



RISC-V Processor OVP Model Simulator

riscvOVPsim User Guide

Imperas Software Ltd
Imperas Buildings, North Weston
Thame, Oxfordshire, OX9 2HA, U.K.
docs@imperas.com



| | |
|----------|----------------------------|
| Author | Imperas Software Ltd |
| Version | 0.7 |
| Filename | riscvOVPsim_User_Guide.pdf |
| Created | 10 Aug 2020 |
| Status | OVP Standard Release |

Copyright Notice

Copyright (c) 2005-2020 Imperas Software Ltd. All rights reserved. This software and documentation contain information that is the property of Imperas Software Limited. The software and documentation are furnished under a license agreement and may be used or copied only in accordance with the terms of the license agreement. No part of the software and documentation may be reproduced, transmitted, or translated, in any form or by any means, electronic, mechanical, manual, optical, or otherwise, without prior written permission of Imperas Software Limited, or as expressly provided by the license agreement.

Right to Copy Documentation

The license agreement with Imperas permits licensee to make copies of the documentation for its internal use only. Each copy shall include all copyrights, trademarks, service marks, and proprietary rights notices, if any.

Destination Control Statement

All technical data contained in this publication is subject to the export control laws of the United States of America. Disclosure to nationals of other countries contrary to United States law is prohibited. It is the readers responsibility to determine the applicable regulations and to comply with them.

Disclaimer

IMPERAS SOFTWARE LIMITED, AND ITS LICENSORS MAKE NO WARRANTY OF ANY KIND, EXPRESS OR IMPLIED, WITH REGARD TO THIS MATERIAL, INCLUDING, BUT NOT LIMITED TO, THE IMPLIED WARRANTIES OF MERCHANTABILITY AND FITNESS FOR A PARTICULAR PURPOSE..

Model Release Status

This software and model is released as part of OVP releases and is included in OVPworld packages. Please visit OVPworld.org.

Contents

| | | |
|----------|---|-----------|
| 1 | Overview of the riscvOVPsim simulator | 1 |
| 1.1 | Description | 1 |
| 1.2 | Usage and Purpose | 2 |
| 1.3 | Licensing | 2 |
| 1.4 | Limitations | 2 |
| 1.5 | Verification | 3 |
| 1.6 | References | 3 |
| 1.7 | About OVP & Imperas Software | 3 |
| 2 | The riscvOVPsim Fixed Platform Simulator | 5 |
| 3 | Host Platforms | 6 |
| 3.1 | Availability | 6 |
| 3.2 | Selecting Host | 6 |
| 4 | Running High Speed Simulations | 7 |
| 4.1 | An Introduction and First Simulation | 7 |
| 4.1.1 | Running using provided scripts and applications | 7 |
| 4.1.2 | Using command line options to show available RISC-V CPU variants | 8 |
| 4.1.3 | Selecting a RISC-V CPU variant | 8 |
| 4.1.4 | Specifying a RISC-V program .elf file to run | 9 |
| 4.1.5 | Specifying Custom Memory Map | 9 |
| 4.1.6 | –help and –helpall command line option | 9 |
| 4.2 | Measuring Instruction Functional Coverage during simulation | 9 |
| 4.3 | Reporting performance statistics when simulation is complete | 10 |
| 4.4 | Running the provided examples | 10 |
| 4.4.1 | Dhrystone, linpack and CoreMark examples | 10 |
| 4.4.2 | Vector examples | 11 |
| 4.4.3 | Bit Manipulation examples | 11 |
| 4.4.4 | Instruction Functional Coverage examples | 11 |
| 5 | The OVP RISC-V processor model | 12 |
| 5.1 | The OVP RISC-V processor model source | 12 |
| 5.2 | The different ‘standard’ RISC-V ISA features and instruction extensions | 12 |
| 5.3 | Selecting a specific RISC-V Processor Variant | 13 |
| 5.4 | Available riscvOVPsim RISC-V variants | 13 |
| 5.4.1 | RV32I | 13 |
| 5.4.2 | RV32IM | 14 |

| | | |
|----------|--|-----------|
| 5.4.3 | RV32IMC | 14 |
| 5.4.4 | RV32IMAC | 14 |
| 5.4.5 | RV32G | 14 |
| 5.4.6 | RV32GC | 14 |
| 5.4.7 | RV32GCN | 14 |
| 5.4.8 | RV32GCV | 14 |
| 5.4.9 | RV32E | 14 |
| 5.4.10 | RV32EC | 14 |
| 5.4.11 | RV64I | 14 |
| 5.4.12 | RV64IM | 15 |
| 5.4.13 | RV64IMC | 15 |
| 5.4.14 | RV64IMAC | 15 |
| 5.4.15 | RV64G | 15 |
| 5.4.16 | RV64GC | 15 |
| 5.4.17 | RV64GCN | 15 |
| 5.4.18 | RV64GCV | 15 |
| 5.5 | Configuring riscvOVPsim to exactly match your processor | 15 |
| 5.5.1 | Detailed Model Configuration options | 16 |
| 5.5.2 | Configuring the model | 16 |
| 5.5.3 | Changing which extensions are enabled in a variant | 16 |
| 5.5.4 | Configuring options for optional Vector Instructions | 17 |
| 5.6 | Adding user extensions to the OVP RISC-V model | 17 |
| 6 | Tracing Program Execution | 18 |
| 6.1 | Simulator Trace commands | 18 |
| 7 | Debugging RISC-V Software with riscvOVPsim | 19 |
| 7.1 | How to debug with standalone GDB | 19 |
| 7.1.1 | Using gdbconsole | 19 |
| 7.1.2 | Using port and manually attaching a debugger | 19 |
| 7.2 | Debugging with Eclipse CDT | 20 |
| 7.2.1 | Getting Eclipse | 20 |
| 7.2.2 | Configuring Eclipse CDT to connect to an external program | 20 |
| 7.2.3 | Starting to debug with Eclipse CDT | 21 |
| 7.3 | How to debug with OVP eGui | 21 |
| 8 | RISC-V Verification and Compliance Usage | 22 |
| 8.1 | How to Verify Tests and the Coverage they are Producing | 22 |
| 8.1.1 | Trace Tools | 22 |
| 8.1.2 | Measuring test coverage to assess the model | 22 |
| 8.1.3 | Measuring functional coverage of tests | 23 |
| 8.1.4 | Configuring RISC-V model for compliance checking | 23 |
| 8.1.5 | Fundamental RISC-V Configuration Options | 23 |
| 8.1.6 | Machine Mode Control and Status Register (CSR) Constraints | 24 |
| 8.1.7 | Interrupts and Exceptions | 25 |
| 8.1.8 | Physical memory | 25 |
| 8.1.9 | Virtual memory | 25 |
| 8.1.10 | Miscellaneous | 26 |

| | | |
|-----------|--|-----------|
| 8.1.11 | Vector instructions | 26 |
| 8.2 | Signature File | 26 |
| 8.2.1 | Introduction | 26 |
| 8.2.2 | Configuration | 27 |
| 8.2.3 | Data Format | 27 |
| 8.2.4 | Usage Example | 27 |
| 8.2.4.1 | Basic operation | 27 |
| 8.3 | Custom Instruction | 28 |
| 8.3.1 | Introduction | 28 |
| 8.3.2 | Usage Example | 28 |
| 9 | Instruction Functional Coverage Usage | 29 |
| 9.1 | Overview of Instruction Functional Coverage | 29 |
| 9.2 | Basic Usage | 30 |
| 9.2.1 | Selecting what is covered | 30 |
| 9.3 | Coverage types | 30 |
| 9.4 | Coverage data files | 31 |
| 9.4.1 | Accumulating coverage across multiple runs | 31 |
| 9.5 | Not measuring start up and shutdown instructions | 32 |
| 9.6 | Covering Pseudo instructions | 32 |
| 9.7 | Measuring Test Quality (Mutation Testing) | 32 |
| 9.8 | Command summary | 33 |
| 10 | Building your own platform and components | 34 |
| 10.1 | Creating Peripheral Models with iGen | 34 |
| 10.2 | Creating Platforms with iGen | 35 |
| 10.3 | Creating Processor Models | 35 |
| 11 | Debugging Multi-Core platforms | 36 |
| | Appendices | 37 |
| A | riscvOVPsim Help Commands | 38 |
| A.1 | help | 38 |
| A.1.1 | control | 38 |
| A.1.2 | diagnostics | 39 |
| A.1.3 | library | 39 |
| A.1.4 | log | 39 |
| A.1.5 | parameters | 39 |
| A.1.6 | platform | 39 |
| A.1.7 | program | 40 |
| A.2 | helpall | 40 |
| A.2.1 | control | 40 |
| A.2.2 | debug | 40 |
| A.2.3 | cover | 40 |
| A.2.4 | diagnostics | 41 |
| A.2.5 | library | 41 |
| A.2.6 | log | 41 |

| | | |
|----------|---|-----------|
| A.2.7 | parameters | 42 |
| A.2.8 | platform | 42 |
| A.2.9 | program | 42 |
| A.2.10 | trace | 43 |
| B | riscvOVPsim model configuration options | 44 |
| C | Compiling RISC-V programs | 47 |
| D | Information on Open Virtual Platforms | 48 |
| E | Information on Imperas Software tools | 50 |
| F | Imperas License governing use of riscvOVPsim | 51 |

Chapter 1

Overview of the riscvOVPsim simulator

This document provides documentation of the riscvOVPsim RISC-V processor model simulator.

1.1 Description

riscvOVPsim is an Instruction Accurate RISC-V processor simulator based on the Imperas Open Virtual Platform (OVP) technology with Just-in-Time Code Morphing simulation that executes RISC-V code on a Linux or Windows host computer.

The included RISC-V models are complete and cover the full RISC-V User and Privilege specifications.

The riscvOVPsim simulator is easy to understand and effective to use. It is flexible, accurate, and exceptionally fast, often over 2,000 MIPS. Suitable as a platform target to develop baremetal, OS Ports (Linux or RTOS), drivers and applications.

riscvOVPsim has been developed by Imperas Software. As a member of the RISC-V community of software and hardware innovators collaboratively driving RISC-V adoption, Imperas has developed the riscvOVPsim simulator to assist RISC-V adopters to become compliant to the RISC-V specifications. riscvOVPsim is included as part of RISC-V International's compliance test suite. The latest RISC-V compliance test suite and framework can be downloaded from www.github.com/riscv/riscv-compliance.

Imperas is revolutionizing the development of embedded software and systems and is the leading independent provider of commercial processor simulators for programmers view models for software development.

Imperas, along with Open Virtual Platforms (OVP), promotes open model availability for a spectrum of processors, IP vendors, CPU architectures, system IP and reference platform models of processors and systems ranging from simple single core bare metal platforms to full heterogeneous multi-core systems booting SMP Linux. Additional information can be found at www.imperas.com and www.OVPworld.org.

1.2 Usage and Purpose

There is no complex installation process or scripts for downloading and installing riscvOVPsim. It is just a matter of downloading and running the executable with appropriate configuration options and cross-compiled RISC-V programs.

riscvOVPsim is configurable to represent exactly the same implementation choices that RISC-V processor implementors choose thus making it an excellent tool for the development of RISC-V application software and verification and compliance test suites.

The simulator can connect to GDB and Eclipse for source code debug and can be run in batch mode for regression testing and use in continuous integration environments. It also has many trace options to assist in program development.

riscvOVPsim has built in instruction functional coverage measurement and reporting to assess what is in tests. It is used to measure the completeness of the RISC-V compliance tests and test suites.

1.3 Licensing

The complete OVP RISC-V processor model is included with riscvOVPsim and is made available as open source under the Apache 2.0 license.

riscvOVPsim includes an industrial quality model and simulator of RISC-V processors for use for compliance and test development. It has been developed for personal, academic, or commercial use, and the model is provided as open source under the Apache 2.0 license. The simulator is provided under the under Open Virtual Platforms (OVP) Fixed Platform Kits license that enables download and usage. riscvOVPsim and Imperas RISC-V support is actively maintained and enhanced. To ensure you make use of the current version of riscvOVPsim this initial release will expire. Please download the latest version.

The full license terms are included within the download package and are listed in an appendix of this document.

Imperas provide a version of riscvOVPsim with full commercial maintenance and support, as well as additional multicore configuration options.

1.4 Limitations

Problems with installation or download may be reported to support@imperas.com.

Feedback and bug reports may be submitted to support@imperas.com.

riscvOVPsim is restricted to only run RISC-V processor model variants in a fixed platform configuration of one processor instance and one memory sub-system. Caches and other processor microarchitecture features are not included in programmer view models. If you need different platform configurations or to extend the platform or models then please contact [Imperas](mailto:support@imperas.com) or visit www.OVPworld.org.

1.5 Verification

Imperas have been developing simulators and processor models for over 10 years and are the leading independent provider of instruction accurate simulators, processor reference models and tools.

Each model is developed with a very controlled and precise methodology where as the model functionality is developed it is carefully stepped through and white box, directed tests are created.

A comprehensive test suite is developed until 100% model line coverage is achieved. Standard publicly available test suites are then used. Complete platforms are then constructed to run full operating systems. All of these tests are incorporated into a continuous integration and regression testing environment to ensure model quality.

The Imperas OVP RISC-V models have been run through the above process and virtual platforms incorporating them are available from Imperas running FreeRTOS, single core Linux, and SMP Linux on a five core RISC-V processor system.

The models have also been run through the full RISC-V.org Foundation's Compliance Suite and all tests pass. (The Imperas RISC-V model is a reference simulator for the RISC-V Compliance Suite.)

1.6 References

The current release of riscvOVPsim models:

- RISC-V Instruction Set Manual, Volume I: User-Level ISA (User Architecture Version 20190305-Base-Ratification).
- RISC-V Instruction Set Manual, Volume II: Privileged Architecture (Privileged Architecture Version 20190405-Priv-MSU-Ratification).
- RISC-V Instruction Bit Manipulation (B) Extension, Version 0.93 with version configurable in the model and regularly updated to track the evolving specification.
- RISC-V Instruction Set Manual, RISC-V base vector extension, version 0.9 (03-Jul-2020) with version configurable in the model and regularly updated to track the evolving specification.

1.7 About OVP & Imperas Software

Open Virtual Platforms (www.OVPworld.org) was set up in 2008 to provide an open standard approach to creating virtual platforms. OVP provides full definitions of standard APIs to enable the modeling and simulation of digital hardware. There are over 500 OVP models with tools to easily create virtual platforms. With OVP, users create their own models and platforms and can develop software on simulations of hardware. OVPworld.org also provides a full simulation and debug capability that is licensed and usable for non-commercial use.

Most OVP models are available under an Apache 2.0 open source license. For a full list of publicly available OVP processor models, visit here: www.ovpworld.org/variants. To browse the OVP library of peripheral models, visit here: www.ovpworld.org/peripherals.

For commercial use, [Imperas](#) provide a full suite of simulators, verification / analysis / profiling, debug, and platform / model development tools. Imperas is the leader in heterogeneous multi-core simulation and debug.

Imperas can be contracted to develop new models of processor, peripheral components, or full platforms.

Imperas also provide a RISC-V processor compliance testing service if you need to ensure that your RISC-V RTL is compliant with RISC-V specifications.

Imperas can also provide additional tools and services to assist with RISC-V processor compliance if you need to ensure that your RISC-V RTL is compliant with either the latest or earlier versions of the RISC-V specifications. Please contact Imperas for the latest information.

Chapter 2

The riscvOVPsim Fixed Platform Simulator

riscvOVPsim has a built-in fixed platform which comprises one CPU instance of a RISC-V processor model variant and one memory sub-system.

The RISC-V processor model variant is selected by a command line switch and the details of its options can be configured using override commands. See the the section below on using the OVP RISC-V processor model.

The memory fully populates the appropriate address space for the configured processor. It is implemented in the simulator using a sparse memory algorithm and so there are no capacity issues.

riscvOVPsim has built in instruction functional coverage measurement and reporting to assess what is in tests. It is used to measure the completeness of the RISC-V compliance tests and test suites.

Chapter 3

Host Platforms

3.1 Availability

riscvOVPsim is available on Windows 64 bit, and Linux 64 bit hosts.

3.2 Selecting Host

There are two different binary directory trees provided with riscvOVPsim. In the directories will be the appropriate binary files needed for the different hosts.

Chapter 4

Running High Speed Simulations

The riscvOVPSim program is a standalone executable that performs the following tasks:

- Sets up the platform with a cpu model and memory
- Configures the behavior of the platform and model by changing run-time command line switches
- Loads application code in .elf format into memory to run on the processor model
- Loads an appropriate semihost library to allow application code to interact with the host computer (for example to display application code 'printf's to the simulation console without the need for a simulated UART)
- Optionally invokes a GDB debugger to enable source code debug
- Runs the simulator which executes the RISC-V cross compiled binary instructions
- Reports performance statistics when simulation is complete

4.1 An Introduction and First Simulation

riscvOVPSim is used to simulate application code in bare metal environments by just loading up a cross compiled .elf file and selecting a CPU variant. There are configuration options to select other parameters.

4.1.1 Running using provided scripts and applications

In the main directory, there is an examples directory with several different sub directories, one for each example. If you open one of these directories, you will see several scripts that are either .bat for Windows or .sh for Linux. These can just be executed. In this document we will assume Linux usage:

```
> cat RUN_RV32_Dhrystone.sh
...
${bindir}/riscvOVPSim.exe --variant RVB32I \
--override riscvOVPSim/cpu/add_Extensions_mask=MACSU \
--program application/dhrystone.RISCV32.elf
```

The '-variant' selects a specific processor model variant to be simulated. The '-program' specifies which application .elf program to run. To run the simulation:

```
> RUN_RV32_Dhrystone.sh
```

The simulator will run, showing the results of the dhrystone simulation:

```
riscvOVPsim (64-Bit) v20180221.0 Open Virtual Platform simulator from www.IMPERAS.com.
Copyright (c) 2005-2020 Imperas Software Ltd. Contains Imperas Proprietary Information.
Licensed Software, All Rights Reserved.
Visit www.IMPERAS.com for multicore debug, verification and analysis solutions.

riscvOVPsim started: Fri Apr 13 02:40:19 2018

Info (OR_OF) Target riscvOVPsim/cpu has object file read from dhrystone.RISCV32-00-g.elf
Info (OR_PH) Program Headers:
Info (OR_PH) Type      Offset      VirtAddr  PhysAddr  FileSiz   MemSiz    Flags Align
Info (OR_PD) LOAD      0x00000000 0x00010000 0x00010000 0x00017dc0 0x00017dc0 R-E 1000
Info (OR_PD) LOAD      0x00017dc0 0x00028dc0 0x00028dc0 0x000009c0 0x00003228 RW- 1000

Dhrystone Benchmark, Version 2.1 (Language: C)

Program compiled without 'register' attribute

Execution starts, 5000000 runs through Dhrystone

...

Measured time too small to obtain meaningful results
Please increase number of runs

Info
Info -----
Info CPU 'riscvOVPsim/cpu' STATISTICS
Info Type : riscv (RV32I+MAC)
Info Nominal MIPS : 100
Info Final program counter : 0x100ac
Info Simulated instructions: 6,955,075,157
Info Simulated MIPS : 1388.9
Info -----
Info
Info -----
Info SIMULATION TIME STATISTICS
Info Simulated time : 69.55 seconds
Info User time : 5.01 seconds
Info System time : 0.00 seconds
Info Elapsed time : 5.01 seconds
Info Real time ratio : 13.89x faster
Info -----

riscvOVPsim finished: Fri Apr 13 02:40:24 2018

riscvOVPsim (64-Bit) v20180221.0 Open Virtual Platform simulator from www.IMPERAS.com.
Visit www.IMPERAS.com for multicore debug, verification and analysis solutions.
```

4.1.2 Using command line options to show available RISC-V CPU variants

To see the list of processor model variants available in riscvOVPsim:

```
> ./bin/Linux64/riscvOVPsim.exe --showvariants
```

4.1.3 Selecting a RISC-V CPU variant

The '-variant' selects a specific processor model variant to be simulated.

```
> ./bin/Linux64/riscvOVPsim.exe --variant RVB64I \
  --override riscvOVPsim/cpu/add_Extensions=MACSU \
  --program application/dhrystone.RISCV64.elf
```

4.1.4 Specifying a RISC-V program .elf file to run

The

```
'--program <app.elf >'
```

specifies which application .elf program to run.

4.1.5 Specifying Custom Memory Map

By default, the memory space is fully populated i.e. 0 to maximum high address contain memory. If a specific memory layout is required it can be specified using the command line argument '--memory memory definition string'. The memory argument takes a string defining the low and high addresses, and, if required, a name and the memory access permissions. The memory access permission defaults to RWX i.e. read, write and execute. The permission is defined by bits 1:Read 2:Write 3:Execute. The memory argument may be supplied multiple times or once with a comma separated list.

```
'--memory [<name>:]<low address>:<high address>[:<permissions >][,repeat]'
```

The following example shows setting up a memory space which has two memory regions, named loram and hiram. The lower has RWX permissions and the upper has only RW permissions. All other memory spaces will cause an access failure.

```
> ./bin/Linux64/riscvOVPsim.exe --memory loram:0x00000000:0x0001ffff:rwx \  
--memory hiram:0xffff0000:0xffffffff:rw
```

which could also be entered as

```
> ./bin/Linux64/riscvOVPsim.exe \  
--memory loram:0x00000000:0x0001ffff:rwx,hiram:0xffff0000:0xffffffff:rw
```

4.1.6 -help and -helpall command line option

There are command line arguments '-help' and '-helpall' that list the options available. For example:

```
> ./bin/Linux64/riscvOVPsim.exe --help
```

See the appendix for details of the help commands.

4.2 Measuring Instruction Functional Coverage during simulation

For any simulation run, you can enable instruction functional coverage to be collected.

The simplest form is:

```
> ./bin/Linux64/riscvOVPsim.exe --variant RVB32I --program prog.elf \  
  --cover basic --extensions RVI --reportfile cover_report.log
```

Which will display one line to the simulation console:

```
TOTAL INSTRUCTION COVERAGE :: threshold : 1 : instructions: seen 2/2 : 100.00%, coverage points hit: 242/542 : 44.65%
```

And will write out a full report in the specified file.

See the chapter on Instruction Functional Coverage for full details.

4.3 Reporting performance statistics when simulation is complete

At the end of a simulation run, the simulator will display results and statistics:

```
...  
Info  
Info -----  
Info CPU 'riscvOVPsim/cpu' STATISTICS  
Info Type : riscv (RV32I+MAC)  
Info Nominal MIPS : 100  
Info Final program counter : 0x100ac  
Info Simulated instructions: 6,955,075,157  
Info Simulated MIPS : 1388.9  
Info -----  
Info  
Info -----  
Info SIMULATION TIME STATISTICS  
Info Simulated time : 69.55 seconds  
Info User time : 5.01 seconds  
Info System time : 0.00 seconds  
Info Elapsed time : 5.01 seconds  
Info Real time ratio : 13.89x faster  
Info -----  
  
riscvOVPsim finished: Fri Apr 13 02:40:24 2018  
  
riscvOVPsim (64-Bit) v20180221.0 Open Virtual Platform simulator from www.IMPERAS.com.  
Visit www.IMPERAS.com for multicore debug, verification and analysis solutions.
```

This shows the fixed platform name (riscvOVPsim), the processor instance (cpu), the variant type (RV32I with extensions MAC). The Nominal MIPS is effectively the clock speed that the CPU is clocked at in the platform (this can be overridden). The Simulated MIPS is the number of instructions simulated per second. The Simulated time is the time simulated in the simulation. User, System, and Elapsed time is how long the simulation took if you looked at your watch. The Real time ratio shows how much faster/slower the simulation was compared to real time.

4.4 Running the provided examples

The examples directory provides some easy to run examples to show how riscvOVPsim is used. These come with a script to run and configure the simulator and the source and elf files that are needed.

4.4.1 Dhrystone, linpack and CoreMark examples

The directory fibonacci is the simplest for just show a program running. The dhrystone, linpack and CoreMark are standard benchmarks.

Chapter 5

The OVP RISC-V processor model

The OVP RISC-V processor model is written in C and makes calls to the standard OVP VMI API interface.

The source of the OVP RISC-V processor model is available as open source under the Apache 2.0 license where you got this document (see below).

For information on how OVP CPU models are written look at the [OVP Processor Modeling Guide](#) and for information on the VMI API look at [OVP VMI Morph-Time Reference](#) and [OVP VMI Run-Time Reference](#).

The model has been written to contain all the functionality of the standard RISC-V specifications and the functionality of the specification is subset within the model into 'model variants' that are selected at runtime and configure the model. When a model variant is selected, only the defined capabilities of that model variant are available. For example if a floating point instruction is attempted to be executed by a variant that does not implement floating point instructions, then an un-implemented instructed exception is triggered. If an instruction accessed a register that was not present in the selected variant, then again the model would indicated an error, for example trying to use register 31 in an E variant.

5.1 The OVP RISC-V processor model source

The full source of the OVP RISC-V processor is provided with this document as a reference. It is the source that is compiled into the model that is being simulated by riscvOVPsim.

If you want to modify the model source and recompile it and use it for simulation, then you need to use either the simulator from OVP or from Imperas as they are simulators that allow this loading of user compiled models. Visit www.ovpworld.org or www.imperas.com.

5.2 The different 'standard' RISC-V ISA features and instruction extensions

The model supports the following architectural features:

- RV32I/64I/128I base ISA
- RV32E base ISA
- extension M (integer multiply/divide instructions)
- extension A (atomic instructions)
- extension B (bit manipulation instructions)
- extension F (single-precision floating point)
- extension D (double-precision floating point)
- extension C (compressed instructions)
- extension N (user-level interrupts)
- extension S (Supervisor mode)
- extension U (User mode)
- extension V (vector instructions)
- 32-bit, 64-bit XLEN

All features and registers in the RISC-V Privilege Specification are implemented and configured as required.

5.3 Selecting a specific RISC-V Processor Variant

To see the list of processor model variants available in riscvOVPsim:

```
> ./bin/Linux64/riscvOVPsim.exe --showvariants
```

The '-variant' command selects a specific processor model variant to be simulated.

NOTE: the variant name is case sensitive.

```
> ./bin/Linux64/riscvOVPsim.exe --variant RVB64I \  
  --override riscvOVPsim/cpu/add_Extensions=MACSU \  
  --program application/dhrystone.RISCV64.elf
```

5.4 Available riscvOVPsim RISC-V variants

For each RISC-V variant there is a detailed document that describes the features and limitations of the implementation. It also lists all the registers, ports, modes, exceptions, etc., and importantly, it lists all the configuration parameters that can be set for that variant.

Each variant is unique and has a different document.

5.4.1 RV32I

A detailed document of the model variant is available: [RV32I](#)

5.4.2 RV32IM

A detailed document of the model variant is available: [RV32IM](#)

5.4.3 RV32IMC

A detailed document of the model variant is available: [RV32IMC](#)

5.4.4 RV32IMAC

A detailed document of the model variant is available: [RV32IMAC](#)

5.4.5 RV32G

A detailed document of the model variant is available: [RV32G](#)

5.4.6 RV32GC

A detailed document of the model variant is available: [RV32GC](#)

5.4.7 RV32GCN

A detailed document of the model variant is available: [RV32GCN](#)

5.4.8 RV32GCV

A detailed document of the model variant is available: [RV32GCV](#)

5.4.9 RV32E

A detailed document of the model variant is available: [RV32E](#)

5.4.10 RV32EC

A detailed document of the model variant is available: [RV32EC](#)

5.4.11 RV64I

A detailed document of the model variant is available: [RV64I](#)

5.4.12 RV64IM

A detailed document of the model variant is available: [RV64IM](#)

5.4.13 RV64IMC

A detailed document of the model variant is available: [RV64IMC](#)

5.4.14 RV64IMAC

A detailed document of the model variant is available: [RV64IMAC](#)

5.4.15 RV64G

A detailed document of the model variant is available: [RV64G](#)

5.4.16 RV64GC

A detailed document of the model variant is available: [RV64GC](#)

5.4.17 RV64GCN

A detailed document of the model variant is available: [RV64GCN](#)

5.4.18 RV64GCV

A detailed document of the model variant is available: [RV64GCV](#)

5.5 Configuring riscvOVPsim to exactly match your processor

The OVP model of the RISC-V specification has many detailed configuration options. These can be set option by option, or, as explained above, the model can be configured by selecting a 'variant'. This is basically a predefined list of settings of many of the different configuration options. To see the details of how a variant configures the model, see the detailed variant documentation as referenced in the previous section.

In many cases, the RISC-V specifications give freedom to the processor implementer to make detailed choices of which parts of the RISC-V specification are implemented and in which way. In a coarse way this might be choosing to not implement hardware floating point, or in a detailed way it might be making a register read only - as allowed in the specifications.

The Imperas OVP RISC-V model can be configured to reflect the specific detailed hardware design decisions that have been chosen.

This detailed configuration of a model is essential when trying to write specification compliance and design tests as the tester needs to know that they are stimulating parts of the specification that should not be in their design and so they need the model to tell them there are errors.

5.5.1 Detailed Model Configuration options

To see the list of processor model configuration options available in riscvOVPsim for a variant:

```
> ./bin/Linux64/riscvOVPsim.exe --variant RVB32E --showmodeloverrides
```

The complete set of configuration options are listed as an appendix to this document.

NOTE: it is important to set the variant as that selects features and thus what can be configured. Each variant may have different configuration parameters.

5.5.2 Configuring the model

An example configuring the model:

```
> ./bin/Linux64/riscvOVPsim.exe --variant RVB64I \  
  --override riscvOVPsim/cpu/add_Extensions=MAFDCNSU \  
  --override riscvOVPsim/cpu/mtvec_is_ro=T \  
  --override riscvOVPsim/cpu/updatePTEA=F \  
  --program app.elf
```

Where `mtvec_is_ro` is a parameter that if set T (true) means `mtvec` is read only, and where `updatePTEA` is a parameter that configures the model saying in this case (false) that hardware update of PTEA is not supported.

5.5.3 Changing which extensions are enabled in a variant

In the RISC-V architecture the `misa` CSR specifies which extensions are implemented. The reset value for the `misa` register's extensions field may be specified as a configuration option by using the `misa.Extensions` parameter, thus allowing the user to control which extensions are implemented by the simulation model.

In the document for each variant (linked to in the sections above) is a description of which extensions are enabled (in the section titled Extensions) and which extensions are available but not enabled (in the sections titled Available (But Not Enabled) Extensions). The bit locations for each extension may be found there.

For example, to model an RV64IMCD configuration we start with an RVB64I variant and enable the M, C and D extensions using the `add_Extensions` override.

```
> ./Linux64/bin/riscvOVPsim.exe --variant RVB64I --override \  
  --override riscvOVPsim/cpu/add_Extensions=MCDSU \  
  --showmodeloverrides | grep "_Extensions=" \  
  --override riscvOVPsim/cpu/misa_Extensions=0x14110c (Uns32)
```

```
(default=0x14110c) (default)
Override default value of misa.Extensions
--override riscvOVPsim/cpu/add_Extensions=MCD (String) (default=)
(override) Add extensions specified by letters to misa Extensions
(for example, specify "VD" to add V and D features)
```

5.5.4 Configuring options for optional Vector Instructions

The RISC-V vector instructions can be configured with many options. For details of the settings either read the model specific documentation (<http://www.ovpworld.org/procmodeldocs>) or use `--showmodeloverrides` to list them.

5.6 Adding user extensions to the OVP RISC-V model

If you want to add new registers or new instructions to the OVP RISC-V model, then there are better ways than modifying the source. Imperas has developed the concept of intercept libraries that can intercept model operation and dynamically modify it - without any of the risks of modifying (maybe incorrectly) the original model source. Imperas has used this very successfully to add user defined custom instructions and registers for different RISC-V customers. For more information contact info@imperas.com.

Chapter 6

Tracing Program Execution

The riscvOVPsim simulator can trace each processor instruction with different levels of detail.

You can use the command line argument `-helpall` to get this listing:

6.1 Simulator Trace commands

| Flag | Short | Argument | Description |
|-----------------|-------|---------------------|--|
| trace | t | [processor] | Trace instructions as they are executed |
| traceafter | | [processor=]integer | Start tracing instructions after this many have executed |
| tracebuffer | | [processor] | Enable the trace buffer |
| tracechange | | [processor] | Trace changed registers |
| tracecount | | [processor=]integer | Trace this number of instructions |
| tracemode | | [processor] | Add the current processor mode to the instruction trace |
| traceregs | | [processor] | Dump registers after each instruction is executed |
| traceregsafter | | [processor] | Dump registers after each instruction is executed |
| traceregsbefore | | [processor] | Dump registers before each instruction is executed |
| traceshowicount | | [processor] | Show instruction count with each instruction |

Table 6.1: Trace command arguments

Chapter 7

Debugging RISC-V Software with riscvOVPsim

An application program running on the processor can be debugged using a GDB or other compatible debugger by attaching to the running simulator. The debugger can be used standalone or under Eclipse. There are several methods that can be used to accomplish this that will be described in the next sections.

7.1 How to debug with standalone GDB

7.1.1 Using gdbconsole

The command line argument `gdbconsole` may be added to the execution of the simulation platform. This will open a port on the simulator and automatically start and connect a compatible GDB to this port.

For example this can be invoked using the command line

```
> riscvOVPsim.exe -program application.elf -gdbconsole
```

7.1.2 Using port and manually attaching a debugger

The command line argument `port` can be used to open a port on the simulation platform to which a compatible GDB (or equivalent) can be manually attached.

Start the simulation and specify a port to open

```
> riscvOVPsim.exe -program application.elf -port 3333
```

Start the GDB, which must be compatible with the processor type to which it is connecting. It is also usual to pass the program to be debugged to the GDB when invoked.

Start the GDB

```
> gdb.exe application.elf
```

At the GDB command line connect to the port that has been opened on the simulation.

```
gdb> target remote localhost:3333
```

You are now able to debug the application.

7.2 Debugging with Eclipse CDT

7.2.1 Getting Eclipse

Eclipse can be downloaded from www.eclipse.org, selecting the Neon release packages and the link *Eclipse IDE for C/C++ Developers*. Download the package for your host and install.

You will also need to install a suitable Java runtime, try www.java.com/en/download and select a Java runtime for your host machine.

7.2.2 Configuring Eclipse CDT to connect to an external program

Start Eclipse

Create a new project containing the application to be debugged, ensure that the application is built and up to date.

Select Debug Configurations ...

Select C/C++ Remote Applications->New

Main Tab

- Select Disable Auto Build
- Click 'skip download to target path.'
- If the Automatic Debugging Launcher is selected
 - Select 'Select Other'
 - Click 'Use configuration specific settings'
 - * Select 'Manual Remote Debugging Launcher'
- Browse or Search project for the application elf file that we want to debug

Debugger Tab

Main

- Change the GDB Debugger to the correct GDB for the processor that is running the application to be debugged

Connection

- Select Type TCP

- Set host name or IP address to localhost (this assume we are running the simulation and the Eclipse on the same machine)
- Set port Number to a fixed port that is available on the host machine and that is used with the *port* argument when the simulation platform is started.

Add a name that indicates the processor and application that this Debug Configuration applies to and click Apply to save.

7.2.3 Starting to debug with Eclipse CDT

The simulation platform should be started, and a debug port manually opened using the *port* argument as detailed in a previous section.

If there are multiple processors in the platform, one should be selected using the *debugprocessor* argument, for example `-debugprocessor riscvOVPsim/cpu2`

```
> riscvOVPsim.exe -program application.elf -port 3333
```

The port number should be selected the same as used in the Eclipse CDT Debug Configuration.

7.3 How to debug with OVP eGui

Imperas/OVP have created an Eclipse plugin that interacts with the CDT package to provide debug capabilities beyond those of CDT. eGui can be included into an existing Eclipse/CDT installation as a plugin or installed as part of the Imperas/OVP installation as standalone.

Getting eGui

This requires that you are registered on the Forum at www.ovpworld.org

Once registered you can go to the downloads page and then download and install the following package:

eGui_Eclipse

Starting eGui

The command line argument *gdbgui* may be added to the execution of the simulation platform. This will open a port on the simulator and automatically start eGui and connect to this port.

For example, this can be invoked using the command line

```
> riscvOVPsim.exe -program application.elf -gdbgui
```

This will start the eGui Eclipse and connect to the simulation.

Chapter 8

RISC-V Verification and Compliance Usage

8.1 How to Verify Tests and the Coverage they are Producing

A test will exercise a specific feature of the processor. This may be a specific set of instructions, virtual memory, exceptions or one of many other things. The tests are small and specific with a measurable outcome.

When a test is executed on the virtual platform it can be observed either by using tools or in a debug environment.

8.1.1 Trace Tools

The simulator has the built-in capability to trace instruction execution and changes to register values. This provides a detailed view of the execution of the test.

There are also processor specific trace capability tools that can be loaded. These can provide detailed analysis of the processor execution. These include mode switches, exceptions, access to system registers and others.

The above tools will give full visibility of the execution of the test application allowing, amongst other things, visibility of the behaviour upon internal and external exceptions, illegal instructions, privilege access etc.

In this way we can be sure that the test is performing the actions that we specifically want to see.

Once a tests detailed operation is verified, it can be used to produce a signature which can be used to determine a pass/fail in future runs.

8.1.2 Measuring test coverage to assess the model

When a suite of tests has been created we want to be sure that they are stimulating all expected aspects of the processor. This can be done by examining the coverage of the processor model.

Tools are provided by Imperas in the M*SDK tool suite that allow code coverage of the model and instruction usage profiles to be generated.

The processor model code coverage can be used to determine if all instructions and variations of those instructions have been executed. Similarly, it can be used to determine if all exceptions have been stimulated, modes entered etc.

The instruction profile can be used to determine how many times each instruction has been executed within each test of the test suite providing further details of how well an instruction is tested.

8.1.3 Measuring functional coverage of tests

The simulator includes a tool to measure instruction functional coverage. This is used to see what instructions, operands, and values are used in tests. See the chapter below.

8.1.4 Configuring RISC-V model for compliance checking

The OVP Fast Processor Model is configured from the base execution model using parameters and overrides. The parameter named variant is used to select between the permitted extension and permitted mode combinations of A, B, C, D, E, F, I, M, N, S, U and V.

The RISC-V processor model is configured using overrides to default model parameter values are applied to the processor model instance in the virtual platform, using the -override argument. For example:

```
-override riscvOVPsim/cpu/parameter=value
```

A list of all the available configuration parameters for the model can be obtained using the argument -showmodeloverrides

These are also described in the RISC-V processor model specific documentation available from the OVP website or in an OVP or Imperas product installation.

8.1.5 Fundamental RISC-V Configuration Options

1. What version of Privileged Architecture is implemented? (e.g. 1.10 or 1.11 or 20190405).

```
parameter user_version
```

2. What version of User Architecture is implemented? (e.g. 2.2 or 2.3 or 20190305) .

```
parameter priv_version
```

3. What extensions and modes are supported?

```
Use -showvariants to get a list of the available variants that can be used and then  
set using -variant
```

8.1.6 Machine Mode Control and Status Register (CSR) Constraints

1. Is misa CSR writable? If so, which bits are writable, and which fixed?

parameter `misa_extension_mask`

2. What is the value of the mvendorid CSR?

parameter `mvendorid`

3. What is the value of the marchid CSR?

parameter `marchid`

4. What is the value of the mimpid CSR?

parameter `mimpid`

5. What is the value of the mhartid CSR?

parameter `mhartid`

6. Is the mtvec CSR writable or fixed?

parameter `mtvec_is_ro` is set to `True` to make the `mtvec` read only

7. Does the mtvec CSR have a defined initial value?

parameter `mtvec` is used to set an initial value

8. Is the time CSR defined, or are accesses to it trapped and emulated?

parameter `time_undefined` is set to cause a trap exception if a `time` instruction is executed

9. Is the cycle CSR defined, or are accesses to it trapped and emulated?

parameter `cycle_undefined` is set to cause a trap exception if a `cycle` instruction is executed

10. Is the instret CSR defined, or are accesses to it trapped and emulated?

parameter `instret_undefined` is set to cause a trap exception if a `instret` instruction is executed

11. On an Illegal Instruction exception, are `mtval` (and `stval`, if present) set to 0 or the instruction bit pattern?

parameter `tval_ii_code` is set to `True` so that the `mtval` (`stval`) registers are set to the instruction bit pattern on an illegal instruction

8.1.7 Interrupts and Exceptions

1. What is the reset vector address

parameter `reset_address` is used to set the reset vector address

2. How many local interrupts are implemented?

parameter `local_int_num` is used to set the number of supplemental local interrupts

3. Is an NMI interrupt implemented?

If the NMI interrupt is implemented a net connection should be made to the `nmi` signal port on the model. If no connection is made the `nmi` is disabled.

4. If NMI is implemented, what is the NMI vector address?

parameter `nmi_address` is used to set the `nmi` vector address

8.1.8 Physical memory

1. What is the physical address bus size?

The physical address bits for the bus port is set to match the size of the bus connected to the processor so no additional configuration need be applied to the processor model.

2. Are Physical Memory protection (PMP) registers implemented? If so, how many regions are there? (up to 16).

parameter `PMP_registers` is used to set the number of implemented PMP address registers

8.1.9 Virtual memory

1. If virtual memory is implemented, what address translation modes are implemented? (model supports Sv32, Sv39, Sv48).

parameter `Sv_modes` is used to set specify a bit mask indicating the number of Sv modes implemented, for example `1<<8` indicates Sv39

2. Is ASID-managed address translation implemented? If so, how many bits of ASID are implemented?

parameter `ASID_bits` is used to specify the number of ASID bits

3. Is update of page table entry A bit performed by hardware or software?

parameter `updatePTEA` is set to `True` to indicate support for hardware update of PTE A bit

4. Is update of page table entry D bit performed by hardware or software?

parameter `updatePTED` is set to `True` to indicate support for hardware update of PTE D bit

8.1.10 Miscellaneous

1. If atomic (A) extension is supported, what is the size in bytes of the lock granule (e.g. 32-byte cache line).

parameter `lr_sc_grain`

2. Is the WFI instruction a true wait or a NOP?

parameter `wfi_is_nop` is set to `True` so that `wfi` is implemented as a `nop` instruction, otherwise halt while waiting for interrupt

3. Does the processor support unaligned memory accesses?

parameter `unaligned` is set to `True` to specify the processor supports unaligned operations.

8.1.11 Vector instructions

1. Parameter `ELEN` is used to specify the maximum size of a single vector element in bits (32 or 64). By default, `ELEN` is set to 64.
2. Parameter `VLEN` is used to specify the number of bits in a vector register (a power of two in the range 32 to 2048). By default, `VLEN` is set to 512.
3. Parameter `SLEN` is used to specify the striping distance (a power of two in the range 32 to 2048). By default, `SLEN` is set to 64.
4. Parameter `Zvlsseg` is used to specify whether the `Zvlsseg` extension is implemented. By default, `Zvlsseg` is set to 1.
5. Parameter `Zvamo` is used to specify whether the `Zvamo` extension is implemented. By default, `Zvamo` is set to 1.
6. Parameter `Zvediv` will be used to specify whether the `Zvediv` extension is implemented. This is not currently supported.

8.2 Signature File

8.2.1 Introduction

A signature file is the contents of a memory region that is output to a file after the execution of an application on a RISC-V processor.

It is used in some of the tests written to validate the RISC-V processor.

By default, the signature file is generated at the end of simulation or when the function `'write_to_host'` is called and it contains the memory contents bounded by the symbols `'signature_begin'` and `'signature_end'`.

The signature file generation is implemented as an Imperas intercept/extension library. It provides both the memory dump and detection of test pass/fail by reading a result register, default `t3`.

8.2.2 Configuration

The signature file operation can be configured from the default using the following arguments

- **SignatureFile** : The name of the file created containing the signature
- **SignatureAtEnd** : Write the signature file at the end of simulation. By default the signature file is written on the ‘write_tohost’ function call.
- **ResultReg** : The register examined to indicate if the test passed or failed. Permitted values 3=gp, 10=a0, 28=t3 (default)

Defining the Start of the memory region containing the signature

- **StartAddress** : The address of the memory
- **StartSymbol** : The symbol, default ‘signature_start’

Defining the End of the memory region containing signature

- **EndAddress** : The address of the memory
- **EndSymbol** : The symbol, default ‘signature_end’
- **ByteCount** : The size in bytes

8.2.3 Data Format

The signature format, defined by RISC-V.org, consists of 16 bytes per line. This requires that the size of the signature memory is always on a 16-byte boundary and is reduced to the previous boundary if too big. By reducing the size we ensure that only data intended for the signature is included and not additional ‘random’ data.

8.2.4 Usage Example

The intercept/extension library is enabled on the virtual platform simulation using the -signedump argument and configured using the override argument on the command line.

8.2.4.1 Basic operation

```
> riscvOVPsim.exe -signedump \  
  -overriderriscvOVPsim/cpu/sigdump/SignatureFile=<my filename>
```

Changing the memory region to use an alternative symbol

```
> riscvOVPsim.exe -signaturedump \  
  -override riscvOVPsim/cpu/sigdump/SignatureFile=<my filename>  
  -override riscvOVPsim/cpu/sigdump/StartSymbol=<symbol of start of memory>  
  -override riscvOVPsim/cpu/sigdump/ByteCount=<number of bytes from start>  
  -override riscvOVPsim/cpu/sigdump/SignatureAtEnd=T
```

If the program does not call ‘write_to_host’ we must also enable the signature to be written when simulation completes, typically this is when ‘exit’ is called.

8.3 Custom Instruction

8.3.1 Introduction

When running basic tests on the processor without C libraries or hardware to provide character output e.g. a UART; a custom instruction can be used to provide character output in the simulation environment. The custom instruction is added to a test using a MACRO so that the test can be compiled without the custom instruction for execution on hardware or with the custom instruction for execution on the simulator. Note: On hardware there is, therefore, no logging of the test execution and so only a pass/fail result can be obtained. On the simulator the logging can be used to indicate the flow of the test and where it diverges from the expected behavior.

8.3.2 Usage Example

The intercept/extension library is enabled on the virtual platform simulation using the -customcontrol argument.

```
> riscvOVPsim.exe -customcontrol
```

If the program executes the custom instruction a character will be displayed at stdout.

Chapter 9

Instruction Functional Coverage Usage

9.1 Overview of Instruction Functional Coverage

Instruction Functional Coverage as it relates to processor verification is a technology solution to measure what is being stimulated in the ISA in terms of which instructions, operands and values are driven into a processor.

If a signature comparison based verification methodology is adopted (as in the RISC-V Compliance suites) for comparison between device under test and reference, then functional coverage is only part of the story, as it is essential to measure the successful propagation of the results of the input instructions/values into the signature. Read more about this in the section below on Mutation Testing.

The Imperas coverage technology is built using the Imperas VAP intercept technology and is available as an extension library as source as a standard part of the Imperas commercial product offerings. This allows users to extend and modify functionality and coverage capability. Contact Imperas for more information.

riscvOVPsim includes a built in functional coverage engine which can be enabled to measure the executing instruction stream during simulation. There is no need for trace files post processing, or any other interaction.

Functional coverage commands are listed below, to see all commands use:

```
> riscvOVPsim.exe --help
> riscvOVPsim.exe --helpall
```

Example coverage command:

```
> riscvOVPsim.exe --variant RVB32I --program eg.elf \
  --cover basic --extensions RVI --reportfile impCov.log
```

9.2 Basic Usage

The Imperas instruction functional coverage works by monitoring every instruction as it retires and recording information about it.

At the end of simulation this data is summarized in the console and simulation log file.

```
COVERAGE :: RVI :: threshold : 1 : instructions: seen 13/40 : 32.50%
           coverage points hit: 262/2952 : 8.88%
```

To see full data and write out a coverage report use **-reportfile**:

```
> $ riscvOVPsim.exe --variant RVB32I --program eg.elf \
  --cover basic --extensions RVI --reportfile impCov.log
```

To see those coverpoints not hit, use **-showuncovered**:

```
> $ riscvOVPsim.exe --variant RVB32I --program eg.elf \
  --cover basic --extensions RVI --reportfile impCov.log --showuncovered
```

9.2.1 Selecting what is covered

To measure coverage across different extensions use **-extensions** with a comma separated list:

```
> $ riscvOVPsim.exe --variant RVB32I --program eg.elf \
  --cover basic --extensions RVI,RVM,RVIC
```

If you want to just see coverage on one instruction, use the **-instructions** command:

```
> $ riscvOVPsim.exe --variant RVB32I --program eg.elf
  --cover basic --instructions add
```

Or for several, use a comma separated list:

```
> $ riscvOVPsim.exe --variant RVB32I --program eg.elf
  --cover basic --instructions mul,div
```

Note: only one of **-extensions** or **-instructions** can be given.

By default a coverpoint is reported as covered if it is hit once, you can change this with **-countthreshold**:

```
> $ riscvOVPsim.exe --variant RVB32I --program eg.elf
  --cover basic --extensions RVI --countthreshold 4
```

Which will report 1 hit as 25%, 4 hits as 100% etc.

9.3 Coverage types

With the **-cover basic** command selected, it will report:

- instructions seen
- operands hit
- sign of operands
- cross of sign of values

With the `-cover extended` command selected, it will report:

- all of basic, plus
- comparison of if same registers used as different operands
- values of min, max, -1, 1, 0, marching 0s, marching 1s

9.4 Coverage data files

At the end of simulation coverage data can be written to a data file (yaml format):

```
> $ riscvOVPsim.exe --variant RVB32I --program eg.elf
  --cover basic --extensions RVI --outputfile run1.yaml
```

This is a text file and can be examined to see what coverpoints have been measured (and their current count values).

9.4.1 Accumulating coverage across multiple runs

If you have saved the data file from one run, you can use that as the start of coverage in a subsequent run:

```
> $ riscvOVPsim.exe --variant RVB32I --program eg.elf \
  --cover basic --extensions RVI --inputfiles run1.yaml \
  --outputfile run2.yaml
```

And so to measure coverage for a complete test suite, run each test with its own output data file, and then at the end read them all in and write a coverage report:

Process each test, creating the data files:

```
> $ riscvOVPsim.exe --variant RVB32I --program eg1.elf \
  --cover basic --extensions RVI --outputfile run1.yaml
> $ riscvOVPsim.exe --variant RVB32I --program eg2.elf \
  --cover basic --extensions RVI --outputfile run2.yaml
> $ riscvOVPsim.exe --variant RVB32I --program eg3.elf \
  --cover basic --extensions RVI --outputfile run3.yaml
```

Then collate the data and write a coverage report:

```
> $ riscvOVPsim.exe --nosimulation \
  --cover basic --extensions RVI \
  --inputfiles run1.yaml,run2.yaml,run3.yaml \
  --reportfile impCov.log
```

Note the `-nosimulation` command does not simulate any instructions but does process the coverage commands.

9.5 Not measuring start up and shutdown instructions

Often when running a test suite there will be target specific code at the start and end of a test. It makes no sense to measure this as it is highly likely that each target will use different instructions. It makes more sense to control when the coverage starts and stops - this can be done using labels or addresses that control when coverage is counting.

There are two commands `-startcover`, `-finishcover`. For example:

```
> $ riscvOVPsim.exe --variant RVB32I --program eg1.elf \  
  --cover basic --extensions RVI \  
  --startcover begin_testcode \  
  --finishcover end_testcode
```

9.6 Covering Pseudo instructions

If you specify main extensions, like RVI, RVM etc., then pseudo instructions will be mapped to these main instructions and the main instructions covered.

Often hand written assembler code will use pseudo instructions and it might be necessary to measure the coverage on those. If you select the pseudo extensions, then any pseudo instruction encountered will not be mapped to main instructions, but will be measured and reported themselves. To see the list of available extensions, put in an illegal extension name, for example:

```
> $ riscvOVPsim.exe --cover basic --extensions RVSS
```

```
Error (ICV_INVI) ISA specification 'RVSS' contains 'RVSS' which is  
not a recognized ISA. Valid ISAs:  
RV32IC, RVI, RVIC, RVIpseudo, RVM,  
RVZicsr, RVZicsrPseudo, RVZifencei,  
RVprivDebug, RVprivM, RVprivS, RVprivU
```

9.7 Measuring Test Quality (Mutation Testing)

The RISC-V Compliance Suites use a methodology of testing where a reference runs the test and during that run records data into memory and subsequently saves the memory into a signature file. The test is then run on a device-under-test which also saves a signature file. The signature file is then compared to see if the device-under-test reports the same signature as the reference run.

Functional coverage measures the input instructions and a signature comparison checks if the device-under-test and the reference device created matching signatures.

So if you have 100% instruction functional coverage and matching signatures - then the device-under-test and the reference device behave the same - right. Well actually it is not yes - but maybe...

What happens if due to bad coding of the test, some of the input values do not actually affect anything in the signature. What happens if the signature writing actually writes the wrong bit of memory. (Don't laugh - that is what one of the RISC-V Compliance tests did for a year until the Imperas Mutating Simulator found that sections of the signature were all 1's as the test had happily been writing initialized memory out and not where it had recorded test results... - so the test passed and none of the test code might have actually ran!)

To measure test quality Imperas have developed an extremely fast mutating fault simulator that automatically detects if test instructions do not affect the signature and thus are not really of any use.

Without use of tool such as the Imperas Mutating Simulator it is not possible to say with certainty that a test is high quality and in fact does what it claims to do.

Functional coverage measures how much is stimulated, and a mutating simulator measures what is detected.

Functional coverage is not a measure of quality - it is only an indication of a hope - and a mutating simulator confirms that hope.

For more information on the Imperas mutating simulator - contact Imperas.

9.8 Command summary

For list of all commands and their short descriptions, see the Appendix.

Chapter 10

Building your own platform and components

Note that an Imperas OVP Fixed Platform is restricted and may only run as provided is and can not be further extended.

However, a platform in OVP is made up from models of processors, memories, and other components such as behavioral peripherals connected using hierarchical bus connections. All components have APIs defined in C and platforms can be created in C/C++ or SystemC that instantiate these components.

You can create models and platforms directly in C/C++ using the standard OVP APIs. To execute and run these models, you need a simulator that implements the OVP APIs. This fixed platform does not support this and you can get access to OVP simulators from Imperas Software and OVPworld.org.

Imperas/OVP provide iGen which is a productivity tool that from a simple iGen input script creates a set of C files in the correct structure, all the main structural parts of the components and provides the placeholders for the behavioral code. For more information on iGen visit this link: www.imperas.com/iGen. To read the iGen user guide, visit this link: www.ovpworld.org/igen-model-generator-introduction.

10.1 Creating Peripheral Models with iGen

A peripheral model template created by iGen as a C file will

1. Construct a model instance
2. Construct bus and net ports for connection to the platform
3. Construct memory mapped registers and memory regions
4. Construct formal parameters which can be set when the peripheral is instantiated in a platform or module and overridden by the simulator to control features of the peripheral model.

The peripheral template will provide empty functions, stubs, that can be filled in by the user to add behavior to the model.

The peripheral template can be compiled and used in simulations to provide the peripheral device programmers view i.e. the register structure and a default behavior.

iGen can also generate a SystemC TLM2 interface for the model. Examples of SystemC TLM2 interfaces for OVP peripherals have been tested with all major SystemC TLM2 simulators.

For more information on iGen and peripherals visit: www.ovpworld.org/igen-peripheral-generator-user-guide.

Most peripherals are available as open source and there over 200 listed on the OVPworld website here: www.ovpworld.org/library. You can download and look at the source and modify it to make it your own peripherals, or you can use them directly in your platforms.

10.2 Creating Platforms with iGen

OVP platforms are a collection of components connected together into levels of hierarchy in a system to be simulated. This is a program in C/C++ making calls into OVP APIs and normally compiled into an executable or as a shared object/dynamically linked library and loaded by the simulator at run time.

Platforms are created by writing scripts and then using iGen to generate C or SystemC code that calls functions from the OP API.

For more information on iGen and platforms/modules visit:

www.ovpworld.org/igen-platform-and-module-creation-user-guide.

10.3 Creating Processor Models

With the OVP open standard APIs you can write your own processor models in C. Imperas has developed over 200 processor models using this standard modeling approach. Visit www.ovpworld.org/variants for more information on the available processor models.

For MIPS there are over 45 different MIPS processor models. See: www.ovpworld.org/library.

For ARM there are over 100 different ARM processor models. See: www.ovpworld.org/library.

For RISC-V there are over 25 different RISC-V models. See: www.ovpworld.org/library.

For most processors model source is available from www.OVPworld.org as source under the Apache 2.0 open source license and so you can download the source and modify it if you want to. However modifying the main model source might not be the best approach in terms of maintainable models with extensions, and so Imperas has developed a standard way to extend existing processor models to add instructions and registers without making changes to the source of the main model. See www.ovpworld.org/creating-instruction-accurate-processor-models-using-the-vmi-api chapter 26 for more information.

Chapter 11

Debugging Multi-Core platforms

When you have a single processor instance in a platform the normal software debug approach is to connect up a GDB to the processor and be able to accomplish source code debug. This works well for a single processor and single GDB but problems occur when you have different processor cores in the platform or have complex peripherals as well. A single GDB is not much help and neither is having a different GDB connected to each processor. You the user become the debug scheduler and having to click continue and step in a variety of different windows etc.

It is very difficult to debug a multicore platform with just GDB.

If the platform has more than one core, Imperas has developed an advanced multi-core debugger called Multi-Processor Debug (MPD). An introduction to this is found: www.imperas.com/MPD.

There is a good video introduction of MPD on a platform incorporating a quad core ARM Cortex-A15MPx4 and an Andes RISC-V N25 core here:

www.imperas.com/mpd-andes-risc-v-n25-running-freertos-and-arm-cortex.

Another good video shows the SiFive RISC-V U540-MC virtual platform running SMP Linux being debugged with the Imperas Multi-Processor debugger:

www.imperas.com/sifive-risc-v-u54-mc-booting-smp-linux-being-debugged-with-MPD.

Appendices

Appendix A

riscvOVPsim Help Commands

To see commonly used command line options:

```
riscvOVPsim.exe --help
```

To see all command line options:

```
riscvOVPsim.exe --helpall
```

To see the list of processor variants:

```
riscvOVPsim.exe --showvariants
```

To run a program:

```
riscvOVPsim.exe --variant <processor variant>  
--program <path to program>
```

To trace instructions please see `-helpall`

A.1 help

A.1.1 control

| Flag | Short | Argument | Description |
|---------------------------|-------|----------------------------------|---|
| <code>-finishafter</code> | I | <code>[processor=]integer</code> | Finish simulation after this many instructions |
| <code>-finishtime</code> | F | <code>[module=]seconds</code> | Finish simulation at this time |
| <code>-showexpiry</code> | | <code>[module]</code> | Show how many days before this executable expires and can no longer run |

Table A.1: control

A.1.2 diagnostics

| Flag | Short | Argument | Description |
|---------------------|-------|----------|--|
| -help | h | | Print list of flags |
| -helpall | | | Print complete list of flags |
| -showmodeloverrides | | [module] | Show all model parameters that can be overridden |

Table A.2: diagnostics

A.1.3 library

| Flag | Short | Argument | Description |
|---------------|-------|-------------|-------------------------|
| -showvariants | | [processor] | Show processor variants |

Table A.3: library

A.1.4 log

| Flag | Short | Argument | Description |
|----------|-------|----------|---------------------------|
| -logfile | | filename | Output log file |
| -output | o | filename | Output log file |
| -version | | | Print version information |

Table A.4: log

A.1.5 parameters

| Flag | Short | Argument | Description |
|-----------|-------|---------------------|--|
| -override | O | name=value | Override a parameter value. Use -showoverrides or -showmodeloverrides for a list |
| -variant | | [processor=]variant | Set a processor variant. Use -showvariants for a list |

Table A.5: parameters

A.1.6 platform

| Flag | Short | Argument | Description |
|--------------------|-------|----------|--|
| -signaturedump | | | Load the signature dump utility |
| -signaturedumphelp | | | Information about the signature dump utility |
| -customcontrol | | | Load the custom control utility |
| -memory | | | Specify memory regions using the format [name:];low address _i :;high address _i [:;permission using rwx- _i][,repeat]. |

Table A.6: platform

A.1.7 program

| Flag | Short | Argument | Description |
|----------|-------|----------------------|---|
| -argv | | arguments | Pass all remaining values to the application main (applies to all processors) |
| -program | | [processor=]filename | Execute this program (on this processor) |

Table A.7: program

A.2 helpall

A.2.1 control

| Flag | Short | Argument | Description |
|-----------------|-------|---------------------|---|
| -callcommand | | command | Call a command in a plugin. Use -showcommands for a list. |
| -finishafter | I | [processor=]integer | Finish simulation after this many instructions |
| -finishtime | F | [module=]seconds | Finish simulation at this time |
| -nosimulation | | [module] | Do not simulate. Simulator will exit after loading the platform |
| -showexpiry | | [module] | Show how many days before this executable expires and can no longer run |
| -stoponcontrolc | | [module] | Simulator will stop on Ctrl-C (SIGINT) |

Table A.8: control

A.2.2 debug

| Flag | Short | Argument | Description |
|-----------------|-------|----------------------|--|
| -gdbcommandfile | | [processor=]filename | GDB will run this startup script |
| -gdbconsole | | [module] | Pop up gdb(s) in console window(s) |
| -gdbgui | | [module] | Start gdb debug in Eclipse (eGui) |
| -gdbflags | | [processor=]flags | Pass additional flags to a gdb |
| -gdbinit | | [processor=]filename | Pass a file to the gdb to execute before the prompt is displayed |
| -gdbpath | | [processor=]filename | Set the gdb path for a processor |
| -nowait | | [module] | Do not wait for RSP connection before simulation |
| -port | | [module=]integer | Open this port number to allow a connection to a GDB using RSP |
| -symbolfile | | [processor=]filename | Read the symbols from this executable |

Table A.9: debug

A.2.3 cover

| Flag | Short | Argument | Description |
|-----------------|-------|-----------|--|
| -cover | | covertype | Enable coverage mode “basic” or “extended” [default: “basic”] |
| -extensions | | exts | List of ISA extensions to cover (comma separated list) |
| -instructions | | ins | List of instructions to cover (comma separated list) |
| -countthreshold | | integer | Number of counts of each cover point required to report 100% coverage [default: 1] |
| -reportfile | | filename | Write a coverage report to this file |
| -showuncovered | | | Show in coverage report a list of coverpoints not hit |
| -outputfile | | filename | Coverage output data file |
| -inputfiles | | filenames | Coverage input data file list, comma separated |
| -startcover | | address | Address of start of code to be covered (label or address) |
| -finishcover | | address | Address of end of code to be covered (label or address) |

Table A.10: debug

A.2.4 diagnostics

| Flag | Short | Argument | Description |
|----------------------|-------|----------|--|
| -help | h | | Print list of flags |
| -helpall | | | Print complete list of flags |
| -showcommands | | [module] | Show commands that can be called with -callcommand |
| -showmodeloverrides | | [module] | Show all model parameters that can be overridden |
| -showoverrides | | [module] | Show all parameters that can be overridden |
| -showsystemoverrides | | [module] | Show all the simulator parameters |

Table A.11: diagnostics

A.2.5 library

| Flag | Short | Argument | Description |
|---------------|-------|-------------|-------------------------|
| -showvariants | | [processor] | Show processor variants |

Table A.12: library

A.2.6 log

| Flag | Short | Argument | Description |
|-------------|-------|----------|---|
| -logfile | | filename | Output log file |
| -logflush | | | Flush data to the log file after each write |
| -nowarnings | w | | Suppress warnings |
| -output | o | filename | Output log file |

| | | | |
|----------|---|--|---------------------------|
| -version | | | Print version information |
| -werror | W | | Treat warnings as errors |

Table A.13: log

A.2.7 parameters

| Flag | Short | Argument | Description |
|-----------|-------|---------------------|--|
| -override | O | name=value | Override a parameter value. Use -showoverrides or -showmodeloverrides for a list |
| -variant | | [processor=]variant | Set a processor variant. Use -showvariants for a list |

Table A.14: parameters

A.2.8 platform

| Flag | Short | Argument | Description |
|---------------------------|-------|----------|---|
| -customcontrol | | | Load the custom control utility |
| -signaturedump | | | Load the signature dump utility |
| -signaturedumphelp | | | Information about the signature dump utility |
| -memory separated list | | | Specify memory regions using the format [name:] <i>i</i> low address: <i>i</i> high address: <i>i</i> permission using rwx- <i>i</i> [,repeat]. |

Table A.15: platform

A.2.9 program

| Flag | Short | Argument | Description |
|------------------|-------|----------------------|---|
| -argv | | arguments | Pass all remaining values to the application main (applies to all processors) |
| -elfusevma | | [processor] | Use ELF VMA addresses rather than LMA |
| -envp | | name=value | Pass values (until the next '-') to the application environment list |
| -loadphysical | | [processor] | Use ELF physical addresses |
| -loadsignextend | | [processor] | Sign-extend ELF addresses from 32 to 64 bits |
| -objfile | | [processor=]filename | Load object onto CPU. Set PC to start address |
| -objfilenoentry | | [processor=]filename | Load object onto CPU. Do not set PC to start address |
| -objfileuseentry | f | [processor=]filename | Load object onto CPU. Set PC to start address |
| -program | | [processor=]filename | Execute this program (on this processor) |

Table A.16: program

A.2.10 trace

| Flag | Short | Argument | Description |
|------------------|--------------|---------------------|--|
| -trace | t | [processor] | Trace instructions as they are executed |
| -traceafter | | [processor=]integer | Start tracing instructions after this many have executed |
| -tracebuffer | | [processor] | Enable the trace buffer |
| -tracechange | | [processor] | Trace changed registers |
| -tracecount | | [processor=]integer | Trace this number of instructions |
| -tracemode | | [processor] | Add the current processor mode to the instruction trace |
| -traceregs | | [processor] | Dump registers after each instruction is executed |
| -traceregsafter | | [processor] | Dump registers after each instruction is executed |
| -traceregsbefore | | [processor] | Dump registers before each instruction is executed |
| -traceshowicount | | [processor] | Show instruction count with each instruction |

Table A.17: trace

Appendix B

riscvOVPsim model configuration options

RV32GC Model Overrides

```
--override riscvOVPsim/cpu/variant=RV32I (Enumeration) (default=RV32I) (override) Selects variant (either a generic UISA or a specific model)
--override riscvOVPsim/cpu/user_version=20190305 (Enumeration) (default=20190305) (default) Specify required User Architecture version
--override riscvOVPsim/cpu/priv_version=20190405 (Enumeration) (default=20190405) (default) Specify required Privileged Architecture version
--override riscvOVPsim/cpu/verbose=T (Boolean) (default=T) (default) Specify verbose output messages
--override riscvOVPsim/cpu/updatePTEA=F (Boolean) (default=F) (default) Specify whether hardware update of PTE A bit is supported
--override riscvOVPsim/cpu/updatePTED=F (Boolean) (default=F) (default) Specify whether hardware update of PTE D bit is supported
--override riscvOVPsim/cpu/unaligned=F (Boolean) (default=F) (default) Specify whether the processor supports unaligned memory accesses
--override riscvOVPsim/cpu/unalignedAMO=F (Boolean) (default=F) (default) Specify whether the processor supports unaligned memory accesses for AMO instructions
--override riscvOVPsim/cpu/wfi_is_nop=F (Boolean) (default=F) (default) Specify whether WFI should be treated as a NOP (if not, halt while waiting for interrupts)
--override riscvOVPsim/cpu/mtvec_is_ro=F (Boolean) (default=F) (default) Specify whether mtvec CSR is read-only
--override riscvOVPsim/cpu/tvec_align=0 (Uns32) (default=0) (default) Specify hardware-enforced alignment of mtvec/stvec/utvec when Vectored interrupt mode enabled
--override riscvOVPsim/cpu/mtvec_mask=0 (Uns64) (default=0) (default) Specify hardware-enforced mask of writable bits in mtvec register
--override riscvOVPsim/cpu/stvec_mask=0 (Uns64) (default=0) (default) Specify hardware-enforced mask of writable bits in stvec register
--override riscvOVPsim/cpu/tval_ii_code=T (Boolean) (default=T) (default) Specify whether tval/stval contain faulting instruction bits on illegal instruction exception
--override riscvOVPsim/cpu/cycle_undefined=F (Boolean) (default=F) (default) Specify that the cycle CSR is undefined (reads to it are emulated by a Machine mode trap)
--override riscvOVPsim/cpu/time_undefined=F (Boolean) (default=F) (default) Specify that the time CSR is undefined (reads to it are emulated by a Machine mode trap)
--override riscvOVPsim/cpu/instrret_undefined=F (Boolean) (default=F) (default) Specify that the instrret CSR is undefined (reads to it are emulated by a Machine mode trap)
--override riscvOVPsim/cpu/enable_CSR_bus=F (Boolean) (default=F) (default) Add artifact CSR bus port, allowing CSR registers to be externally implemented
--override riscvOVPsim/cpu/d_requires_f=F (Boolean) (default=F) (default) If D and F extensions are separately enabled in the misa CSR, whether D is enabled only if F is
--override riscvOVPsim/cpu/fs_always_dirty=F (Boolean) (default=F) (default) When FPU is enabled, whether mstatus.FS is always 3 (indicating dirty)
--override riscvOVPsim/cpu/xret_preserves_lr=F (Boolean) (default=F) (default) Whether an xRET instruction preserves the value of LR
--override riscvOVPsim/cpu/ASID_bits=9 (Uns32) (default=9) (default) Specify the number of implemented ASID bits
--override riscvOVPsim/cpu/lr_sc_grain=1 (Uns32) (default=1) (default) Specify byte granularity of ll/sc lock region (constrained to a power of two)
--override riscvOVPsim/cpu/reset_address=0 (Uns64) (default=0) (default) Override reset vector address
--override riscvOVPsim/cpu/mmi_address=0 (Uns64) (default=0) (default) Override NMI vector address
--override riscvOVPsim/cpu/PMP_grain=0 (Uns32) (default=0) (default) Specify PMP region granularity, G (0 => 4 bytes, 1 => 8 bytes, etc)
--override riscvOVPsim/cpu/PMP_registers=16 (Uns32) (default=16) (default) Specify the number of implemented PMP address registers
--override riscvOVPsim/cpu/Sv_modes=3 (Uns32) (default=3) (default) Specify bit mask of implemented Sv modes (e.g. 1<<8 is Sv39)
--override riscvOVPsim/cpu/local_int_num=0 (Uns32) (default=0) (default) Specify number of supplemental local interrupts
--override riscvOVPsim/cpu/ndian=none (Enum) (default=none) (default) Model endian
--override riscvOVPsim/cpu/misa_MXL=1 (Uns32) (default=1) (default) Override default value of misa.MXL
--override riscvOVPsim/cpu/misa_MXL_mask=0 (Uns32) (default=0) (default) Override mask of writable bits in misa.MXL
--override riscvOVPsim/cpu/misa_Extensions=0x14112d (Uns32) (default=0x14112d) (default) Override default value of misa.Extensions
--override riscvOVPsim/cpu/add_Extensions=MAFDC (String) (default=) (override) Add extensions specified by letters to misa.Extensions (for example, specify "VD" to add V)
--override riscvOVPsim/cpu/misa_Extensions_mask=0x112d (Uns32) (default=0x112d) (default) Override mask of writable bits in misa.Extensions
--override riscvOVPsim/cpu/add_Extensions_mask= (String) (default=) (default) Add extensions specified by letters to mask of writable bits in misa.Extensions (for example)
--override riscvOVPsim/cpu/mvendordir=0 (Uns64) (default=0) (default) Override mvendordir register
--override riscvOVPsim/cpu/marchid=0 (Uns64) (default=0) (default) Override marchid register
--override riscvOVPsim/cpu/mimpid=0 (Uns64) (default=0) (default) Override mimpid register
--override riscvOVPsim/cpu/mhartid=0 (Uns64) (default=0) (default) Override mhartid register
--override riscvOVPsim/cpu/mtvec=0 (Uns64) (default=0) (default) Override mtvec register
--override riscvOVPsim/cpu/mstatus_FS=0 (Uns32) (default=0) (default) Override default value of mstatus.FS (initial state of floating point unit)
--override riscvOVPsim/cpu/pk/userargv=0x0 (Pointer) (default=0x0) (default) Pointer to argv structure
--override riscvOVPsim/cpu/pk/userenvp=0x0 (Pointer) (default=0x0) (default) Pointer to envp structure
--override riscvOVPsim/cpu/pk/initsp=0 (Uns64) (default=0) (default) Stack Pointer initialization
--override riscvOVPsim/cpu/sigdump/ResultReg=28 (Uns32) (default=28) (default) Result Register for RISCv.org Conformance Test. 3=GP, 10=A0 or 28=T3 (default)
--override riscvOVPsim/cpu/sigdump/SignatureFile=(null) (String) (default=(null)) (default) Name of the signature file
--override riscvOVPsim/cpu/sigdump/SignatureAtEnd=F (Boolean) (default=F) (default) Generate a Signature file at the end of simulation (default to generate on detection)
--override riscvOVPsim/cpu/sigdump/StartAddress=0 (Uns32) (default=0) (default) Address of the Start Symbol
--override riscvOVPsim/cpu/sigdump/StartSymbol=begin_signature (String) (default=begin_signature) (default) Name of the Start Symbol
--override riscvOVPsim/cpu/sigdump/EndAddress=0 (Uns32) (default=0) (default) Address of the End Symbol
--override riscvOVPsim/cpu/sigdump/EndSymbol=end_signature (String) (default=end_signature) (default) Name of the End Symbol
--override riscvOVPsim/cpu/sigdump/ByteCount=0 (Uns32) (default=0) (default) Size of region in bytes (must be 16 byte blocks)
```

RV64GCN Model Overrides

```

--override riscvOVPsim/cpu/variant=RV64I (Enumeration) (default=RV32I) (override) Selects variant (either a generic UISA or a specific model)
--override riscvOVPsim/cpu/user_version=20190305 (Enumeration) (default=20190305) (default) Specify required User Architecture version
--override riscvOVPsim/cpu/priv_version=20190405 (Enumeration) (default=20190405) (default) Specify required Privileged Architecture version
--override riscvOVPsim/cpu/verbose=T (Boolean) (default=T) (default) Specify verbose output messages
--override riscvOVPsim/cpu/updatePTEA=F (Boolean) (default=F) (default) Specify whether hardware update of PTE A bit is supported
--override riscvOVPsim/cpu/updatePTED=F (Boolean) (default=F) (default) Specify whether hardware update of PTE D bit is supported
--override riscvOVPsim/cpu/unaligned=F (Boolean) (default=F) (default) Specify whether the processor supports unaligned memory accesses
--override riscvOVPsim/cpu/unalignedAMO=F (Boolean) (default=F) (default) Specify whether the processor supports unaligned memory accesses for AMO instructions
--override riscvOVPsim/cpu/wfi_is_nop=F (Boolean) (default=F) (default) Specify whether WFI should be treated as a NOP (if not, halt while waiting for interrupts)
--override riscvOVPsim/cpu/mtvec_is_ro=F (Boolean) (default=F) (default) Specify whether mtvec CSR is read-only
--override riscvOVPsim/cpu/tvec_align=0 (Uns32) (default=0) (default) Specify hardware-enforced alignment of mtvec/stvec/utvec when Vectored interrupt mode enabled
--override riscvOVPsim/cpu/mtvec_mask=0 (Uns64) (default=0) (default) Specify hardware-enforced mask of writable bits in mtvec register
--override riscvOVPsim/cpu/stvec_mask=0 (Uns64) (default=0) (default) Specify hardware-enforced mask of writable bits in stvec register
--override riscvOVPsim/cpu/utvec_mask=0 (Uns64) (default=0) (default) Specify hardware-enforced mask of writable bits in utvec register
--override riscvOVPsim/cpu/tval_ii_code=T (Boolean) (default=T) (default) Specify whether mtval/stval contain faulting instruction bits on illegal instruction exception
--override riscvOVPsim/cpu/cycle_undefined=F (Boolean) (default=F) (default) Specify that the cycle CSR is undefined (reads to it are emulated by a Machine mode trap)
--override riscvOVPsim/cpu/time_undefined=F (Boolean) (default=F) (default) Specify that the time CSR is undefined (reads to it are emulated by a Machine mode trap)
--override riscvOVPsim/cpu/instrret_undefined=F (Boolean) (default=F) (default) Specify that the instrret CSR is undefined (reads to it are emulated by a Machine mode trap)
--override riscvOVPsim/cpu/enable_CSR_bus=F (Boolean) (default=F) (default) Add artifact CSR bus port, allowing CSR registers to be externally implemented
--override riscvOVPsim/cpu/d_requires_f=F (Boolean) (default=F) (default) If D and F extensions are separately enabled in the misa CSR, whether D is enabled only if F is
--override riscvOVPsim/cpu/fs_always_dirty=F (Boolean) (default=F) (default) When FPU is enabled, whether mstatus.FS is always 3 (indicating dirty)
--override riscvOVPsim/cpu/xret_preserves_lr=F (Boolean) (default=F) (default) Whether an xRET instruction preserves the value of LR
--override riscvOVPsim/cpu/ASID_bits=16 (Uns32) (default=16) (default) Specify the number of implemented ASID bits
--override riscvOVPsim/cpu/lr_sc_grain=1 (Uns32) (default=1) (default) Specify byte granularity of ll/sc lock region (constrained to a power of two)
--override riscvOVPsim/cpu/reset_address=0 (Uns64) (default=0) (default) Override reset vector address
--override riscvOVPsim/cpu/nmi_address=0 (Uns64) (default=0) (default) Override NMI vector address
--override riscvOVPsim/cpu/PMP_grain=0 (Uns32) (default=0) (default) Specify PMP region granularity, G (0 => 4 bytes, 1 => 8 bytes, etc)
--override riscvOVPsim/cpu/PMP_registers=16 (Uns32) (default=16) (default) Specify the number of implemented PMP address registers
--override riscvOVPsim/cpu/Sv_modes=0x301 (Uns32) (default=0x301) (default) Specify bit mask of implemented Sv modes (e.g. 1<8 is Sv39)
--override riscvOVPsim/cpu/local_int_num=0 (Uns32) (default=0) (default) Specify number of supplemental local interrupts
--override riscvOVPsim/cpu/endianness=none (Enum) (default=none) (default) Model endian
--override riscvOVPsim/cpu/misa_MXL=2 (Uns32) (default=2) (default) Override default value of misa.MXL
--override riscvOVPsim/cpu/misa_MXL_mask=0 (Uns32) (default=0) (default) Override mask of writable bits in misa.MXL
--override riscvOVPsim/cpu/misa_Extensions=0x14312d (Uns32) (default=0x14312d) (default) Override default value of misa.Extensions
--override riscvOVPsim/cpu/add_Extensions=MAFDCN (String) (default=) (override) Add extensions specified by letters to misa.Extensions (for example, specify "VD" to add V)
--override riscvOVPsim/cpu/misa_Extensions_mask=0x312d (Uns32) (default=0x312d) (default) Override mask of writable bits in misa.Extensions
--override riscvOVPsim/cpu/add_Extensions_mask= (String) (default=) (default) Add extensions specified by letters to mask of writable bits in misa.Extensions (for example)
--override riscvOVPsim/cpu/mvendorid=0 (Uns64) (default=0) (default) Override mvendorid register
--override riscvOVPsim/cpu/marchid=0 (Uns64) (default=0) (default) Override marchid register
--override riscvOVPsim/cpu/mimpid=0 (Uns64) (default=0) (default) Override mimpid register
--override riscvOVPsim/cpu/mhartid=0 (Uns64) (default=0) (default) Override mhartid register
--override riscvOVPsim/cpu/mtvec=0 (Uns64) (default=0) (default) Override mtvec register
--override riscvOVPsim/cpu/mstatus_FS=0 (Uns32) (default=0) (default) Override default value of mstatus.FS (initial state of floating point unit)
--override riscvOVPsim/cpu/pk/userargv=0x0 (Pointer) (default=0x0) (default) Pointer to argv structure
--override riscvOVPsim/cpu/pk/userenvp=0x0 (Pointer) (default=0x0) (default) Pointer to envp structure
--override riscvOVPsim/cpu/pk/initsp=0 (Uns64) (default=0) (default) Stack Pointer initialization
--override riscvOVPsim/cpu/sigdump/ResultReg=28 (Uns32) (default=28) (default) Result Register for RISC-V.org Conformance Test. 3=GP, 10=A0 or 28=T3 (default)
--override riscvOVPsim/cpu/sigdump/SignatureFile=null (String) (default=null) (default) Name of the signature file
--override riscvOVPsim/cpu/sigdump/SignatureAtEnd=F (Boolean) (default=F) (default) Generate a Signature file at the end of simulation (default to generate on detection)
--override riscvOVPsim/cpu/sigdump/StartAddress=0 (Uns32) (default=0) (default) Address of the Start Symbol
--override riscvOVPsim/cpu/sigdump/StartSymbol=begin_signature (String) (default=begin_signature) (default) Name of the Start Symbol
--override riscvOVPsim/cpu/sigdump/EndAddress=0 (Uns32) (default=0) (default) Address of the End Symbol
--override riscvOVPsim/cpu/sigdump/EndSymbol=end_signature (String) (default=end_signature) (default) Name of the End Symbol
--override riscvOVPsim/cpu/sigdump/ByteCount=0 (Uns32) (default=0) (default) Size of region in bytes (must be 16 byte blocks)

```

RV64GCV Model Overrides

```

--override riscvOVPsim/cpu/variant=RV64I (Enumeration) (default=RV32I) (override) Selects variant (either a generic UISA or a specific model)
--override riscvOVPsim/cpu/user_version=20190305 (Enumeration) (default=20190305) (default) Specify required User Architecture version
--override riscvOVPsim/cpu/priv_version=20190405 (Enumeration) (default=20190405) (default) Specify required Privileged Architecture version
--override riscvOVPsim/cpu/vector_version=0.7.1-draft-20190605 (Enumeration) (default=0.7.1-draft-20190605) (default) Specify required Vector Architecture version
--override riscvOVPsim/cpu/verbose=T (Boolean) (default=T) (default) Specify verbose output messages
--override riscvOVPsim/cpu/updatePTEA=F (Boolean) (default=F) (default) Specify whether hardware update of PTE A bit is supported
--override riscvOVPsim/cpu/updatePTED=F (Boolean) (default=F) (default) Specify whether hardware update of PTE D bit is supported
--override riscvOVPsim/cpu/unaligned=F (Boolean) (default=F) (default) Specify whether the processor supports unaligned memory accesses
--override riscvOVPsim/cpu/unalignedAMO=F (Boolean) (default=F) (default) Specify whether the processor supports unaligned memory accesses for AMO instructions
--override riscvOVPsim/cpu/wfi_is_nop=F (Boolean) (default=F) (default) Specify whether WFI should be treated as a NOP (if not, halt while waiting for interrupts)
--override riscvOVPsim/cpu/mtvec_is_ro=F (Boolean) (default=F) (default) Specify whether mtvec CSR is read-only
--override riscvOVPsim/cpu/tvec_align=0 (Uns32) (default=0) (default) Specify hardware-enforced alignment of mtvec/stvec/utvec when Vectored interrupt mode enabled
--override riscvOVPsim/cpu/mtvec_mask=0 (Uns64) (default=0) (default) Specify hardware-enforced mask of writable bits in mtvec register
--override riscvOVPsim/cpu/stvec_mask=0 (Uns64) (default=0) (default) Specify hardware-enforced mask of writable bits in stvec register
--override riscvOVPsim/cpu/tval_ii_code=T (Boolean) (default=T) (default) Specify whether mtval/stval contain faulting instruction bits on illegal instruction exception
--override riscvOVPsim/cpu/cycle_undefined=F (Boolean) (default=F) (default) Specify that the cycle CSR is undefined (reads to it are emulated by a Machine mode trap)
--override riscvOVPsim/cpu/time_undefined=F (Boolean) (default=F) (default) Specify that the time CSR is undefined (reads to it are emulated by a Machine mode trap)
--override riscvOVPsim/cpu/instrret_undefined=F (Boolean) (default=F) (default) Specify that the instrret CSR is undefined (reads to it are emulated by a Machine mode trap)
--override riscvOVPsim/cpu/enable_CSR_bus=F (Boolean) (default=F) (default) Add artifact CSR bus port, allowing CSR registers to be externally implemented
--override riscvOVPsim/cpu/d_requires_f=F (Boolean) (default=F) (default) If D and F extensions are separately enabled in the misa CSR, whether D is enabled only if F is
--override riscvOVPsim/cpu/fs_always_dirty=F (Boolean) (default=F) (default) When FPU is enabled, whether mstatus.FS is always 3 (indicating dirty)
--override riscvOVPsim/cpu/xret_preserves_lr=F (Boolean) (default=F) (default) Whether an xRET instruction preserves the value of LR
--override riscvOVPsim/cpu/ASID_bits=16 (Uns32) (default=16) (default) Specify the number of implemented ASID bits
--override riscvOVPsim/cpu/lr_sc_grain=1 (Uns32) (default=1) (default) Specify byte granularity of ll/sc lock region (constrained to a power of two)
--override riscvOVPsim/cpu/reset_address=0 (Uns64) (default=0) (default) Override reset vector address
--override riscvOVPsim/cpu/nmi_address=0 (Uns64) (default=0) (default) Override NMI vector address
--override riscvOVPsim/cpu/PMP_grain=0 (Uns32) (default=0) (default) Specify PMP region granularity, G (0 => 4 bytes, 1 => 8 bytes, etc)
--override riscvOVPsim/cpu/PMP_registers=16 (Uns32) (default=16) (default) Specify the number of implemented PMP address registers

```

```
--override riscvOVPsim/cpu/Sv_modes=0x301 (Uns32) (default=0x301) (default) Specify bit mask of implemented Sv modes (e.g. 1<<8 is Sv39)
--override riscvOVPsim/cpu/local_int_num=0 (Uns32) (default=0) (default) Specify number of supplemental local interrupts
--override riscvOVPsim/cpu/Endian=none (Endian) (default=none) (default) Model endian
--override riscvOVPsim/cpu/misa_MXL=2 (Uns32) (default=2) (default) Override default value of misa.MXL
--override riscvOVPsim/cpu/misa_MXL_mask=0 (Uns32) (default=0) (default) Override mask of writable bits in misa.MXL
--override riscvOVPsim/cpu/misa_Extensions=0x34112d (Uns32) (default=0x34112d) (default) Override default value of misa.Extensions
--override riscvOVPsim/cpu/add_Extensions=MAFDCV (String) (default=) (override) Add extensions specified by letters to misa.Extensions (for example, specify "VD" to add V
--override riscvOVPsim/cpu/misa_Extensions_mask=0x20112d (Uns32) (default=0x20112d) (default) Override mask of writable bits in misa.Extensions
--override riscvOVPsim/cpu/add_Extensions_mask= (String) (default=) (default) Add extensions specified by letters to mask of writable bits in misa.Extensions (for example
--override riscvOVPsim/cpu/mvendorid=0 (Uns64) (default=0) (default) Override mvendorid register
--override riscvOVPsim/cpu/marchid=0 (Uns64) (default=0) (default) Override marchid register
--override riscvOVPsim/cpu/mimpid=0 (Uns64) (default=0) (default) Override mimpid register
--override riscvOVPsim/cpu/mhartid=0 (Uns64) (default=0) (default) Override mhartid register
--override riscvOVPsim/cpu/mtvec=0 (Uns64) (default=0) (default) Override mtvec register
--override riscvOVPsim/cpu/mstatus_FS=0 (Uns32) (default=0) (default) Override default value of mstatus.FS (initial state of floating point unit)
--override riscvOVPsim/cpu/ELEN=64 (Uns32) (default=64) (default) Override ELEN (vector extension)
--override riscvOVPsim/cpu/SLEN=64 (Uns32) (default=64) (default) Override SLEN (vector extension)
--override riscvOVPsim/cpu/VLEN=0x200 (Uns32) (default=0x200) (default) Override VLEN (vector extension)
--override riscvOVPsim/cpu/Zvlsseg=T (Boolean) (default=T) (default) Specify that Zvlsseg is implemented (vector extension)
--override riscvOVPsim/cpu/Zvamo=T (Boolean) (default=T) (default) Specify that Zvamo is implemented (vector extension)
--override riscvOVPsim/cpu/Zvediv=F (Boolean) (default=F) (default) Specify that Zvediv is implemented (vector extension)
--override riscvOVPsim/cpu/pk/userargv=0x0 (Pointer) (default=0x0) (default) Pointer to argv structure
--override riscvOVPsim/cpu/pk/userenvp=0x0 (Pointer) (default=0x0) (default) Pointer to envp structure
--override riscvOVPsim/cpu/pk/initsp=0 (Uns64) (default=0) (default) Stack Pointer initialization
--override riscvOVPsim/cpu/sigdump/ResultReg=28 (Uns32) (default=28) (default) Result Register for RISC-V.org Conformance Test. 3=GP, 10=A0 or 28=T3 (default)
--override riscvOVPsim/cpu/sigdump/SignatureFile=(null) (String) (default=(null)) (default) Name of the signature file
--override riscvOVPsim/cpu/sigdump/SignatureAtEnd=F (Boolean) (default=F) (default) Generate a Signature file at the end of simulation (default to generate on detection o
--override riscvOVPsim/cpu/sigdump/StartAddress=0 (Uns32) (default=0) (default) Address of the Start Symbol
--override riscvOVPsim/cpu/sigdump/StartSymbol=begin_signature (String) (default=begin_signature) (default) Name of the Start Symbol
--override riscvOVPsim/cpu/sigdump/EndAddress=0 (Uns32) (default=0) (default) Address of the End Symbol
--override riscvOVPsim/cpu/sigdump/EndSymbol=end_signature (String) (default=end_signature) (default) Name of the End Symbol
--override riscvOVPsim/cpu/sigdump/ByteCount=0 (Uns32) (default=0) (default) Size of region in bytes (must be 16 byte blocks)
```

Appendix C

Compiling RISC-V programs

The Imperas and OVP simulators load programs compiled into .elf format. So to execute RISC-V programs you need to cross compile the C programs or assemble the asm files into .elf files.

To accomplish this you need to download and install compiler tool chains - either GNU GCC or LLVM.

You can use any tool chain that produces an elf file and load this with one of the built-in loaders.

Note: Although not supported by the fixed platform an Imperas or OVP platform can use the OVP APIs to directly load any binary into memory from which it can be simulated.

Installing GNU GCC tool chains from OVP

As a convenience OVP makes available a pre-built GCC tool chain that is compatible with its simulators and models. This can be obtained here: www.ovpworld.org/riscv.toolchains.

For instructions on using the cross compilers, please consult: www.ovpworld.org/installation chapter 7.

Appendix D

Information on Open Virtual Platforms



Imperas and others announced OVP in March 2008 and have since put the OVPSim simulator, full documentation, and examples / demos and processor models on www.ovpworld.org site. There are many models of processors from many ISA families: - ARM, MIPS, Synopsys ARC, Renesas v850 / RH850 / RL78 / M16C, openCores OR1K, PowerPC, Altera Nios II, Xilinx MicroBlaze, SiFive, Andes, Microsemi, RISC-V, single core, multicore, manycore, C, C++, SystemC, TLM2 etc.

Imperas and others have put many of the processor and peripheral models into open source and made them available on the OVP site on the www.ovpworld.org/downloads and www.ovpworld.org/library pages.

What is OVP?

It is simulation to develop software on: Fast Simulation, Free open source models, Easy to use!

[Imperas Software Ltd](http://www.imperas.com) developed some fantastic virtual platform and modeling technology to enable simulating embedded systems running real application code. These simulations run at speeds of 100s and 100s of MIPS on typical desktop PCs and are completely Instruction Accurate and model the whole system.

| | RISC-V RV32G | | | ARM32 | | | Imagination MIPS32 | | |
|------------|------------------------|----------|----------------|------------------------|----------|----------------|------------------------|----------|----------------|
| Benchmark | Simulated Instructions | Run time | Simulated MIPS | Simulated Instructions | Run time | Simulated MIPS | Simulated Instructions | Run time | Simulated MIPS |
| linpack | 5,942,442,478 | 3.24s | 1834 | 1,214,194,084 | 0.81s | 1506 | 1,665,624,452 | 0.99s | 1682 |
| Dhrystone | 5,564,075,544 | 3.75s | 1488 | 4,920,070,302 | 3.38s | 1458 | 1,560,089,486 | 0.84s | 1857 |
| Whetstone | 12,726,977,092 | 8.46s | 1504 | 1,269,185,283 | 1.09s | 1164 | 1,894,381,527 | 0.76s | 2493 |
| peakSpeed2 | 27,000,012,085 | 3.61s | 7500 | 27,500,007,040 | 3.95s | 6962 | 5,600,004,984 | 0.79s | 7124 |
| | RISC-V RV64GC | | | ARM AARCH64 | | | Imagination MIPS64 | | |
| Benchmark | Simulated Instructions | Run time | Simulated MIPS | Simulated Instructions | Run time | Simulated MIPS | Simulated Instructions | Run time | Simulated MIPS |
| linpack | 2,423,371,379 | 1.1s | 2203 | 4,999,878,343 | 2.76s | 1812 | 1,843,945,304 | 0.95s | 1962 |
| Dhrystone | 5,600,060,511 | 3.43s | 1637 | 2,390,060,024 | 1.67s | 1431 | 1,794,088,951 | 1.59s | 1130 |
| Whetstone | 1,782,196,148 | 1.11s | 1606 | 1,576,656,496 | 1.68s | 939 | 1,453,142,044 | 0.64s | 2274 |
| peakSpeed2 | 28,000,002,559 | 4.98s | 5623 | 27,500,004,076 | 4s | 6875 | 28,000,004,416 | 5.34s | 5243 |
| | PowerPC | | | Renesas v850 | | | Synopsys ARC | | |
| Benchmark | Simulated Instructions | Run time | Simulated MIPS | Simulated Instructions | Run time | Simulated MIPS | Simulated Instructions | Run time | Simulated MIPS |
| linpack | 3,143,920,699 | 2.02s | 1557 | 5,372,682,210 | 3.62s | 1488 | 996,212,491 | 0.86s | 1159 |
| Dhrystone | 802,066,836 | 0.55s | 1458 | 12,790,132,941 | 8.01s | 1597 | 2,470,110,910 | 2.11s | 1171 |
| Whetstone | 6,424,865,755 | 3.94s | 1631 | 10,296,940,591 | 6.04s | 1708 | 1,214,268,961 | 0.68s | 1774 |
| peakSpeed2 | 27,500,003,291 | 6.48s | 4246 | 27,500,009,239 | 3.89s | 7069 | 28,500,007,430 | 3.97s | 7179 |
| | Altera Nios II | | | Xilinx MicroBlaze | | | OpenCores OR1K | | |
| Benchmark | Simulated Instructions | Run time | Simulated MIPS | Simulated Instructions | Run time | Simulated MIPS | Simulated Instructions | Run time | Simulated MIPS |
| linpack | 3,494,897,435 | 1.93s | 1811 | 10,871,290,698 | 4.39s | 2477 | 5,027,664,578 | 3.53s | 1426 |
| Dhrystone | 3,610,082,777 | 3.08s | 1176 | 7,620,119,106 | 4.98s | 1530 | 2,062,114,425 | 1.02s | 2042 |
| Whetstone | 5,850,887,389 | 2.67s | 2193 | 27,108,532,655 | 10.39s | 2609 | 11,151,873,005 | 5.2s | 2145 |
| peakSpeed2 | 27,000,014,679 | 3.71s | 7278 | 16,500,024,223 | 3.33s | 4955 | 39,000,012,784 | 7.35s | 5308 |

All measurements on 3.50GHz Intel i7-4770K, Linux FC20, OVPsim 201802210

Imperas decided to open up this technology and OVP is the vehicle to make it public.

OVP has three main components - the OVP APIs that enable a C model to be written, a library of free open source processor and peripheral models, and OVPsim a fast, easy to download and use reference simulator that executes these models.

There is also the iGen Model Building Wizard that is part of the OVP download and makes it easy to create platforms and models.

With OVP you can put together a simulation model of a platform, compile it to an executable, and connect it to your debugger to provide a very efficient fast embedded software development environment.

To read more about OVP visit: [Why?](#), [Virtual Platforms?](#), [Rationale?](#), [Continuous Integration](#), [Partners](#), [Licensing](#), [Downloading](#).

Appendix E

Information on Imperas Software tools



For the last 10 years [Imperas Software Limited](#) has been developing simulation technology, models, and tools to assist embedded software developers getting their software written, tested, and debugged.

For information on the Imperas Advanced Multicore Software Development Kit (M*SDK), the CPU Model Generator (cpuGen), Virtual Platform Simulation Acceleration (QuantumLeap), the Instruction Set Simulator (ISS), Virtual Platform Development and Simulation (C*DEV, S*DEV, M*DEV), or RISC-V solutions (RISC-V) - please visit: www.imperas.com/products.

To read about how Imperas solutions accelerate Embedded Software Development, how developers use simulation of virtual platforms in their continuous integration environments, and how automotive users adopt simulation for failsafe reliability verification - please visit: www.imperas.com/solutions. There are several case studies: www.imperas.com/imperas-case-studies.

To find out more about Imperas have a look at some of the many videos: www.imperas.com/imperas-videos.

Appendix F

Imperas License governing use of riscvOVPsim

Imperas Open Virtual Platforms Fixed Platform Technology
License for Fixed Platform Kits. Revised May 2018.
Imperas Software Limited.

Software License Agreement

This is a legal agreement between you, the user (“Licensee”) and Imperas Software Limited (“Imperas”). By downloading any Imperas Software Program including Binaries, Executables, and Application Programming Interfaces (“Software”) from the internet, or by otherwise installing or using the Software, Licensee agrees to be bound by the terms of this Software License Agreement (the “Agreement”).

If you do not agree to the terms on this license, you may not install, use or copy the software, and return the software to your supplier for a refund of any license fee paid (if any).

If Licensee is obtaining an update, then the term “Software” also includes, and the terms and conditions of this Agreement also apply to, any pre-existing Software and data provided within earlier Software releases, to the extent such earlier Software and data is retained by, embodied in or in any way used or accessed by the upgraded Software provided with this Agreement.

1) License for Software

Imperas grants to Licensee, a nonexclusive, nontransferable right to use the Software for a period of one year from the date of this release or until the Software expires (if earlier).

2) Copyright

Licensee shall not copy the Software, in whole or in part, except as necessary to archive such Software in accordance with the terms and conditions contained herein. All copies of the Software will be subject to all of the terms and conditions of this Agreement. Whenever Licensee is permitted to copy all or any part of the Software, all titles, trademark symbols, copyright symbols and legends and other proprietary markings must be reproduced. Licensee may not copy any part of the documentation, nor modify, adapt, translate into any language, or create derivative works based on the documentation without the prior written consent of Imperas.

3) Ownership

Imperas retains all right, title, and interest in the Software and documentation (and any copy thereof), and reserves all rights not expressly granted to Licensee. This License is not a sale of the original Software or of any copy.

4) Restrictions

This Software is licensed to Licensee for internal use only. Licensee acknowledges that the scope of the licenses granted hereunder do not permit Licensee (and Licensee shall not allow any third party) to:

- (i) Decompile, disassemble, reverse engineer or attempt to reconstruct, identify or discover any source code, underlying ideas, underlying user interface techniques or algorithms of the Software by any means whatever, or disclose any of the foregoing;
- (ii) Modify, incorporate into or with other Software, or create a derivative work of any part of the Software;
- (iii) Disclose the results of any benchmarking of the Software, or use such results for its own competing Software development activities, without the prior written permission of Imperas.

5) Transfer, Distribution

Licensee shall not sublicense, transfer or assign this Agreement or any of the rights or licenses granted under this Agreement, without the prior written consent of Imperas. Licensee shall not redistribute or otherwise provide the Software to any third party.

6) Termination

Imperas may terminate this Agreement or any license granted under it, without notice, in the event of breach or default by Licensee. Upon termination, Licensee will relinquish all rights under this Agreement, and must cease using the Software and return or destroy, at Imperas' discretion, all copies (and partial copies) of the Software and documentation, and if destroyed, provide written certification of destruction. The provisions of sections 2, 3, 6, 9 and 11 shall survive any termination of this Agreement.

7) Export

Licensee agrees not to allow the Software to be sent or used in any country except in compliance with applicable U.K. and US laws and regulations.

8) Warranty and Disclaimer

8.1 Limited Warranty

Imperas warrants that the Software will perform substantially in accordance with the accompanying documentation for a period of ninety (90) days from the date of receipt, provided that it is used in accordance with the product documentation provided by Imperas, that all associated products (such as hardware, Software, firmware and the like) used in combination with the Software properly exchange data with it, and that Licensee is covered under a services or maintenance agreement with Imperas regarding the Software.

Imperas' entire liability and Licensee's exclusive remedy for a breach of the preceding limited warranties shall be, at Imperas' option, either (a) return of the license fee, or (b) providing a fix, patch, or replacement of the Software that does not meet such limited warranty. Any replacement will be warranted for the remainder of the original warranty period or 30 days, whichever is longer.

8.2 Disclaimer

EXCEPT AS EXPRESSLY SET FORTH ABOVE, NO OTHER WARRANTIES OR CONDITIONS, EITHER EXPRESSED OR IMPLIED, ARE MADE BY IMPERAS WITH RESPECT TO THE SOFTWARE AND THE ACCOMPANYING DOCUMENTATION (STATUTORY OR OTHERWISE), AND IMPERAS EXPRESSLY DISCLAIMS ALL WARRANTIES AND CONDITIONS NOT EXPRESSLY STATED HEREIN, INCLUDING BUT NOT LIMITED TO THE IMPLIED WARRANTIES OR CONDITIONS OF MERCHANTABILITY, NONINFRINGEMENT, AND FITNESS FOR A PARTICULAR PURPOSE. IMPERAS DOES NOT WARRANT THAT THE FUNCTIONS CONTAINED IN THE SOFTWARE WILL MEET LICENSEE'S REQUIREMENTS, BE UNINTERRUPTED OR ERROR FREE, OR THAT ALL DEFECTS IN THE PROGRAM WILL BE CORRECTED.

Licensee assumes the entire risk as to the results and performance of the Software.

9) Limitation of Liability

LICENSEE AGREES THAT IN NO EVENT SHALL IMPERAS OR ITS AGENTS BE LIABLE FOR ANY INDIRECT, SPECIAL, CONSEQUENTIAL OR INCIDENTAL DAMAGES WHATSOEVER (INCLUDING, WITHOUT LIMITATION, DAMAGES FOR LOSS OF BUSINESS PROFITS, BUSINESS INTERRUPTIONS, LOSS OF BUSINESS INFORMATION, OR OTHER PECUNIARY LOSS) ARISING OUT OF USE OF OR INABILITY TO USE THESE IMPERAS PRODUCTS, EVEN IF IMPERAS HAS BEEN ADVISED OF THE POSSIBILITY OF SUCH DAMAGES.

In no event will Imperas be liable to Licensee for damages in an amount greater than the fees paid for the use of the Software.

10) Indemnity

In the event that a claim alleging infringement of an intellectual property right arises concerning the Software (including but not limited to patent, trade secret, copyright or trademark rights), Imperas in its sole discretion may elect to defend or settle such claim. Imperas in the event of such a claim may also in its sole discretion elect to terminate this Agreement and all rights to use the Software, and require the return or destruction of the Software, with a refund of the fees paid for use of the Software less a reasonable allowance for use.

11) Miscellaneous

If Licensee is a corporation, partnership or similar entity, then the license to the Software that is granted under this Agreement is expressly conditioned upon acceptance by a person who is authorized to sign for and bind the entity. This Agreement is the entire agreement between Licensee and Imperas with respect to the license to the Software, and supersedes any previous oral or written communications or documents (including, if you are obtaining an update, any agreement that may have been included with the initial version of the Software). This Agreement is with Imperas Software Limited, a company registered in England # 6779752 having its registered office at North Weston Thame OX9 2HA, U.K. and will be construed, interpreted, and applied in accordance with the laws of England and Wales (excluding its body of law controlling conflicts of law). This Agreement is the complete and exclusive statement regarding the subject matter of this Agreement and supersedes all prior agreements, understandings and communications, oral or written, except a valid Software License Agreement, between the parties regarding the subject matter of this Agreement. This Agreement will not be governed by the U.N. Convention on Contracts for the International Sale of Goods. If any provision of this Agreement is found to be invalid or unenforceable, it will be enforced to the extent permissible and the remainder of this Agreement will remain in full force and effect. Failure to prosecute a party's rights with respect to a default hereunder will not constitute a waiver of the right to enforce rights with respect to the same or any other breach.

12) U.S. Government Users

Use, reproduction, release, modification, or disclosure of this commercial computer Software, or of any related documentation of any kind, is restricted in accordance with FAR 12.212 and DFARS 227.7202, and further restricted by this License Agreement.

13) Bugs and Issues

It is a condition of use of the Software that you promptly report any bugs or issues to support@imperas.com; any modifications to the Software, Documentation, or related models arising out of any such report shall be the sole property of Imperas.

14) Publicity

Imperas may at its discretion include your organization in its published list of users.

Imperas Privacy Statement may be found at this link <http://www.imperas.com/privacy-statement>

.

15) Third Party Software

A deliverable may include third party software and usage of these are covered by their own appropriate licenses.

(License for Fixed Platform Kits. Revised May 2018.) #