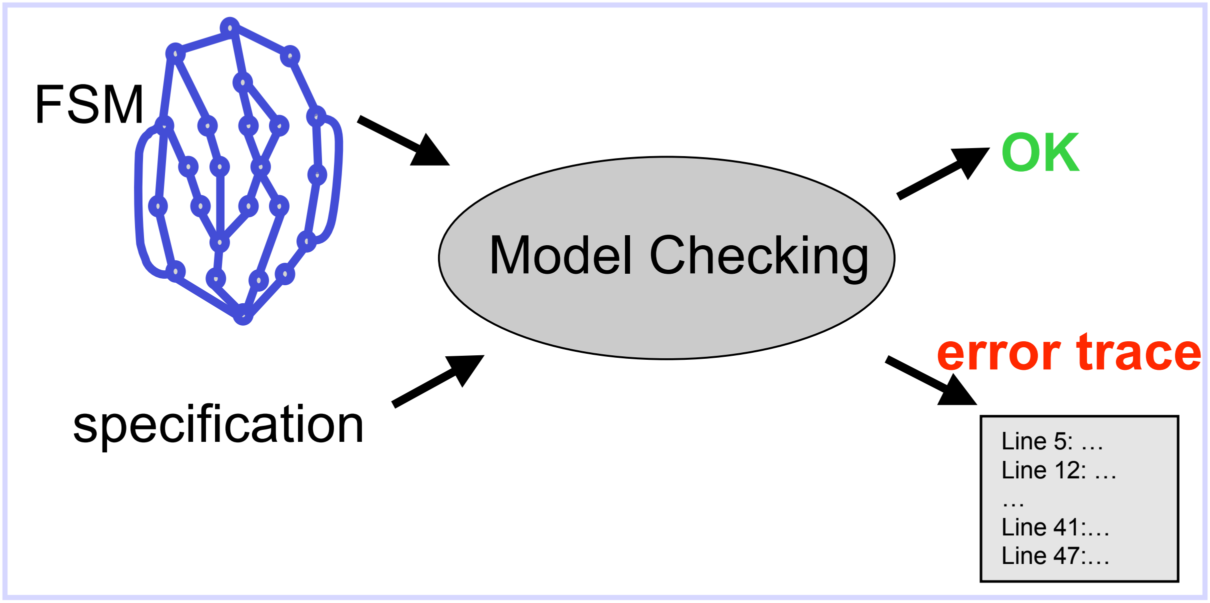
- The number of combinations of failures is overwhelming
- Manual test generation is expensive and time consuming

Automatic Test Generation

- **Manual test generation for software is time consuming and error-prone**
  - Lots of tests needed for full code coverage
  - Hard to create tests that cover specific code paths
- **Manually testing concurrent code is especially difficult**
- **Model Checking offers a way out**
  - Automatically generates all paths through the code
  - When combined with Symbolic Execution, it can create a test case for each code path
  - For concurrent code, exercises not only each code path, but also each thread scheduler decision

Model Checking vs Testing/Simulation





```
Line 5: …
Line 12: …
…
Line 41:…
Line 47:…
```

- **Model individual state machines for subsystems / features**
- **Simulation/Testing:**
  - Checks only **some** of the system executions
  - May miss errors
- **Model Checking:**
  - Automatically combines behavior of state machines
  - **Exhaustively** explores **all** executions in a systematic way
  - Handles millions of combinations – hard to perform by humans
  - Reports errors as traces and simulates them on system models

Java PathFinder (JPF)

- **Developed by RSE group at NASA Ames**
- **Explicit state model checker for Java bytecode**
  - Version targeting C/C++ is under development
- **Focus is on finding bugs**
  - Concurrency related: deadlocks, (races), missed signals etc.
  - Java runtime related: unhandled exceptions, heap usage, (cycle budgets)
  - Complex application specific assertions
- **Recipient of NASA "Turning Goals into Reality" Award, 2007.**
- **Open sourced since 04/2005 under NOSA 1.3 license: <javapathfinder.sourceforge.net>**
  - First NASA system development hosted on public site
  - ~14000 downloads since publication
  - ~25000 read transactions in 2007

Symbolic Execution

- **JPF– SE:**
  - Recent extension to JPF that enables automated test case generation
  - Symbolic execution with model checking and constraint solving
  - Applies to (executable) **models** and to code
  - Generates an optimized test suite that exercise **all the behavior** of the system under test
  - Reports coverage
  - Checks for errors during test generation process

Symbolic Execution
Generating and Solving Constraints

```
[pres = 460; pres_min = 640; pres_max = 960]
if( (pres < pres_min) || (pres > pres_max)) {
        …
} else {
    …
}
```

[pres = Sym_1; pres_min = MIN; pres_max = MAX] [path condition PC: TRUE]

```
if ((pres < pres_min) ||
    (pres > pres_max)) {
        [PC1: Sym1< MIN]
} else {
        …
}
```

```
if ((pres < pres_min)) ||
    (pres > pres_max)) {
        [PC2: Sym1 > MAX]
} else {
        …
}
```

```
if ((pres < pres_min) ||
    (pres > pres_max)) {
        …
} else {
        [PC3: Sym1 >= MIN &&
              Sym1 <= MAX]
}
```

Solve path conditions PC_1, PC_2, PC_3 → test inputs

Previous Applications

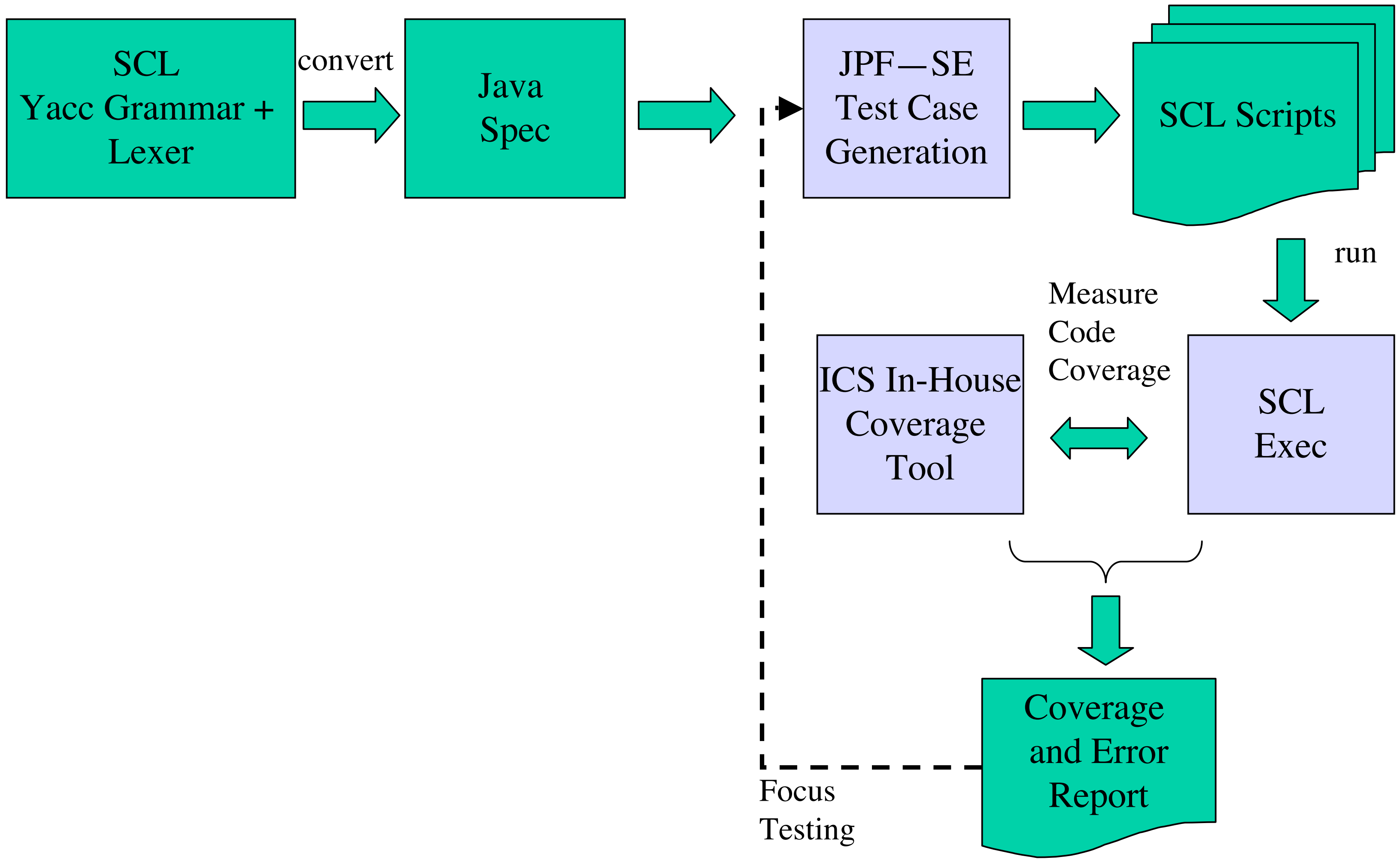
- **Onboard abort executive**
  - Prototype for CEV ascent abort handling being developed by JSC GN&C
  - Manual testing: time consuming (~1 week)
  - Guided random testing could not cover all aborts
  - JPF-SE
    - Generated 151 tests to cover all aborts and flight rules
    - Total execution time is < 1 min
    - Found major bug in new version of OAE
- **K9 Rover Executive**
  - Executive developed at NASA Ames
  - Automated plan generation based on CRL grammar
  - Generated hundreds of plans to test Exec engine

Applications to the TacSat Project

- **Test Case Generation for SCL**
  - SCL from Interface and Control Systems, Inc. is a rule- and script-based runtime executive for aerospace applications

  - Use JPF–SE to generate SCL scripts based on SCL Yacc grammar
  - Run SCL exec engine on these scripts and measure coverage
  - Focus SCL script generation on particular features of the language/engine

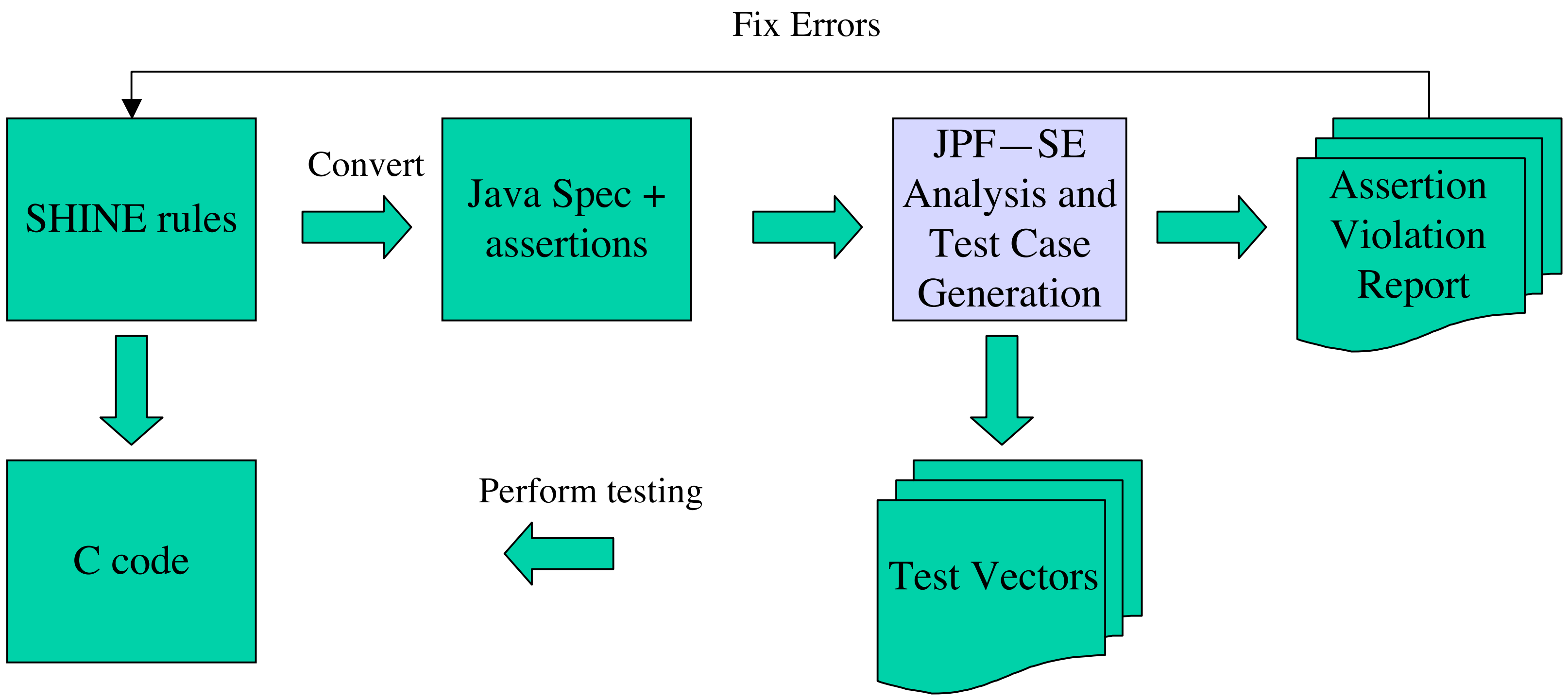
Test Case Generation for SCL



Applications to the TacSat Project

- **Test case generation for SHINE models**
  - SHINE from JPL is a very high-performance rule engine for embedded systems
  - Shine can generate C and Java code from its rule bases
  - We will apply JPF-SE to the SHINE java code to generate testcases for all paths through the rules
  - We will also apply JPF to the SHINE Java code to verify that critical safety properties hold under all possible executions

Test Case Generation for SHINE models



Early Results

- **SCL Results**
  - We have part of the SCL Yacc grammar translated to Java and have generated test scripts covering that part of the grammar
  - After coverage feedback from ICS, we will extend the translation and focus it on uncovered paths
- **SHINE Results**
  - The SHINE-to-Java translator working and we are beginning to generate test cases for simple rule sets
  - We have tested sample safety properties with our rule sets and generated both test cases and code traces showing the paths to the violations

Handout

Automatic Testcase Generation for Flight Software

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Sample SCL Grammar and Java Code

SCL Grammar

```
complex_expression
  : function
  | expression  NE expression
  | expression  LT expression
...etc...
;
```

Java Code

```
public String complex_expression() {
  int selector = Verify.random(1);
  switch (selector) {
  case 0:
    return expression() + “!=" + expression();
  case 1:
    return expression() + "<" + expression();
...etc...
  default:
      throw new GrammarException();
  }
}
```

Java Pathfinder Output for SCL Grammar

```
... etc...

-- Script Set:
SCRIPT TestScript070
  MESSAGE "a message"
  battvolts = battvolts
  MESSAGE "a message"
  battvolts = 1
END TestScript070

... etc...

-- Script Set:
SCRIPT TestScript17007
  if  battvolts  then
    EXECUTE TestScript07006 ,  PRIORITY = 4
  end if
END TestScript17007

SCRIPT TestScript07006
  MESSAGE "a message"
  battvolts = battvolts + battvolts
END TestScript07006
```

Sample SHINE Rules and Java Code

SHINE Rules

```
(Def_Rule JR01
  :Order 1
  :If (= J01 1)
  :Then (:Set J02 2))

(Def_Rule JR02
  :Order 1
  :If (= J02 2)
  :Then (:Set J03 3))

(Def_Rule JR03
  :Order 1
  :If (= J03 3)
  :Then (printf "Done\\n"))
```

Java Code

```
private void sr_JR01() {
  sa_J02 = 2;
  ep_RFC_Flag = true;
  ep_DS_RFC_S[ep_DS_RFC_PSO].rdfv_JR02_Flag
        = true;
}

private void sr_JR02() {
  sa_J03 = 3;
  ep_RFC_Flag = true;
  ep_DS_RFC_S[ep_DS_RFC_PSO].rdfv_JR03_Flag
        = true;
}

private void sr_JR03() {
  System.out.printf("Done\n");
}
```

Java Pathfinder Output for SHINE Rules

```
Symbolic Execution Mode
JavaPathfinder v4.1 - (C) 1999-2007 RIACS/NASA Ames Research Center

Execute symbolic INVOKESPECIAL: doTEST(III)V  ( J01_1_SYMINT, J02_2_SYMINT, J03_3_SYMINT )
Done
Done
Done
doTEST: # = 3
J03_3_SYMINT[3] == CONST_3 && J02_2_SYMINT[2] == CONST_2 && J01_1_SYMINT[1] == CONST_1
Done
Done
doTEST: # = 3
J03_3_SYMINT[-10000] != CONST_3 && J02_2_SYMINT[2] == CONST_2 && J01_1_SYMINT[1] == CONST_1
```

...etc...

```
doTEST: # = 3
J03_3_SYMINT[3] == CONST_3 && J02_2_SYMINT[-10000] != CONST_2
                                    && J01_1_SYMINT[-10000] != CONST_1
doTEST: # = 3
J03_3_SYMINT[-10000] != CONST_3 && J02_2_SYMINT[-10000] != CONST_2
                                         && J01_1_SYMINT[-10000] != CONST_1
```

References

- **Java Pathfinder source code and documentation:**
  http://javapathfinder.sourceforge.net/

- **Java Pathfinder and Symbolic Execution:**
  JPF--SE: A Symbolic Execution Extension to Java PathFinder
  http://ti.arc.nasa.gov/people/pcorina/papers/jpfseTACAS07.pdf