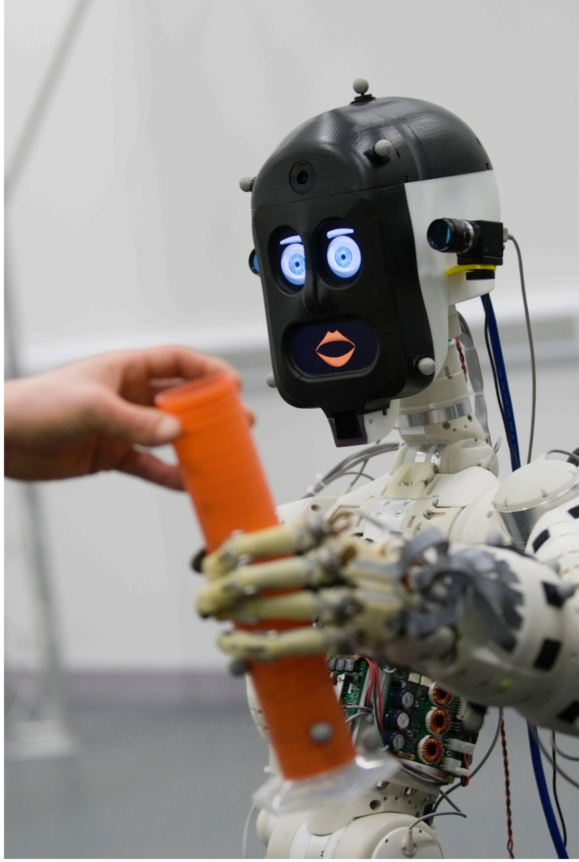
Practical Techniques for Verification and Validation of Robots

Kerstin Eder and
with a demo by Dejanira Araiza Illan

University of Bristol and
Bristol Robotics Laboratory

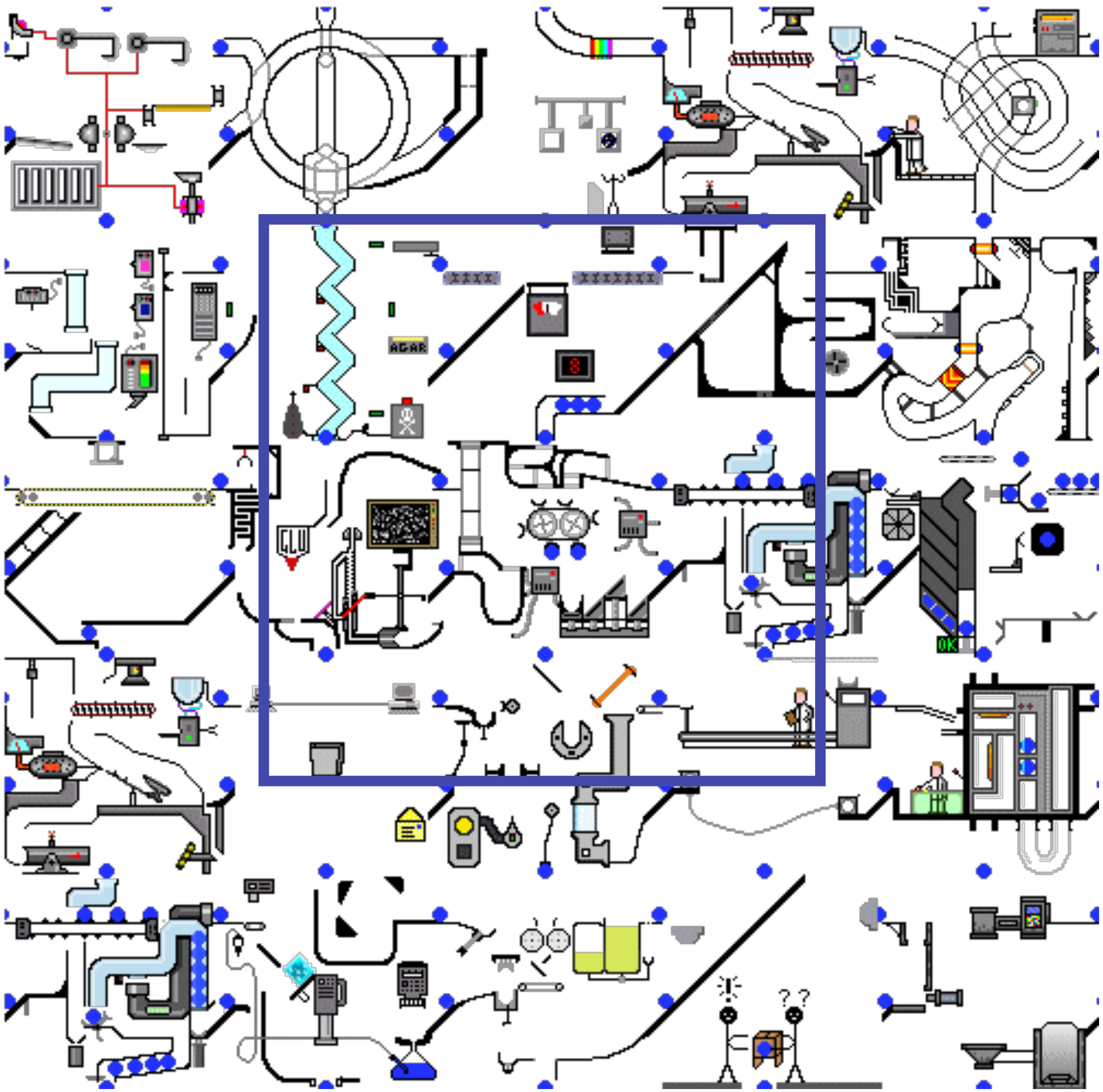
Simulation-based testing
Why and how?



D. Araiza Illan, D. Western, A. Pipe, K. Eder.
Coverage-Driven Verification - An approach to verify code for robots that directly interact with humans. Proceedings of HVC 2015, Lecture Notes in Computer Science 9434, pp. 69-84. Springer, November 2015.
DOI: 10.1007/978-3-319-26287-1_5 http://arxiv.org/abs/1509.04852

D. Araiza Illan, D. Western, A. Pipe, K. Eder.
Model-Based, Coverage-Driven Verification and Validation of Code for Robots in Human-Robot Interactions.
(under review) http://arxiv.org/abs/1511.01354

System Complexity



“Model checking works best for well defined models that are not too huge.

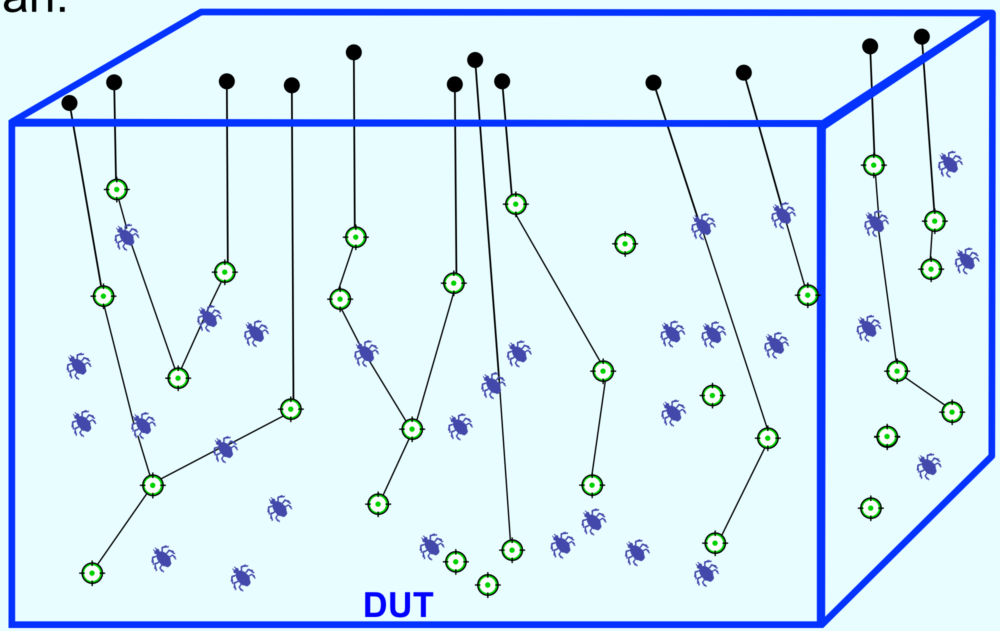
Most of the world is thus not covered.”

Yaron Kashai,
Fellow at the Systems and Verification R&D Division of Cadence


impossible

Traditional Approach: Directed Testing

Verification engineer sets goals and writes directed test for each item in the Verification Plan:



Redo if design changes

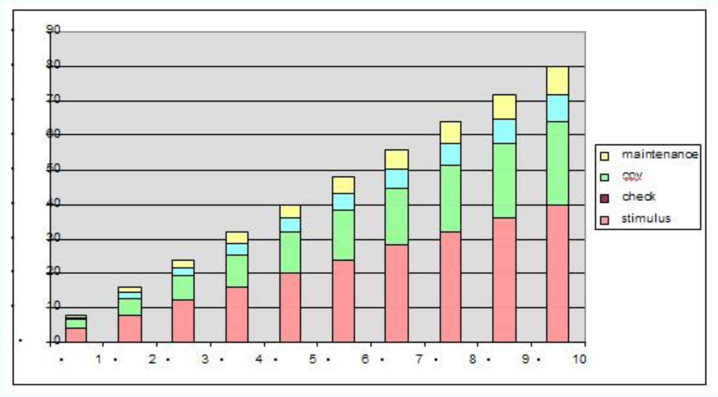
Automation Significant manual effort to write all the tests

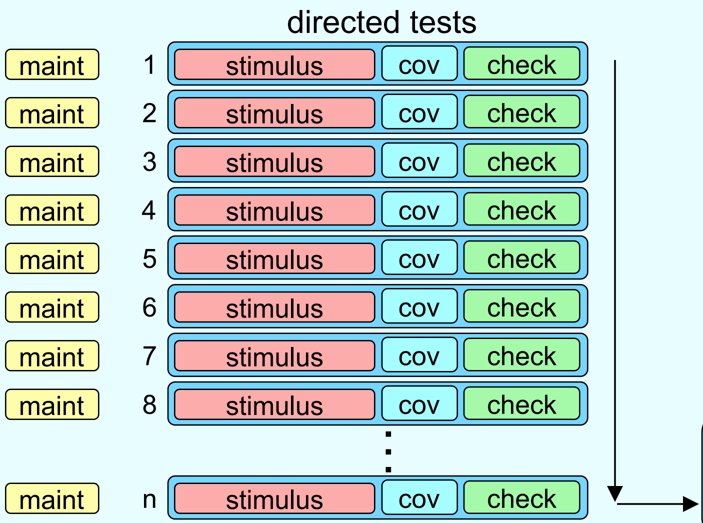
Automation Work required to verify each goal was reached

Completeness Poor coverage of non-goal scenarios
… especially the cases that you didn't "think of"

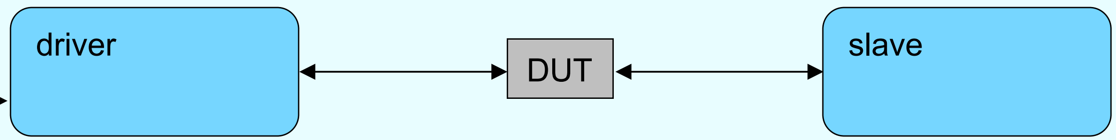
Directed Test Environment

- Composition of a directed test
  - Directed tests contain more than just stimulus.
  - Checks are embedded into the tests to verify correct behavior.
  - The passing of each test is the indicator that a functionality has been exercised.
- Reusability and maintenance
  - Tests can become quite complex and difficult to understand the intent of what functionality is being verified
  - Since the checking is distributed throughout the test suite, it is a lot of maintenance to keep checks updated
  - It is usually difficult or impossible to reuse the tests across projects or from module to system level
- The more tests you have the more effort is required to develop and maintain them





Directed test approach



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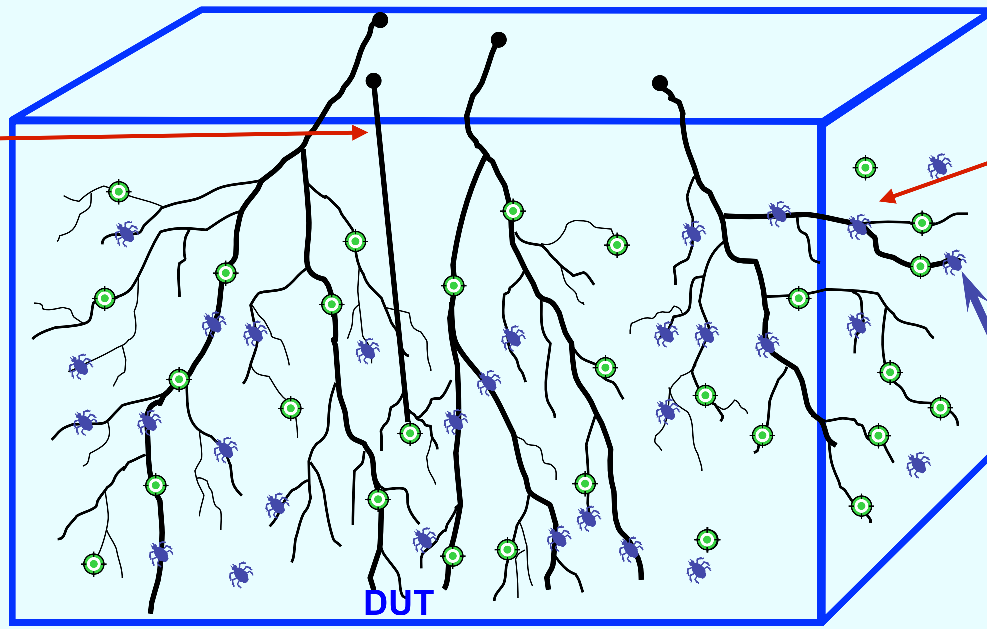
Coverage Driven Verification Methodology

Focuses on reaching **goal areas** (*versus execution of test lists*):

Add constraints to target a specific corner case

Simply changing seeds generates new stimulus

Defining Coverage "Goals" Enables Automation



Constrained-random stimulus **generation** explores goal areas (& beyond).

Coverage shows which ***goals*** have been exercised and which need attention.

(Self-Checking ensures proper DUT response.)

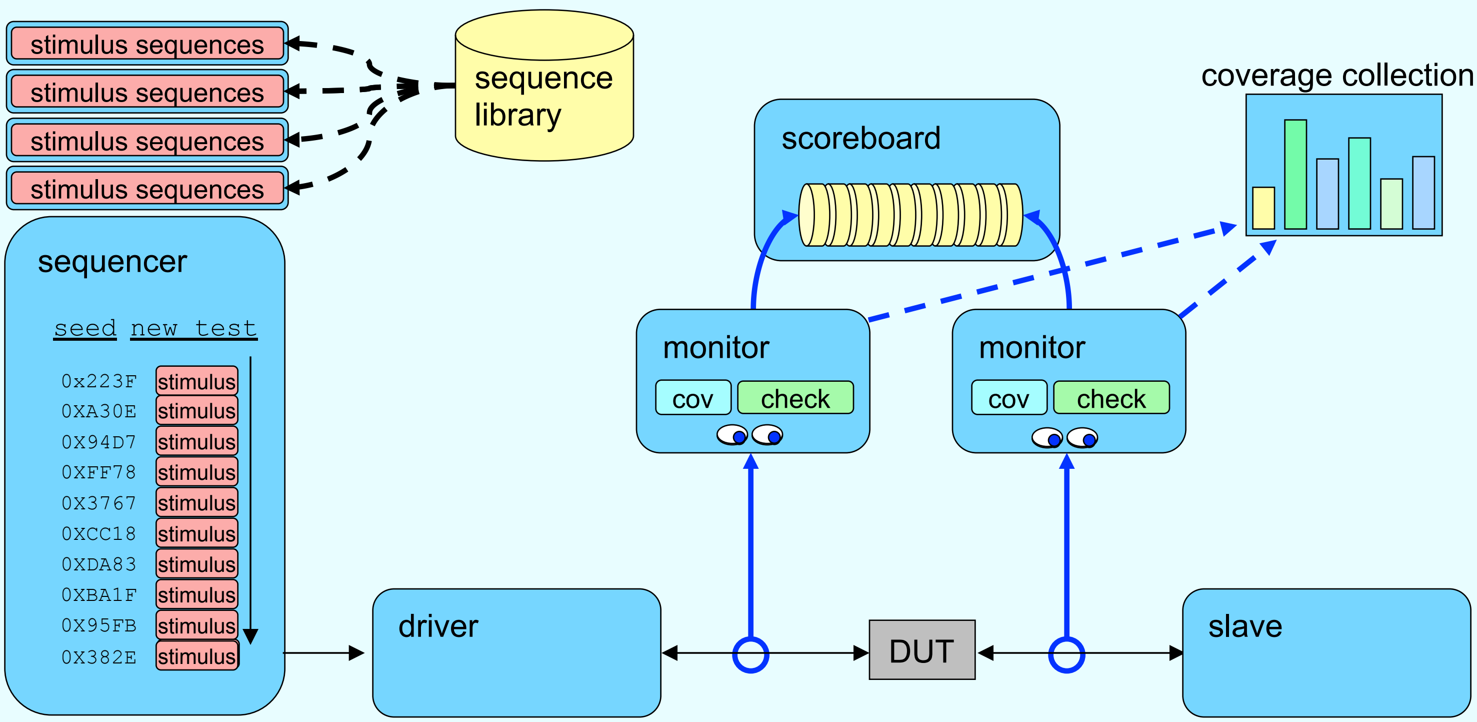
Even for non-goal states!

Automation – Constrained-random stimulus accelerates hitting coverage goals and exposing bugs. Coverage and checking results indicate effectiveness of each simulation, which enables scaling many parallel runs.

Coverage-Driven Verification

Components of a coverage-driven verification environment

- Reusable **stimulus sequences** developed with **"constrained random" generation.**
- Running **unique seeds** allows the environment to exercise different functionality.
- **Monitors** independently watch the environment.
- **Independent checks** ensure correct behavior.
- **Independent coverage points** indicate which functionality has been exercised.



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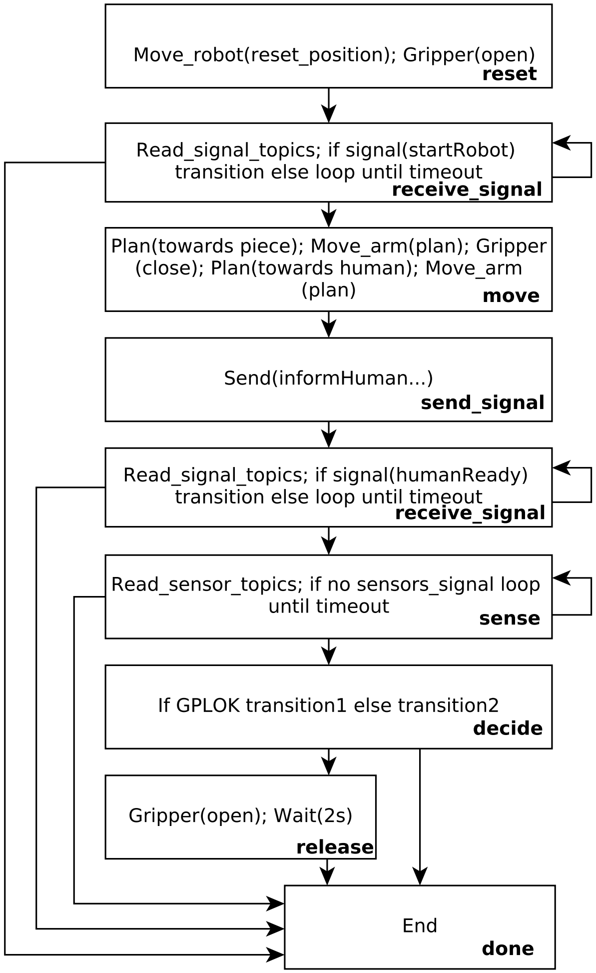
Coverage-Driven Verification

SUT

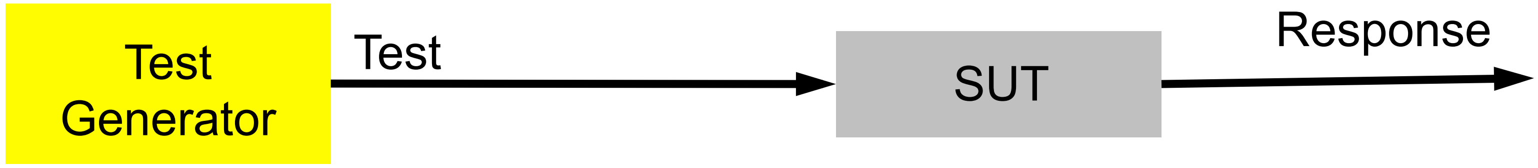
Robotic Code



J. Boren and S. Cousins, "The SMACH High-Level Executive," IEEE Robotics & Automation Magazine, vol. 17, no. 4, pp. 18–20, 2010.

Coverage-Driven Verification

Coverage-Driven Verification



Test Generator

- Effective tests:
  - meaningful events
  - interesting events
  - while exploring the system
- Efficient tests:
  - minimal set of tests (regression)
- Strategies:
  - Pseudorandom (repeatability)
  - Constrained pseudorandom
  - Model-based to target coverage directly

Model-based test generation

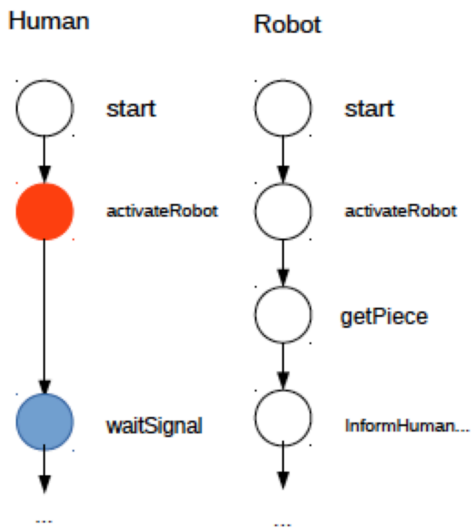
Formal model → Traces from model checking → Test template → Test components:
- High-level actions
- Parameter instantiation

System + environment

Environment to drive system

Model-based Test Generation

Formal model



Example trace

```
State: robot.start,
human.start

Transitions:
human to human.activateRobot
robot to robot.activateRobot

State: robot.activateRobot,
human.activateRobot, time+=40

Transitions:
robot to robot.getPiece

State: robot.getPiece,
human.activateRobot

Transitions:
human to human.waitSignal
robot to robot.informHuman...

State: robot.informHuman...,
human.waitSignal
...
```

High-level stimulus

```
send_signal  activateRobot

set_param  time = 40

receive_signal  informHumanOfHandoverStart

send_signal  humanIsReady

set_param  time = 10

set_param  h_onTask = true

set_param  h_gazeOk = true
set_param  h_pressureOk = true
set_param  h_locationOk = true
```

Model-based Test Generation

High-level stimulus

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send_signal  activateRobot

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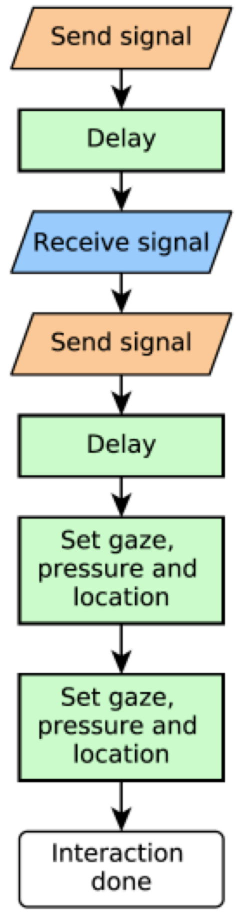
```

"Human" actions in ROS



Parameter instantiation:

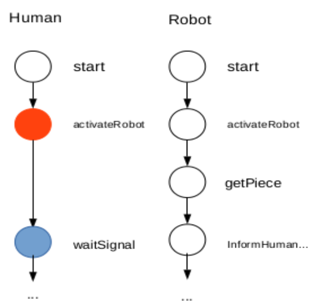
2 s

0.5 s

Gaze: (0.1 m, 0.5 m, 40 $^{\circ}$)
Location: (0.45 m, 0.05 m, 0.73 m)

Gaze: (0.1 m, 0.5 m, 30 $^{\circ}$)
Pressure: (15, 120, 140) to (7, 90, 100)
Location: (0.45 m, 0.05 m, 0.73 m)

Model-based test generation

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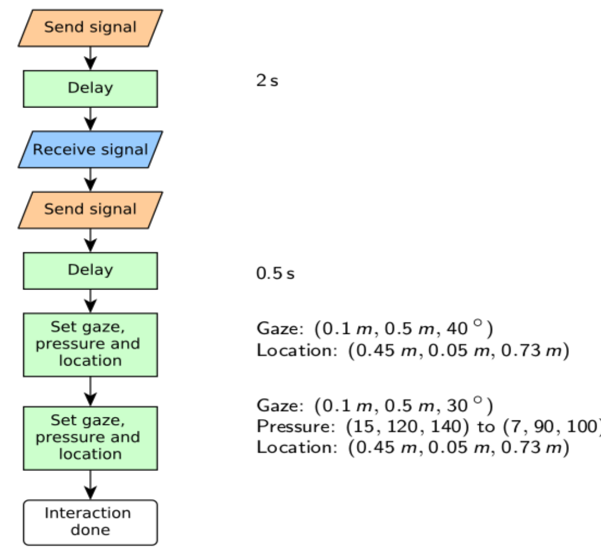
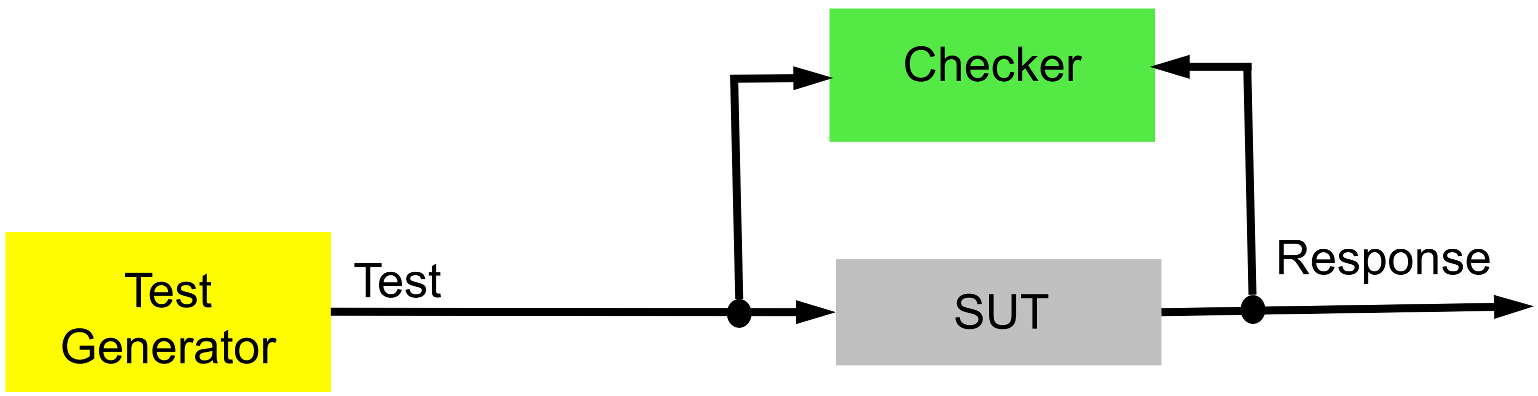


Formal model → Traces from model checking → Test template → Test components:
- High-level actions
- Parameter instantiation

System + environment

Environment to drive system

Coverage-Driven Verification



Checker

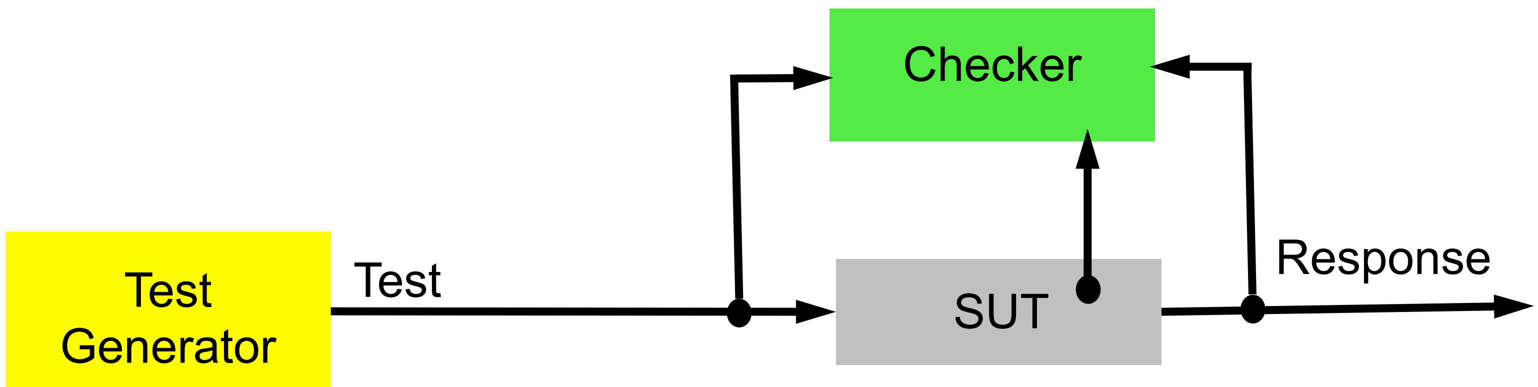
- Requirements as assertions monitors:
  - `if [precondition], check [postcondition]`

    "If the robot decides the human is not ready, then the robot never releases an object".

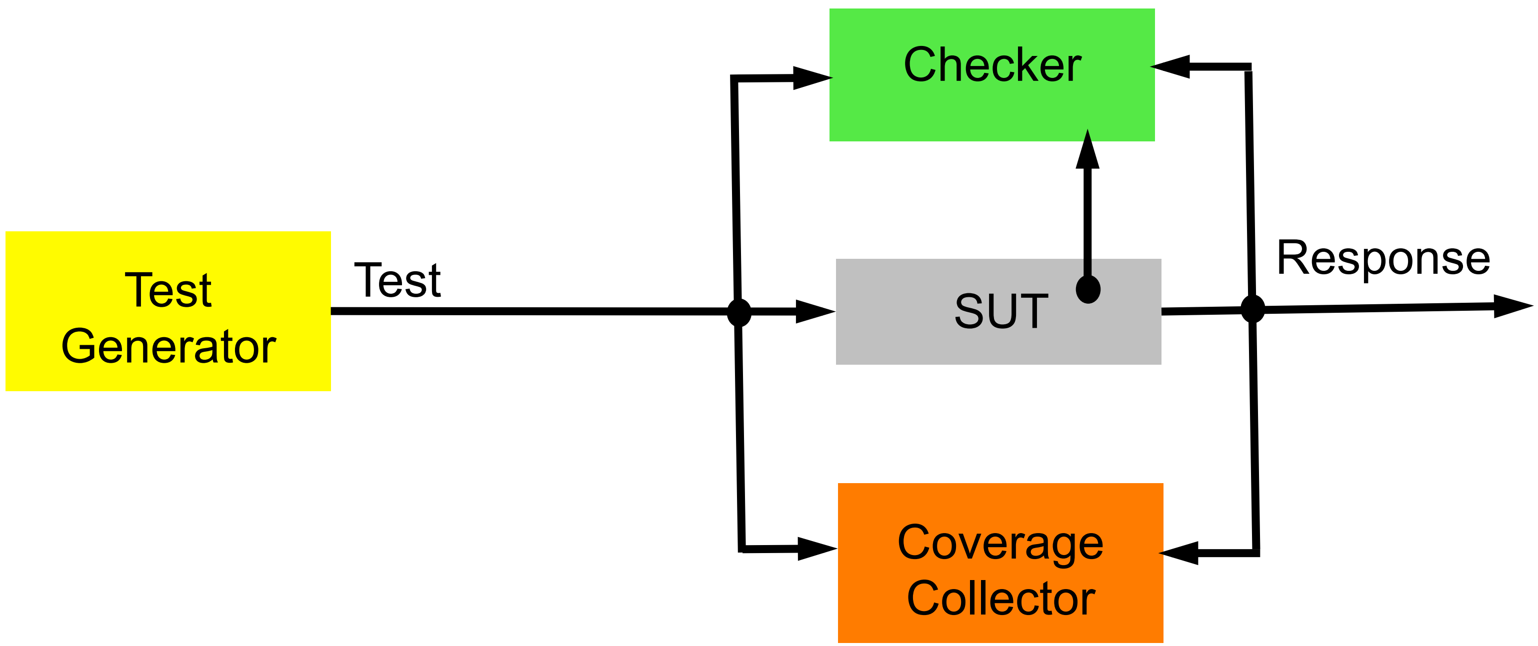
  - Implemented as automata
- Continuous monitoring at runtime, self-checking
  - High-level requirements
  - Lower-level requirements depending on the simulation's detail (e.g., path planning, collision avoidance).

```
assert {! (robot_3D_space == human_3D_space)}
```

Coverage-Driven Verification

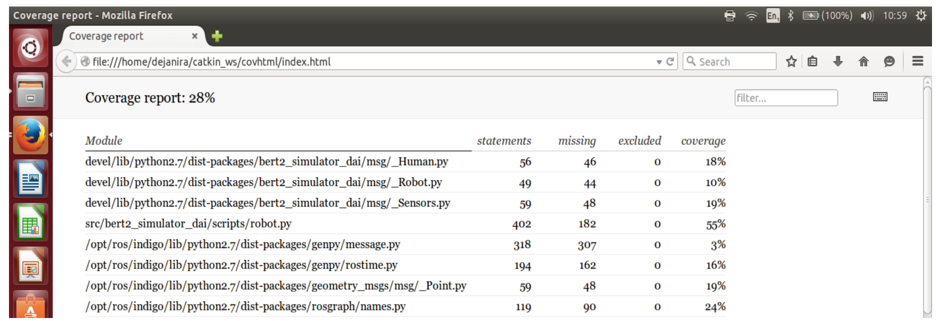


Coverage-Driven Verification

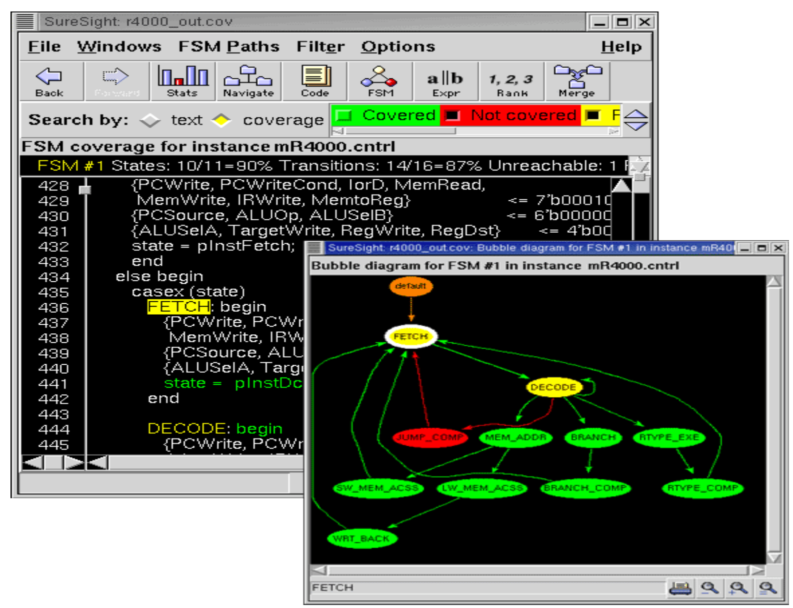


Coverage Collector

- Coverage models:
  - **Code coverage**
    - statement
    - branch
    - expression
    - MC/DC
  - **Structural coverage**
    - FSM



Module	statements	missing	excluded	coverage
devel/lib/python2.7/dist-packages/bert2_simulator_dai/msg/_Human.py	56	46	0	18%
devel/lib/python2.7/dist-packages/bert2_simulator_dai/msg/_Robot.py	49	44	0	10%
devel/lib/python2.7/dist-packages/bert2_simulator_dai/msg/_Sensors.py	59	48	0	19%
src/bert2_simulator_dai/scripts/robot.py	402	182	0	55%
/opt/ros/indigo/lib/python2.7/dist-packages/genpy/message.py	318	307	0	3%
/opt/ros/indigo/lib/python2.7/dist-packages/genpy/rostime.py	194	162	0	16%
/opt/ros/indigo/lib/python2.7/dist-packages/geometry_msgs/msg/_Point.py	59	48	0	19%
/opt/ros/indigo/lib/python2.7/dist-packages/rosgraph/names.py	119	90	0	24%



Code Coverage - Limitations

- Coverage questions not answered by code coverage tools
  - Did every operation take every exception?
  - Did two instructions access the register at the same time?
  - How many times did cache miss take more than 10 cycles?
  - Does the implementation cover the functionality specified?
  - …(and many more)
- Code coverage indicates how thoroughly the test suite exercises the source code!
  - Can be used to identify outstanding corner cases
- Code coverage lets you know if you are not done!
  - It does not indicate anything about the functional correctness of the code!
- 100% code coverage does not mean very much. ☹
- Need another form of coverage!

Functional Coverage

- It is important to cover the **functionality** of the DUV.
  - Most functional requirements can't easily be mapped into lines of code!

- **Functional coverage models** are designed to assure that various aspects of the functionality of the design are verified properly, they link the requirements/specification with the implementation

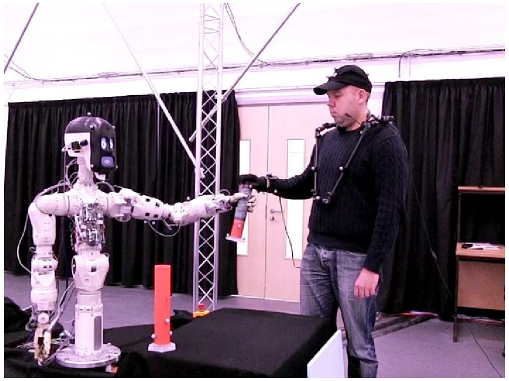
- Functional coverage models are specific to a given design or family of designs

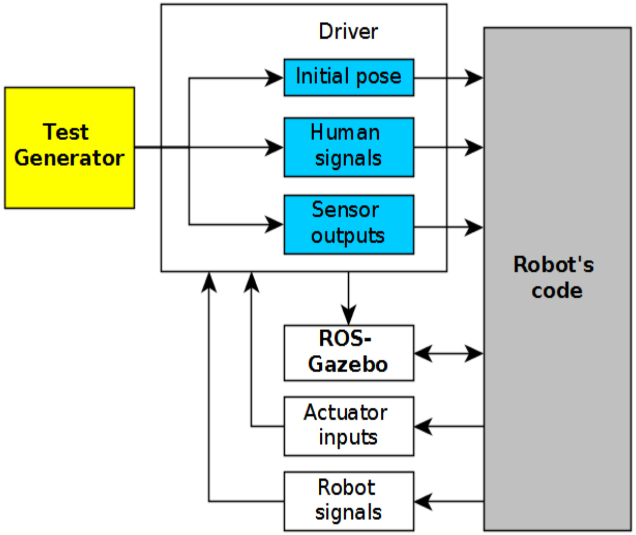
- Models cover
  - The inputs and the outputs
  - Internal states or micro architectural features
  - Scenarios
  - Parallel properties
  - Bug Models

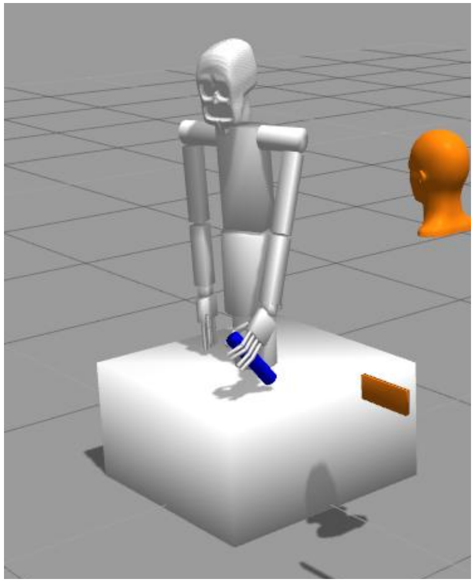
Coverage Collector

- Coverage models:
  - **Code coverage**
  - **Structural coverage**
  - **Functional coverage**
    - Requirements coverage

HRI Handover Scenario







Requirements:

- Functional and safety (ISO 13482:2014, ISO 10218-1)

Requirements based on ISO 13482 and ISO 10218

1. If the gaze, pressure and location are sensed as correct, then the object shall be released.
2. If the gaze, pressure or location are sensed as incorrect, then the object shall not be released.
3. The robot shall make a decision before a threshold of time.
4. The robot shall always either time out, decide to release the object, or decide not to release the object.
5. The robot shall not close the gripper when the human is too close.
6. The robot shall start in restricted speed and force.
7. The robot shall not collide with itself at high speeds.
8. The robot shall operate within allowable maximum values to avoid dangerous unintentional collisions with humans and other safety-related objects.

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Requirements based on ISO 13482 and ISO 10218

Considering a speed threshold of 250 mm/s (from ISO 120218-1), last requirement implemented as:

- 8a The robot hand speed is always less than 250 mm/s.
- 8b If the robot is within 10 cm of the human, the robot's hand speed is less than 250 mm/s.
- 8c If the robot collides with anything, the robot's hand speed is less than 250 mm/s.
- 8d If the robot collides with the human, the robot's hand speed is less than 250 mm/s.

Coverage Collector

- Coverage models:
  - **Code coverage**
  - **Structural coverage**
  - **Functional coverage**
    - Requirements coverage
    - Cross-product functional coverage
      - Cartesian product of environment actions, sensor states and robot actions

"Cross-product" Coverage

[O Lachish, E Marcus, S Ur and A Ziv. Hole Analysis for Functional Coverage Data. Design Automation Conference (DAC), June 10-14, 2002]

A cross-product coverage model is composed of the following parts:

1. A semantic **description** of the model (story)
2. A list of the **attributes** mentioned in the story
3. A set of all the **possible values** for each attribute (the attribute value **domains**)
4. A list of **restrictions** on the legal combinations in the cross-product of attribute values

A **functional coverage space** is defined as the Cartesian product over the attribute value domains.

Cross-Product Models in *e*

Verification Languages, such as *e*, support cross-product coverage models natively.

```
(ADD, 00000000)
(ADD, 00000001)
(ADD, 00000010)
(ADD, 00000011)
    …
(XOR, 11111110)
(XOR, 11111111)
```

```
struct instruction {
   opcode: [NOP, ADD, SUB, AND, XOR];
   operand1 : byte;
   event stimulus;
   cover stimulus is {
      item opcode;
      item operand1;
      cross opcode, operand1
         using ignore = (opcode == NOP);
   };
};
```

Situation Coverage [2015]

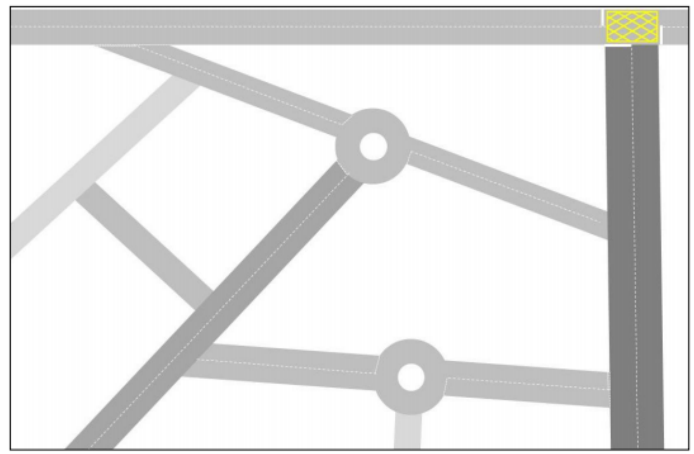
Situation coverage – a coverage criterion for testing autonomous robots

Rob Alexander*, Heather Hawkins*, Drew Rae [†]

* *University of York, York, United Kingdom*

[†] *Griffith University, Brisbane, Australia*

rob.alexander@york.ac.uk

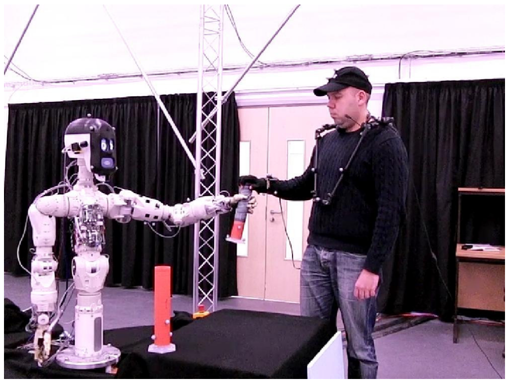


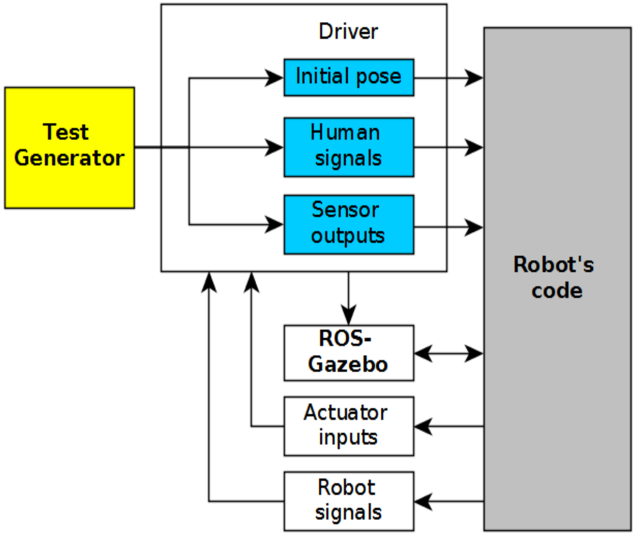
	┬	┤	┘	┐	─	╹	╴	┼	┴	├	└	┌	│	╻	╶
Car															
Bike															
HGV															
Ped															

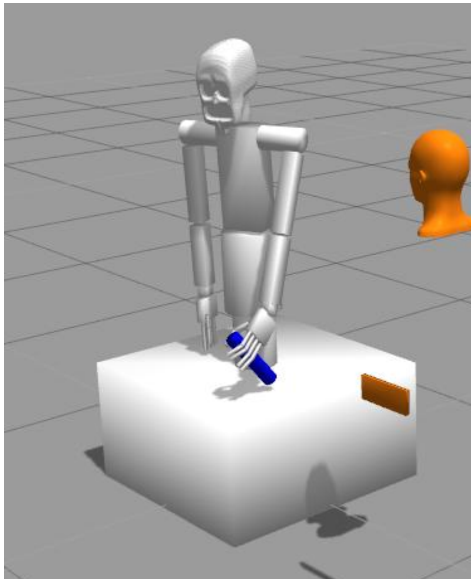
Functional Coverage

(Gaze, Pressure, Location)	Sense timeout	Release piece	No release		
$(\bar{1}, \bar{1}, \bar{1})$					
$(\bar{1}, \bar{1}, 1)$					
$(\bar{1}, 1, \bar{1})$					
$(\bar{1}, 1, 1)$					
$(1, \bar{1}, \bar{1})$					
$(1, \bar{1}, 1)$					
$(1, 1, \bar{1})$					
$(1, 1, 1)$					
Action	Sense timeout	Release piece	No release	Signal 1 timeout	Signal 2 timeout
No activation					
Activation signal 1					
Not on task					

HRI Handover Scenario





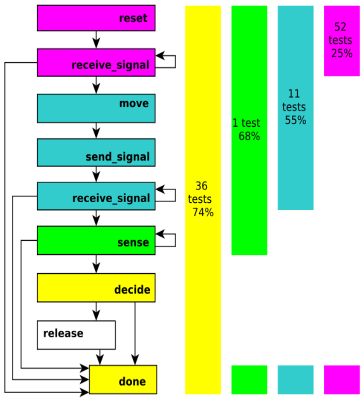


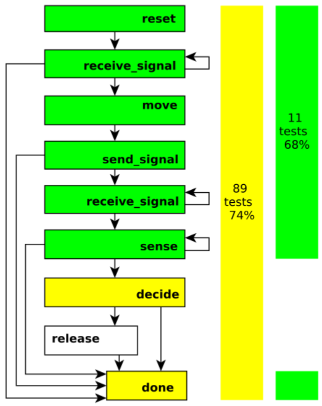
Coverage models:

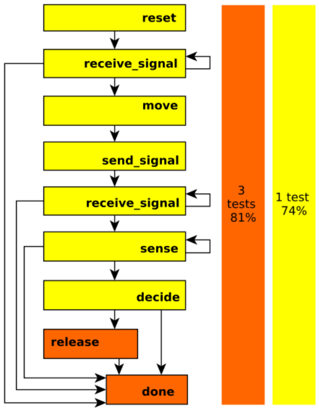
- Code statement (robot high-level control)
- Requirements in the form of Assertions
- Cross-product functional coverage

DEMO 2:

Model-Based, Coverage-Driven Verification and Validation of Code for Robots in Human-Robot Interactions.





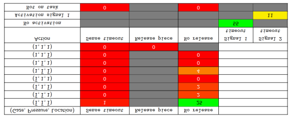


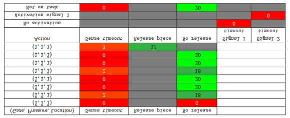
Req.	Pass	Fail	Assertion coverage
1	0/100	0/100	0
2	30/100	0/100	30
3	30/100	0/100	30
4	100/100	0/100	100
5	44/100	2/100	46
6	0/100	100/100	100
7	14/100	0/100	14
8a	0/100	100/100	100
8b	0/100	98/100	98
8c	5/100	91/100	96
8d	0/100	0/100	0

Req.	Pass	Fail	Assertion coverage
1	0/100	0/100	0
2	94/100	0/100	94
3	94/100	0/100	94
4	100/100	0/100	100
5	100/100	0/100	100
6	0/100	100/100	100
7	22/100	0/100	22
8a	0/100	100/100	100
8b	0/100	100/100	100
8c	0/100	99/100	100
8d	0/100	0/100	0

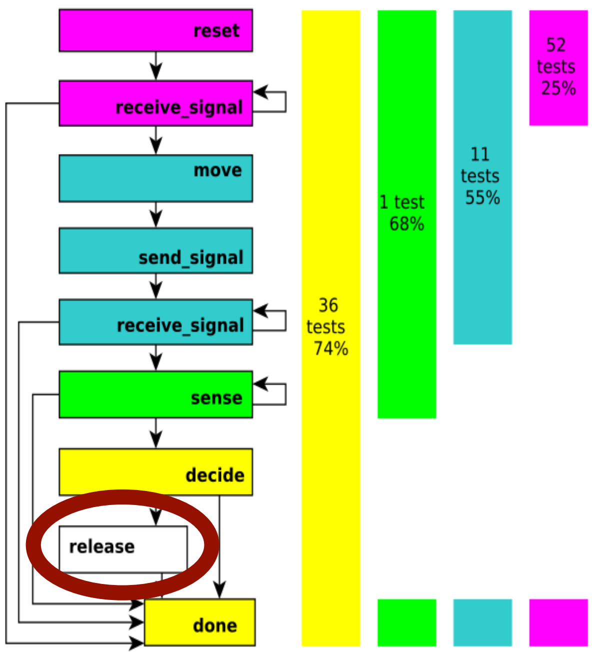
Req.	Pass	Fail	Assertion coverage
1	2/4	0/4	2
2	2/4	0/4	2
3	4/4	0/4	4
4	4/4	0/4	4
5	4/4	0/4	4
6	0/4	4/4	4
7	2/4	0/4	2
8a	0/4	4/4	4
8b	0/4	4/4	4
8c	0/4	4/4	4
8d	0/4	1/4	1

Coverage Results

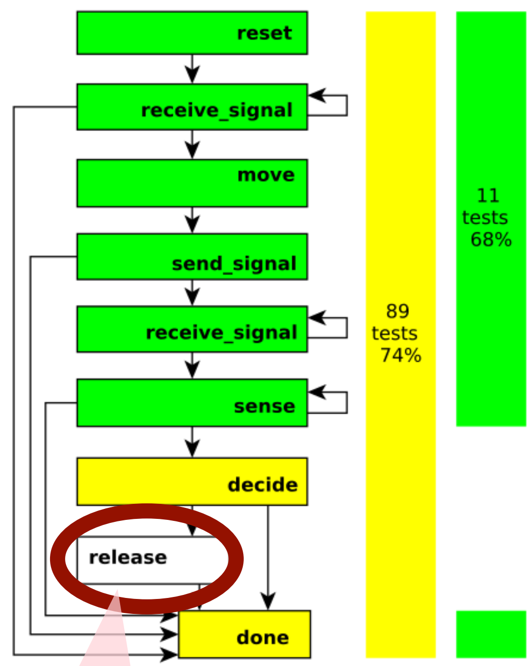




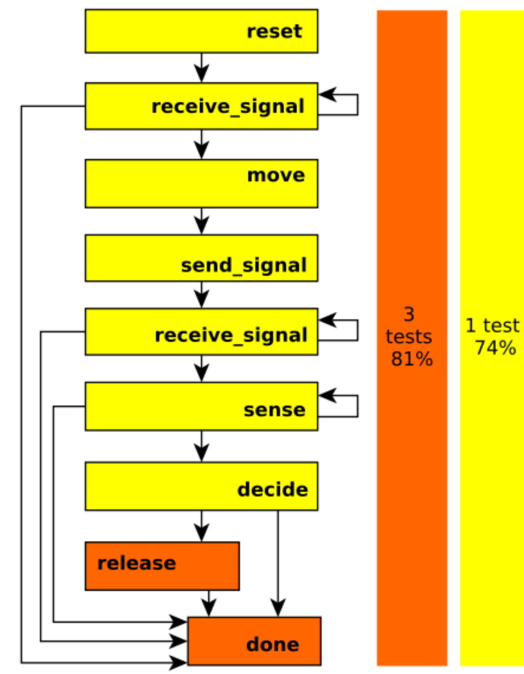
Code Coverage Results



Pseudorandom



Constrained



Model-based

Coverage Hole

Assertion Coverage Results

- 100 pseudorandomly generated tests

Req.	Pass	Fail	Assertion coverage
1	0/100	0/100	0
2	30/100	0/100	30
3	30/100	0/100	30
4	100/100	0/100	100
5	44/100	2/100	46
6	0/100	100/100	100
7	14/100	0/100	14
8a	0/100	100/100	100
8b	0/100	98/100	98
8c	5/100	91/100	96
8d	0/100	0/100	0

- 100 *constrained* pseudorandomly generated tests

Req.	Pass	Fail	Assertion coverage
1	0/100	0/100	0
2	94/100	0/100	94
3	94/100	0/100	94
4	100/100	0/100	100
5	100/100	0/100	100
6	0/100	100/100	100
7	22/100	0/100	22
8a	0/100	100/100	100
8b	0/100	100/100	100
8c	0/100	99/100	100
8d	0/100	0/100	0

- 4 model-based tests

Req.	Pass	Fail	Assertion coverage
1	2/4	0/4	2
2	2/4	0/4	2
3	4/4	0/4	4
4	4/4	0/4	4
5	4/4	0/4	4
6	0/4	4/4	4
7	2/4	0/4	2
8a	0/4	4/4	4
8b	0/4	4/4	4
8c	0/4	4/4	4
8d	0/4	1/4	1

Functional Coverage Results

- 100 pseudorandomly generated tests
- 160 model-based tests
- 180 model-based constrained tests
- 440 tests in total

(Gaze, Pressure, Location)	Sense timeout	Release piece	No release		
$(\bar{1}, \bar{1}, \bar{1})$	1		25		
$(\bar{1}, \bar{1}, 1)$	0		2		
$(\bar{1}, 1, \bar{1})$	0		2		
$(\bar{1}, 1, 1)$	0		0		
$(1, \bar{1}, \bar{1})$	0		4		
$(1, \bar{1}, 1)$	0		0		
$(1, 1, \bar{1})$	0		0		
$(1, 1, 1)$	0	0			
Action	Sense timeout	Release piece	No release	Signal 1 timeout	Signal 2 timeout
No activation				55	
Activation signal 1					11
Not on task	0		0		

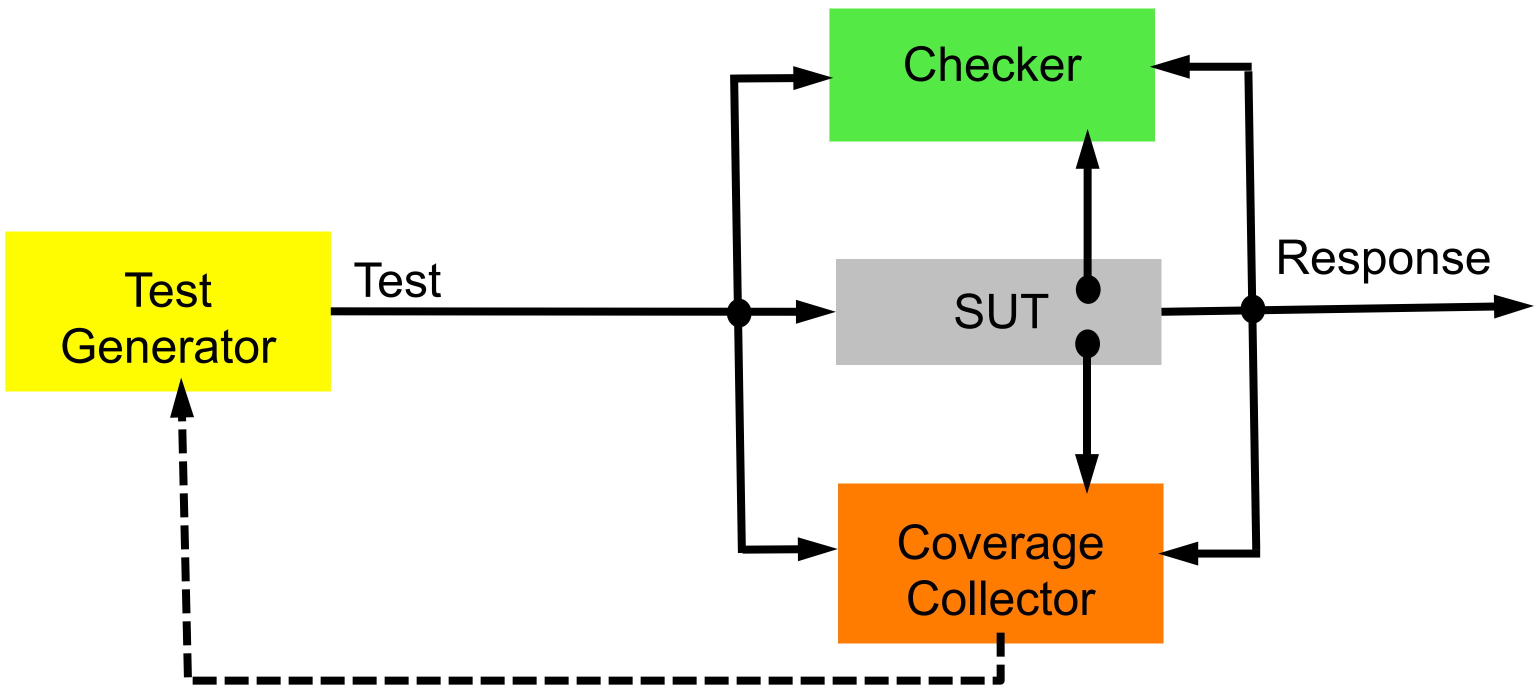
(Gaze, Pressure, Location)	Sense timeout	Release piece	No release		
$(\bar{1}, \bar{1}, \bar{1})$	0		0		
$(\bar{1}, \bar{1}, 1)$	2		18		
$(\bar{1}, 1, \bar{1})$	0		20		
$(\bar{1}, 1, 1)$	0		20		
$(1, \bar{1}, \bar{1})$	2		18		
$(1, \bar{1}, 1)$	0		20		
$(1, 1, \bar{1})$	0		20		
$(1, 1, 1)$	3	17			
Action	Sense timeout	Release piece	No release	Signal 1 timeout	Signal 2 timeout
No activation				0	
Activation signal 1					0
Not on task	0		20		

(Gaze, Pressure, Location)	Sense timeout	Release piece	No release		
$(\bar{1}, \bar{1}, \bar{1})$	19		1		
$(\bar{1}, \bar{1}, 1)$	18		2		
$(\bar{1}, 1, \bar{1})$	16		4		
$(\bar{1}, 1, 1)$	17		3		
$(1, \bar{1}, \bar{1})$	18		2		
$(1, \bar{1}, 1)$	18		2		
$(1, 1, \bar{1})$	19		1		
$(1, 1, 1)$	18	2			
Action	Sense timeout	Release piece	No release	Signal 1 timeout	Signal 2 timeout
No activation				0	
Activation signal 1					0
Not on task	17		3		

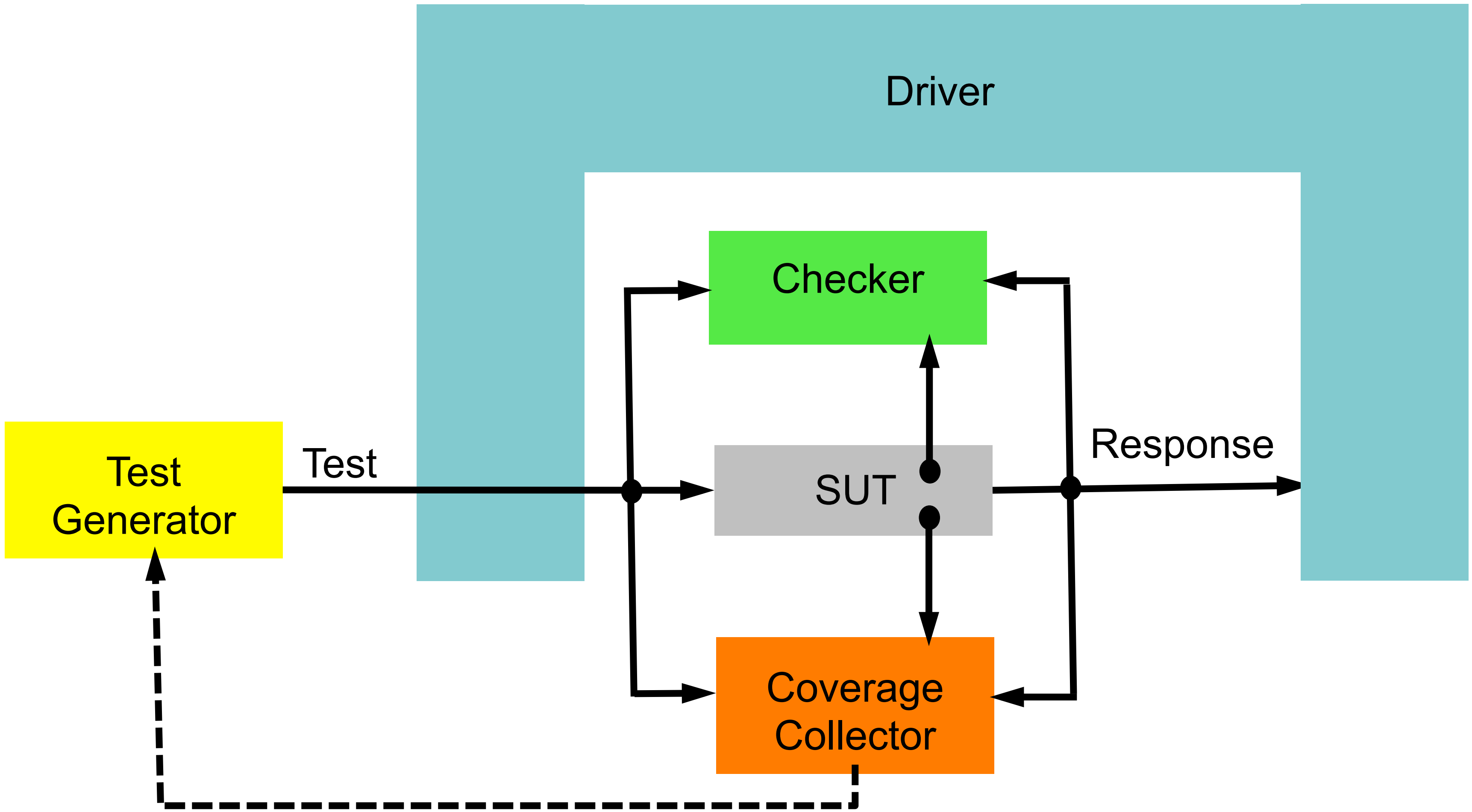
(Gaze, Pressure, Location)	Sense timeout	Release piece	No release		
$(\bar{1}, \bar{1}, \bar{1})$	20		26		
$(\bar{1}, \bar{1}, 1)$	20		22		
$(\bar{1}, 1, \bar{1})$	16		24		
$(\bar{1}, 1, 1)$	17		23		
$(1, \bar{1}, \bar{1})$	20		24		
$(1, \bar{1}, 1)$	18		22		
$(1, 1, \bar{1})$	19		21		
$(1, 1, 1)$	21	19			
Action	Sense timeout	Release piece	No release	Signal 1 timeout	Signal 2 timeout
No activation				55	
Activation signal 1					11
Not on task	17		23		

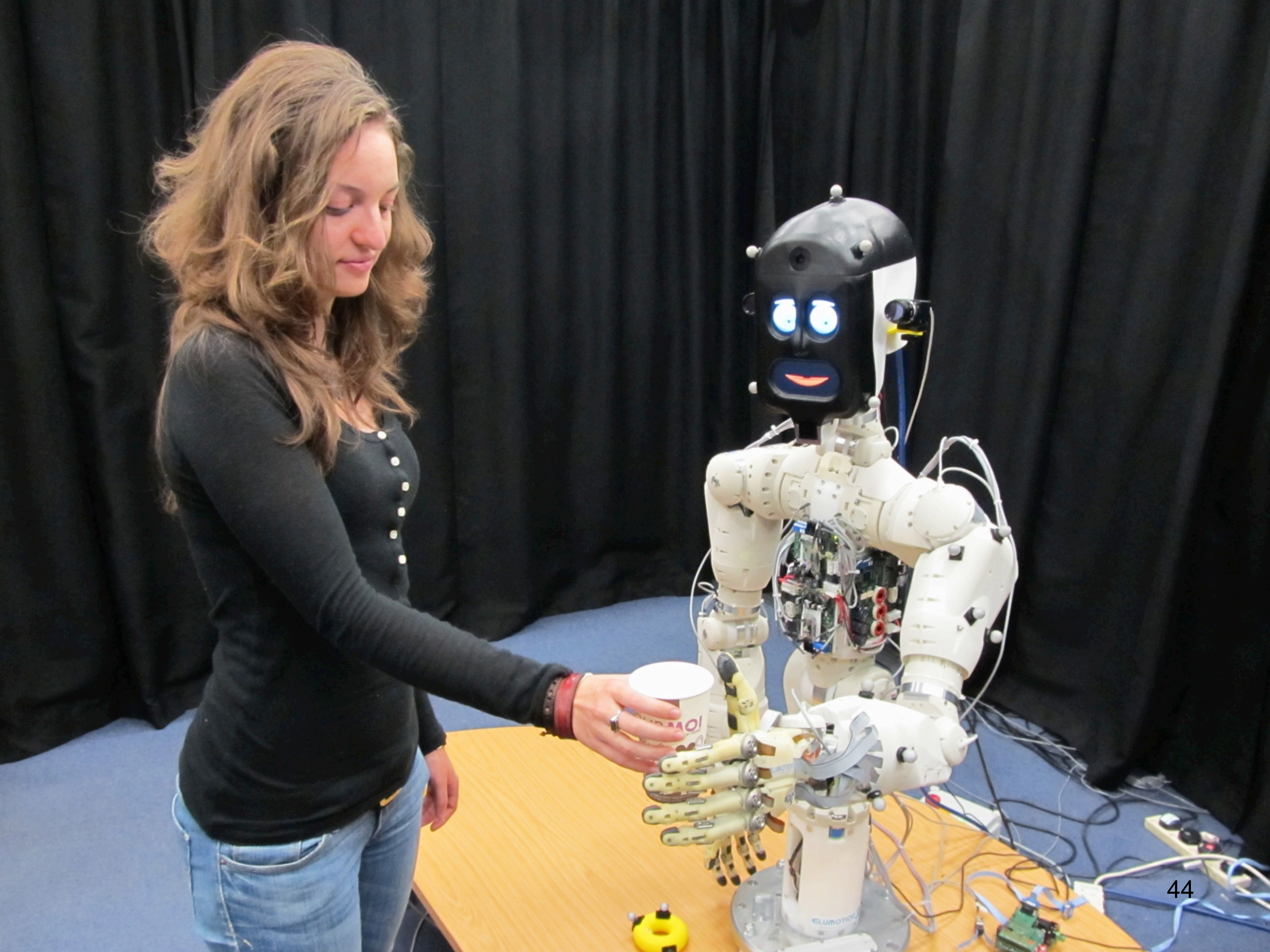
Coverage-Driven Verification

Coverage analysis enables feedback to test generation

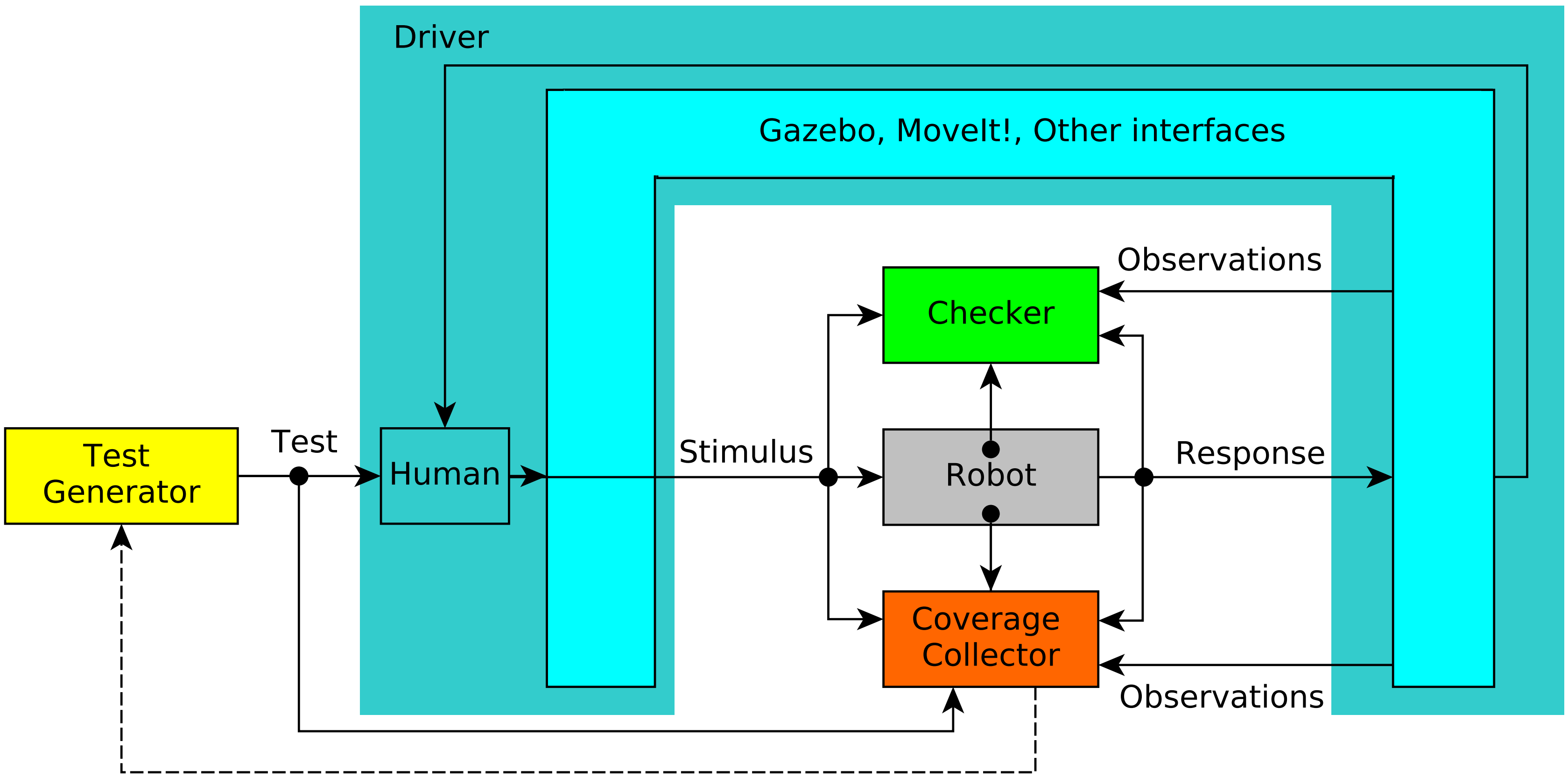


Stimulating the SUT

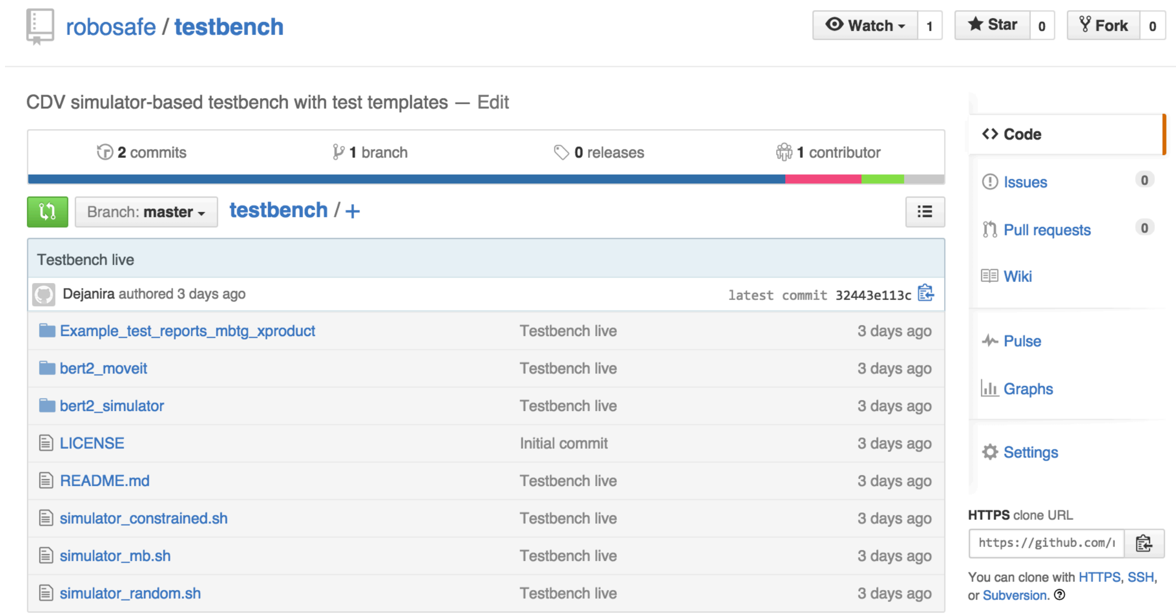




CDV for Human-Robot Interaction



D. Araiza Illan, D. Western, A. Pipe, K. Eder. **Model-Based, Coverage-Driven Verification and Validation of Code for Robots in Human-Robot Interactions.** (under review) http://arxiv.org/abs/1511.01354



http://github.com/robosafe/testbench

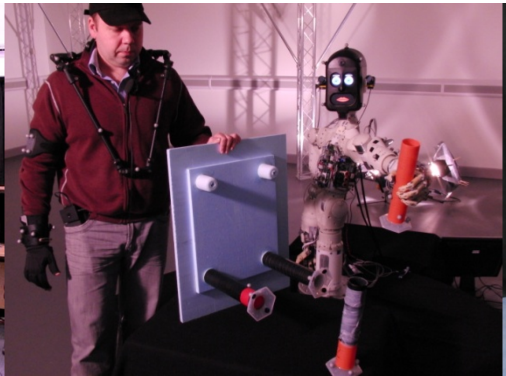
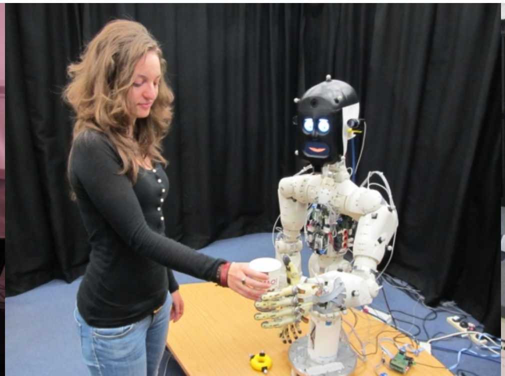
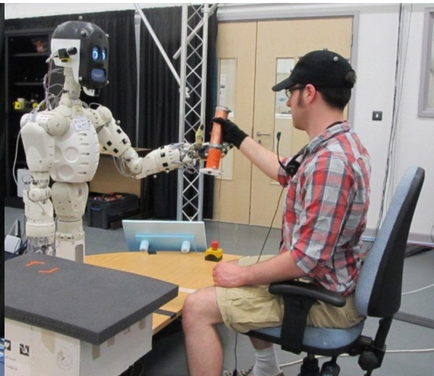
D. Araiza Illan, D. Western, A. Pipe, K. Eder.
Coverage-Driven Verification - An approach to verify code for robots that directly interact with humans. Proceedings of HVC 2015, Lecture Notes in Computer Science 9434, pp. 69-84. Springer, November 2015.
DOI: 10.1007/978-3-319-26287-1_5 http://arxiv.org/abs/1509.04852

D. Araiza Illan, D. Western, A. Pipe, K. Eder.
Model-Based, Coverage-Driven Verification and Validation of Code for Robots in Human-Robot Interactions.
(under review) http://arxiv.org/abs/1511.01354

What can YOU do?

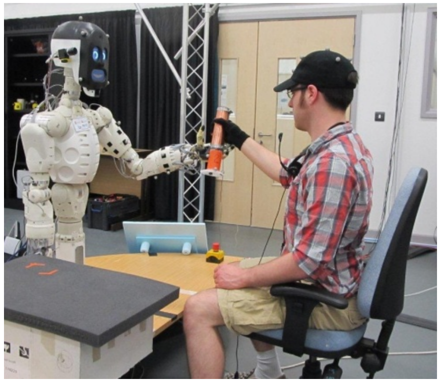
K. Eder, C. Harper and U. Leonards
Towards the safety of human-in-the-loop robotics: Challenges and opportunities for safety assurance of robotic co-workers

RO-MAN 2014: The 23rd IEEE International Symposium on Robot and Human Interactive Communication, pages 660-665, August 2014.
DOI: [10.1109/ROMAN.2014.6926328](https://doi.org/10.1109/ROMAN.2014.6926328)

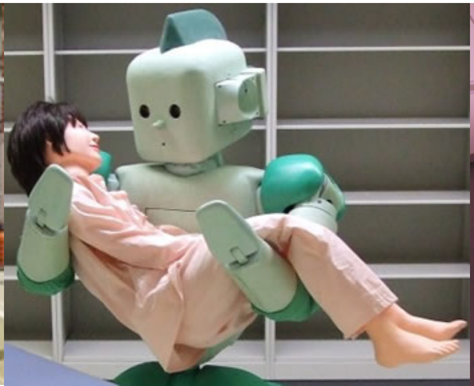
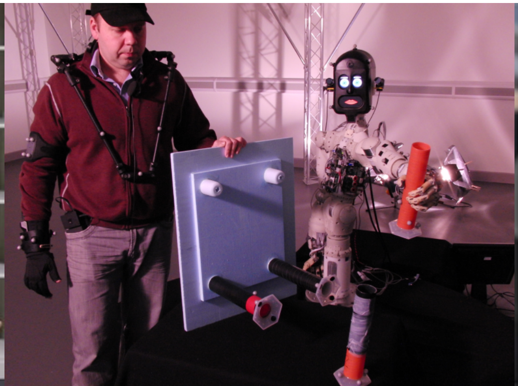
What next?

- Sophisticated Test Generation
  - model-based TG
  - refinement and abstraction
- Safety of human assistive robots
  - decision making, foresight windows
  - physical interaction
- Adaptive systems:
  - flexible specifications
  - verification at runtime
- Walking with robots



Summary

- Use the right tools for the job.
- No single technique is adequate to verify an entire system in practice.
  - Combine verification techniques
- Learn from areas where verification techniques are (more) mature.
- **Design *for* verification!**


Thank you

EPSRC
Engineering and Physical Sciences Research Council

Any questions?

Kerstin.Eder@bristol.ac.uk

Dejanira.AraizaIllan@bristol.ac.uk

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University of BRISTOL

brl
Bristol Robotics Laboratory

Why red wine is so important for Christmas

Merry Christmas and a Happy New Year